Impulsive decision-making

Psychometric, experimental and neuroimaging approaches

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Abstract

Impulsivity is a highly heterogeneous umbrella term, subsuming various traits and behaviours. An important behavioural construct is impulsive decision-making, often measured as temporal discounting in intertemporal choices, i.e., the tendency to discount future rewards as a function of delay until receipt. While impulsivity and impulsive decision-making have been extensively studied, many research questions remain unanswered. First, given the heterogeneity of impulsivity, its psychometric structure needs to be examined further. Second, impulsive decision-making has been shown to be malleable using time framing. Specifically, the date/delay effect demonstrates that temporal discounting is reduced when time is displayed in terms of dates rather than delay units. However, the cognitive and neural mechanisms of this effect are unclear. Third, recent findings suggest that temporal discounting could be a transdiagnostic marker of multiple mental disorders. Yet, transdiagnostic studies on temporal discounting are scarce.

This dissertation therefore examined the topic of impulsivity as well as the malleability and transdiagnostic changes of impulsive decision-making across five empirical studies and two narrative reviews. In Study I, the structure of impulsivity was examined using confirmatory factor and network analyses of trait and intertemporal choice measures. In Studies II and III, the cognitive and neural mechanisms of the date/delay effect were investigated using eye-tracking and functional magnetic resonance imaging (fMRI). In Studies IV and V, dimensional approaches to mental disorders were used to test associations between temporal discounting, the date/delay effect and schizotypy as well as a broader range of psychopathological dimensions. Finally, in Reviews I and II, the literature on individual differences and time perception in intertemporal choice was summarised.

Taken together, the studies and reviews confirmed the heterogeneous nature of impulsivity, detecting low yet significant correlations between most measures. The findings challenge the previously postulated separability of positive and negative urgency and suggest that lack of premeditation is central within the trait impulsivity network (Study I). Moreover, the date/delay effect was consistently replicated (Studies II–V). Compared to the delay condition, the date condition was associated with longer fixation times on and more saccades between time attributes as well as higher activation of brain regions relevant to episodic processing. This indicates that time perception differs in the two conditions (Studies II–III). Finally, whilst results on the association between schizotypy and temporal discounting were ambiguous, transdiagnostic dimensions reflecting anxiety/depression and inattention/impulsivity/overactivity were positively associated with temporal discounting. The date/delay effect was particularly effective in people scoring higher on positive schizotypy and the inattention/impulsivity/overactivity dimension (Studies IV–V). Overall, the findings give insights into the heterogeneous nature of impulsivity, the robustness and mechanisms of the date/delay effect and the transdiagnostic role of temporal discounting.

Zusammenfassung

Impulsivität stellt einen heterogenen Oberbegriff für verschiedene Eigenschaften und Verhaltensweisen dar. Ein wichtiges behaviorales Konstrukt besteht in der impulsiven Entscheidungsfindung. Diese wird oft als Temporal Discounting im Rahmen von intertemporalen Entscheidungen erfasst, d.h. als die Tendenz, künftige Belohnungen in Abhängigkeit der Verzögerung bis zu deren Erhalt abzuwerten. Auch wenn Impulsivität und impulsive Entscheidungsfindung bereits umfassend erforscht wurden, bleiben viele Forschungsfragen unbeantwortet. Erstens sollte die psychometrische Struktur von Impulsivität angesichts der Heterogenität des Begriffs weiter untersucht werden. Zweitens konnte bereits belegt werden, dass impulsive Entscheidungsfindung durch das Framing von Zeitangaben beeinflusst werden kann. So zeigt der Date/Delay Effect, dass Temporal Discounting verringert wird, wenn Zeit in Form von Daten anstelle von Zeiteinheiten präsentiert wird. Allerdings sind die kognitiven und neuronalen Mechanismen dieses Effekts unklar. Drittens legen jüngste Erkenntnisse nahe, dass Temporal Discounting ein transdiagnostischer Marker mehrerer psychischer Störungen sein könnte. Bislang gibt es aber nur wenige Studien zur transdiagnostischen Rolle von Temporal Discounting.

Diese Dissertation untersuchte daher das Thema Impulsivität sowie die Beeinflussbarkeit und transdiagnostischen Veränderungen von impulsiver Entscheidungsfindung in fünf Studien und zwei Überblicksartikeln. In Studie I wurde die Struktur von Impulsivität mithilfe konfirmatorischer Faktoren- sowie Netzwerkanalysen von Persönlichkeits- und intertemporalen Entscheidungsmaßen der Impulsivität untersucht. In den Studien II und III wurden die kognitiven und neuronalen Mechanismen des Date/Delay Effects mithilfe von Eye-Tracking und funktioneller Magnetresonanztomographie (fMRT) erforscht. In den Studien IV und V wurden dimensionale Ansätze zu psychischen Störungen verwendet, um Erkenntnisse über Assoziationen zwischen Temporal Discounting, dem Date/Delay Effect und Schizotypie bzw. einem umfassenderen Spektrum an psychopathologischen Dimensionen zu gewinnen. Schließlich wurde in zwei Überblicksartikeln Literatur zu individuellen Unterschieden (Überblick I) und Zeitwahrnehmung (Überblick II) in intertemporalen Entscheidungen zusammengefasst.

Insgesamt bestätigten die Studien und die Überblicksartikel die Heterogenität von Impulsivität, da sie geringe, aber signifikante Korrelationen zwischen den meisten Impulsivitätsmaßen feststellten. Die Ergebnisse stellen die zuvor postulierte Trennbarkeit von positiver und negativer Dringlichkeit infrage und legen nahe, dass Mangel an Vorbedacht zentral im Persönlichkeitsnetzwerk der Impulsivität ist (Studie I). Darüber hinaus wurde der Date/Delay Effect konsistent repliziert (Studien II–V). Im Vergleich zur Delay-Bedingung war die Date-Bedingung mit längeren Fixationszeiten auf und mehr Sakkaden zwischen Zeitattributen sowie einer höheren Aktivität von Hirnregionen, die für die Verarbeitung episodischer Informationen relevant sind, assoziiert. Dies weist auf eine

unterschiedliche Zeitwahrnehmung in den beiden Bedingungen hin (Studien II–III). Während die Ergebnisse bezüglich der Assoziation von Schizotypie und Temporal Discounting uneindeutig waren, waren transdiagnostische Dimensionen, die Ängstlichkeit/Depression und Unaufmerksamkeit/Impulsivität/Überaktivität abbilden, positiv mit Temporal Discounting assoziiert. Der Date/Delay Effect war besonders effektiv bei Personen, die höhere Werte in positiver Schizotypie und der Dimension Unaufmerksamkeit/Impulsivität/Überaktivität aufwiesen (Studien IV–V). Alles in allem liefern die Befunde Erkenntnisse über die Heterogenität von Impulsivität, die Robustheit und Mechanismen des Date/Delay Effects und die transdiagnostische Rolle von Temporal Discounting.

Declaration

I hereby declare that:

i. the thesis comprises only my original work towards the Doctor of Philosophy except where indicated in the preface;
ii. due acknowledgement has been made in the text to all other material used; and
iii. the thesis is fewer than the maximum word limit (100,000 words) in length, exclusive of tables, maps, bibliographies and appendices.

Signed:

Kristof Keidel

Preface

The work presented in this thesis is a product of fruitful collaborations with my supervisors and co-authors, and I thank them for their invaluable support.

Contribution Declaration: Empirical Studies

All studies presented in Chapter 3.1 and Appendices A–E of this work are based on multi-co-authored publications to which I contributed more than 50% of the content. Although the conditions of the Graduate Research Training Policy of the University of Melbourne to include these studies as chapters were met, for conciseness, only summaries were provided in Chapter 3.1 (full versions in Appendices A–E).

Study I

Kristof Keidel, Ulrich Ettinger, Carsten Murawski, Bertalan Polner
The network structure of impulsive personality and temporal discounting
Published by the *Journal of Research in Personality* on 13/11/2021.

Author contributions:

- KK contributed 75% of the content of the article.
- KK, UE, and BP conceptualised the study; KK collected and curated the data; KK, UE, CM and BP analysed the data; KK and BP visualised the data; KK wrote the first draft of the manuscript; KK, UE, CM and BP all contributed to manuscript writing and revision and read and approved the final version of the manuscript.

Study II

Kristof Keidel, Carsten Murawski, Ulrich Ettinger
Attentional mechanisms of the date/delay effect in intertemporal choice: An eye-tracking study
Published by the *Journal of Experimental Psychology: Learning, Memory, and Cognition* on 20/06/2024.

Author contributions:

- KK contributed 80% of the content of the article.
- KK and UE conceptualised the study; KK collected and curated the data; KK, CM and UE analysed the data; KK visualised the data; KK wrote the first draft of the manuscript; KK, CM and UE all contributed to manuscript writing and revision and read and approved the final version of the manuscript.

Study III

Kristof Keidel, Rebekka Schröder, Peter Trautner, Alexander Radbruch, Carsten Murawski, Ulrich Ettinger
The date/delay effect in intertemporal choice: A combined fMRI and eye-tracking study
Published by *Human Brain Mapping* on 24/02/2024.

Author contributions:

- KK contributed 75% of the content of the article.
- KK, CM and UE conceptualised the study; KK and RS collected and curated the data; KK and UE analysed the data; KK visualised the data; KK wrote the first draft of the manuscript; KK, RS, PT, AR, CM and UE all contributed to manuscript writing and revision and read and approved the final version of the manuscript.

Study IV

Kristof Keidel, Carsten Murawski, Christos Pantelis, Ulrich Ettinger
The relationship between schizotypal personality traits and temporal discounting: The role of the date/delay effect
Accepted for publication by *Schizophrenia Bulletin* on 13/07/2023.

Author contributions:

- KK contributed 80% of the content of the article.
- KK and UE conceptualised the study; KK collected and curated the data; KK, CM and UE analysed the data; KK visualised the data; KK wrote the first draft of the manuscript; KK, CM, CP and UE all contributed to manuscript writing and revision and read and approved the final version of the manuscript.

Study V

Kristof Keidel, Xiaping Lu, Shinsuke Suzuki, Carsten Murawski, Ulrich Ettinger
Association of temporal discounting with transdiagnostic symptom dimensions
Published by *npj Mental Health Research* on 16/04/2024.

Author contributions:

- KK contributed 75% of the content of the article.
- KK, XL, SS, CM and UE conceptualised the study; KK and XL collected and curated the data; KK, CM and UE analysed the data; KK visualised the data; KK wrote the first draft of the manuscript; KK, XL, SS, CM and UE all contributed to manuscript writing and revision and read and approved the final version of the manuscript.

Contribution Declaration: Narrative Reviews

The two narrative reviews presented in Chapter 3.2 and Appendices F–G of this work are based on multi-co-authored publications to which I contributed less than 50% of the content. In line with the Graduate Research Training Policy of the University of Melbourne, the publications were not used to form a thesis chapter, but summaries were provided in Chapter 3.2 (full versions in Appendices F–G).

Review I

Kristof Keidel, Qëndresa Rramani, Bernd Weber, Carsten Murawski, Ulrich Ettinger
Individual differences in intertemporal choice
Published by *Frontiers in Psychology* on 16/04/2021.

Author contributions:

- KK contributed 35% of the content of the article; KK and QR contributed equally to this work.
- UE, CM, and BW developed the idea of the review; KK, QR, CM and UE decided on the concrete conception and did the literature research; KK, QR, CM and UE wrote the manuscript; KK, QR, BW, CM and UE contributed to manuscript writing and revision and read and approved the final version of the manuscript.

Review II

Ulrich Ettinger, Kristof Keidel, Carsten Murawski
Temporal cognition, impulsivity and intertemporal choice
Published by *Verlag Karl Alber* in the book *Mind and Time* (Ed. D. Sturma) in 2023 (not peer-reviewed).

Author contributions:

- KK contributed 30% of the content of the article.
- UE developed the idea of the review; UE, KK and CM decided on the concrete conception and did the literature research; UE, KK and CM wrote the manuscript. UE, KK and CM contributed to manuscript writing and revision and read and approved the final version of the manuscript.

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Finally, I want to thank my partner, Marie-Claire. You encouraged me to ask Uli about a PhD position in the first place, and your unwavering confidence and support continued throughout my whole PhD journey. I can't thank you enough for being there all of the time, even when it meant that you needed to move to the other side of the globe with me. Wherever our future travels will lead us and whatever is yet to come, I will be happy because you are with me. Always.

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List of Abbreviations

Abbreviation	Meaning
ACC	anterior cingulate cortex
ADHD	attention-deficit/hyperactivity disorder
AIC	Akaike information criterion
AOI	area of interest
AQ-Short	Autism-Spectrum Quotient Short
ASRS	Adult ADHD Self-Report Scale V1.1
AUC	area under the curve
BIS	Barratt's Impulsiveness Scale
BOLD	Blood Oxygen Level Dependent
CFI	comparative fit index
CFM	computational factor modelling
CNG test	Cartell-Nelson-Gorsuch test
COG	constraints on generality
DASS-21	Depression Anxiety Stress Scales 21
dlPFC	dorsolateral prefrontal cortex
DSM	Diagnostic and Statistical Manual of Mental Disorders
EEG	electroencephalography
fMRI	functional magnetic resonance imaging
GLM	general linear model
GWAS	genome-wide association studies
HiTOP	Hierarchical Taxonomy of Psychopathology
HRF	haemodynamical response function
ICD	International Classification of Diseases
lOFC	lateral orbitofrontal cortex
MCC	mid-cingulate cortex
MCMC	Markov chain Monte Carlo

Abbreviation	Meaning
MCQ	Monetary Choice Questionnaire
MFG	middle frontal gyrus
mOFC	medial orbitofrontal cortex
mPFC	medial prefrontal cortex
MR signal	magnetic resonance signal
MRI	magnetic resonance imaging
OCD	obsessive-compulsive disorder
OCI–R	Obsessive-Compulsive Inventory–Revised
O-LIFE	Oxford-Liverpool Inventory of Feelings and Experiences
PCA	principal component analysis
PCC	posterior cingulate cortex
P–CR	pupil–corneal reflection
PET	positron emission tomography
pMFC	posterior medial frontal cortex
RDoC	Research Domain Criteria
RMSEA	root mean square error of approximation
ROI	region of interest
SFG	superior frontal gyrus
sO-LIFE	Short Oxford-Liverpool Inventory of Feelings and Experiences
SRMR	standardised root mean square residual
STAI-S	State-Trait Anxiety Inventory (state version)
STAI-T	State-Trait Anxiety Inventory (trait version)
sUPPS-P	Short UPPS-P Impulsive Behavior Scale
TE	echo time
TFEQ-R18	Three-Factor Eating Questionnaire-R18
TLI	Tucker-Lewis index
TMS	transcranial magnetic stimulation
TR	repetition time

Abbreviation	Meaning
UPPS	UPPS Impulsive Behavior Scale
UPPS-P	UPPS-P Impulsive Behavior Scale
vlPFC	ventrolateral prefrontal cortex
vmPFC	ventromedial prefrontal cortex
vS	ventral striatum

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Figures

Figure 2 | Search strategies in intertemporal choice (p. 35)

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Figure 3 | Neural mechanisms of intertemporal choice (p. 43)

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Figure 5 | Computational factor modelling (p. 65)

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Figure 8 | Key results of Study I (p. 75)

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Panel E: Adapted from *Journal of Research in Personality*, *98*, Keidel, K., Ettinger, U. Murawski, C., & Polner, B., Corrigendum to 'The network structure of impulsive personality and temporal discounting' [J. Res. Pers. 96 (2022) 104166], Article 104241 (corrected Figure 4 on p. 2), Copyright (2022). The reuse of figures is in accordance with Elsevier's copyright policy and author rights.

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Adapted from *Human Brain Mapping*, *45*(3), Keidel, K., Schröder, R., Trautner, P., Radbruch, A., Murawski, C., & Ettinger, U., The date/delay effect in intertemporal choice: A combined fMRI and eye-tracking study, Article e26585 (Figures 4 and 5 on pp. 12 and 14), Copyright (2024). Licensed under CC BY 4.0.

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Adapted from *npj Mental Health Research*, Keidel, K., Lu, X., Suzuki, S., Murawski, C., Ettinger, U., Association of temporal discounting with transdiagnostic symptom dimensions, *3*, Article 13 (Figure 3 on p. 7), Copyright (2024). Licensed under CC BY 4.0.

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Table 4 | Key result of Study IV: Pearson correlations (p. 81)

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Table 5 | Key result of Study IV: Regression predicting the date/delay effect (p. 81)

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I want it all,
And I want it now.

– Brian Harold May, Queen (1989)

1 Introduction

1.1 The Umbrella of Impulsivity

Have you ever felt the urge to throw something around the room because you were upset? Have you ever said something you did not mean to say because it just burst out of you? Have you ever chosen to eat a doughnut instead of a much healthier apple?

The behaviours listed above are commonly referred to as *impulsive*. However, given that these exemplary behaviours intuitively differ, the question arises as to how they can be put under a single umbrella. In other words, how can impulsivity be comprehensively defined?

1.1.1 Definition of Impulsivity

To understand the heterogeneous nature of the psychological construct *impulsivity*, it may help to examine its origins. Etymologically, impulsivity stems from the Latin word *impellere* (Klein, 1971), which has many different but mostly related meanings, such as *to strike or beat against*, *set in motion*, *drive*, *push*, *compel to go*, *overthrow*, *impel*, *urge on* or *constrain* (Oxford Latin Dictionary, 1968). Regarding the psychological origins, the term impulsivity seems to be rooted in as many historical perspectives as there are etymological meanings. To name just a few, impulsive behaviours have been associated with phrenological regions, psychiatric phenotypes, personality traits and behavioural task results (Moeller, 2012). Considering these various approaches to impulsivity, it is unsurprising that the perspective on impulsivity in modern psychology is not unitary. Instead, three general perspectives have evolved (Moeller, 2012). The first is a clinical perspective that classifies symptoms of pathological groups as extremely impulsive, which is helpful in the diagnosis and treatment of mental disorders such as impulse-control disorders, attention-deficit/hyperactivity disorder (ADHD) or behavioural addictions (American Psychiatric Association, 2013). The second is a personality perspective that defines impulsivity as a dimensional trait with interindividually varying manifestations. The third is a behavioural perspective that investigates impulsivity based on observable behaviours (e.g., laboratory tasks). In an attempt to subsume these various perspectives, a general definition in modern psychology presents impulsivity as “a predisposition toward rapid, unplanned reactions to internal or external stimuli without regard to the negative consequences of these reactions to the impulsive individual or to others” (Moeller et al., 2001, p. 1784). Of note, this definition only refers to actions with *negative* consequences, thus excluding views that also comprise a functional part of impulsivity (Dickman, 1990). However, despite the existence of such comprehensive definitions, the examples,

etymological and historical roots as well as different modern approaches substantiate that impulsivity is a highly heterogeneous umbrella term (Evenden, 1999). This is a problem given that the numerous phenomena associated with impulsivity may lead to misunderstandings (Strickland & Johnson, 2021; Whiteside & Lynam, 2001), such as the so-called *jingle-* (i.e., two different constructs are perceived to be the same because they are named the same) or *jangle-fallacies* (i.e., two identical constructs are perceived to be different because they are named differently; Marsh, 1994). Ultimately, the heterogeneity of impulsivity on psychometric, neuroscientific and clinical levels has led to claims to reject impulsivity as a unitary psychological construct (see Strickland & Johnson, 2021, for a comprehensive discussion). Different researchers have therefore proposed that impulsivity comprises several correlated constructs (Evenden, 1999; Strickland & Johnson, 2021). While following the broad definition by Moeller et al. (2001), I will build upon this idea in this dissertation.

1.1.2 Assessment of Impulsivity

The three currently dominant perspectives on impulsivity in psychology (psychopathology, traits, behaviour) suggest that impulsivity can be assessed in different ways. While practical clinical approaches usually employ diagnostic interviews and semi-standardised procedures to deduce categorical diagnoses or ratings of symptom severity, psychological research mainly focuses on self-report questionnaires to assess dimensional personality traits and laboratory tasks to measure concrete behaviours (MacKillop et al., 2016; L. Sharma et al., 2014).

Many self-report questionnaires assess different constructs within the framework of trait impulsivity. Prominent among them are *Eysenck's Impulsiveness Scale* (S. B. G. Eysenck et al., 1985), *Dickman's Impulsivity Inventory* (Dickman, 1990), *Barratt's Impulsiveness Scale* (BIS; Barratt, 1959; Patton et al., 1995) and the *UPPS* or *UPPS-P Impulsive Behavior Scale* (Cyders et al., 2014; Lynam et al., 2006; Whiteside & Lynam, 2001). According to the number of citations reported in Web of Science (last checked: 19/02/24), the BIS (newest revision by Patton et al., 1995: 5,607 citations) and the UPPS (Whiteside & Lynam, 2001: 2,731 citations) have been the most widely used impulsivity questionnaires in research.

The BIS was originally created in an attempt to relate impulsivity, separate from anxiety, to psychomotor learning (Barratt, 1959). While Barratt conceptualised impulsivity as a unidimensional construct in the original version, later studies analysing the factor structure of impulsivity (e.g., Barratt, 1965) convinced him of its multidimensionality, thereby influencing the further development of the BIS (Barratt, 1994; Stanford et al., 2009). The BIS has been subject to numerous revisions, the latest of which (BIS-11; Patton et al., 1995) assesses 30 items reflecting the three second-order factors *attentional impulsiveness*

(tendency to lack focused attention and concentration), *motor impulsiveness* (tendency to act without thinking) and *nonplanning impulsiveness* (tendency to act without considering future consequences), each separated into two first-order factors. Interestingly, despite Barratt's change of mind towards a multidimensional conception of impulsivity, subscale scores have often been combined into a total score, i.e., a general impulsivity index (Stanford et al., 2009).

In contrast to the original version and common scoring practice of the BIS, the UPPS was constructed to explicitly disentangle different impulsivity-related constructs. Specifically, to identify latent dimensions of trait impulsivity across common self-report measures, Whiteside and Lynam (2001) conducted a principal component analysis (PCA) on responses by 437 young adults to items from well-known questionnaires of impulsivity and related constructs. They discovered four distinct yet related personality traits: *urgency* (tendency to act rashly under negative affect), *lack of premeditation* (tendency to act without thinking), *lack of perseverance* (tendency to give up on bland and monotone tasks) and *sensation seeking* (tendency to engage in new and exciting activities). Based on the factor loadings, Whiteside and Lynam (2001) constructed a 45-item measure of trait impulsivity (UPPS) to assess these four distinct constructs. Five years later, a 14-item *positive urgency* (tendency to act rashly under positive affect) scale was added (Lynam et al., 2006). After renaming the original urgency factor *negative urgency*, the UPPS-P scale comprises 59 items and assesses five impulsivity constructs. A short scale (sUPPS-P) comprising 20 items was developed in 2014 (Cyders et al., 2014).

Both the BIS and the UPPS/UPPS-P measure different trait impulsivity constructs, are widely used and have generally proven valid by their associations with affect, cognitions and behaviour in non-clinical samples and with various diagnostic categories in clinical samples (Berg et al., 2015; Hook et al., 2021; Sperry et al., 2016, 2018; Vasconcelos et al., 2012). However, differences in their development and commonly used scorings illustrate that the UPPS-P aligns better than the BIS with the heterogeneous understanding of impulsivity. Therefore, most studies of this dissertation assessed trait impulsivity using the UPPS-P or sUPPS-P (**Studies I, II, III and V**).

While there seems to be a general agreement that impulsive personality comprises a moderate number of distinct yet related constructs, there is less consensus regarding conceptualisations of behavioural impulsivity tasks (Dick et al., 2010; Fineberg et al., 2014; Stahl et al., 2014; Strickland & Johnson, 2021). This is probably because behavioural approaches were developed not only independently of personality approaches but also largely independently of each other (Strickland & Johnson, 2021). As such, behavioural impulsivity tasks tap different factors (Dick et al., 2010; Fineberg et al., 2014; Stahl et al., 2014; Strickland & Johnson, 2021), such as *behavioural/response inhibition* (inability to stop prepotent motor responses; Bari & Robbins, 2013), *impulsive decision-making* or *choice impulsivity* (tendency to prefer smaller-sooner over larger-later rewards; Hamilton et al., 2015), *reflection impulsivity* (tendency to collect insufficient information before making a decision; Kagan, 1966; Messer, 1976) or *disadvantageous, risky decision-making*

(tendency to make too risky decisions; Buelow & Blaine, 2015). While different terms are often used to refer to the factors, it is noteworthy that the subdivisions of behavioural impulsivity have clear commonalities. Perhaps most consistently, most models include a component referring to the tendency to prefer smaller-sooner over larger-later rewards, i.e., impulsive decision-making. Impulsive decision-making is a central topic of this dissertation, which will be comprehensively introduced in Section 1.2.

1.1.3 Structure of Impulsivity

This dissertation will focus on the UPPS-P constructs reflecting trait impulsivity and impulsive decision-making as a construct reflecting behavioural impulsivity. However, it should be emphasised that even when narrowing down impulsivity to these constructs, many definitory questions are yet to be answered.

For instance, regarding the UPPS-P, the proposed five-factor structure of both the UPPS-P and the sUPPS-P was replicated in later studies (Cyders et al., 2014; Cyders & Smith, 2007; Teese et al., 2021), but recent studies raised considerable doubts about the structure of the UPPS-P by finding overlaps between some constructs. Specifically, hierarchical models in which positive and negative urgency loaded onto an overall urgency factor and lack of premeditation and lack of perseverance onto a lack of conscientiousness factor also provided a reasonably good fit (Cyders & Smith, 2007; Teese et al., 2021; Zsila et al., 2020). Consequentially, the separability of positive and negative urgency on the one hand and lack of premeditation and lack of perseverance on the other has been questioned (Berg et al., 2015; Billieux et al., 2021; Goh et al., 2020; Sperry et al., 2018), potentially representing jangle-fallacies.

Moreover, considering the high heterogeneity within impulsivity, one may ask what is at its definitory core. According to L. Sharma et al. (2014), a cognitive factor may be a promising candidate because, while independent of affect in the first place, it influences affective responses more indirectly and generally. Such a cognitive factor may be the lack of premeditation factor in the UPPS-P, as it seems to reflect the definition by Moeller et al. (2001) most closely and is at least moderately correlated with all other UPPS-P constructs (Cyders et al., 2014; Goh et al., 2020; MacKillop et al., 2016; J. Miller et al., 2003; Whiteside & Lynam, 2001). On the other hand, low correlations with some behavioural tasks (MacKillop et al., 2016) and psychopathologies (Berg et al., 2015; J. Miller et al., 2003) challenge the central role of lack of premeditation for the whole impulsivity construct. So far, however, studies on core features of impulsivity are sparse.

A novel approach that may not only give new insights into the structure of impulsivity but also uncover its core features is the *network approach*. Often contrasted with the factor analytical approach, the network approach, which is based on *psychological network theory*, posits that psychological phenomena such as psychopathological symptoms

(Borsboom & Cramer, 2013) or personality traits (Costantini et al., 2015, 2021; Cramer et al., 2012) arise not necessarily through higher-order factors but through interplays between elements, i.e., nodes in a network. As such, they allow to examine the structure of (trait) impulsivity from a new perspective, delivering insights beyond traditional factor analytical approaches. Additionally, the possibility to map the relative importance of psychological constructs such as mental disorders (Borsboom & Cramer, 2013; Robinaugh et al., 2020) or personality traits (Costantini et al., 2015, 2021; Cramer et al., 2012) to each other by using various centrality parameters (see Section 2.2.3) allows to identify core features of impulsivity. However, no study had examined the network of impulsivity at the start of this PhD. After preregistration of **Study I**, a study was published focusing on the UPPS-P at scale level (Goh et al., 2020). Results underscore the close relations between the urgency constructs as well as between lack of premeditation and lack of perseverance and a potentially central position of lack of premeditation within a scale-network (Goh et al., 2020). Further research is clearly needed to replicate this result in larger samples and on a more specific item level. Beyond that, network associations between *different* types of impulsivity have hardly been studied, constituting a critical gap in the literature. Therefore, one aim of the current dissertation was to further investigate the structure of the sUPPS-P combining factor analytical and network approaches and to examine network associations between impulsivity traits and a behavioural measure of impulsivity, i.e., impulsive decision-making (**Study I**).

1.2 Impulsive Decision-Making

In his chapter on the historical perspectives on impulsivity and impulse control disorders, Moeller (2012) summarised that "[i]n the future study of impulsivity [...], it will become increasingly important to be specific in defining what is being referred to" (p. 19). Similarly, though more explicitly, Strickland and Johnson (2021) proposed in their review to reject impulsivity as a psychological construct and "shift focus [from the term impulsivity] to the more clearly labeled and defined constructs" (p. 353). Therefore, this dissertation henceforth explicitly focuses not on the umbrella term *impulsivity* but on specific constructs within impulsivity. An important construct is *impulsive decision-making*, i.e., a tendency to prefer smaller-sooner over larger-later rewards. It should be noted that in different conceptualisations, it has also been referred to as *choice impulsivity* (Fineberg et al., 2014), *motivational impulsivity* (Stahl et al., 2014), *delay response* (Dick et al., 2010) or *delayed consequence sensitivity* (Strickland & Johnson, 2021).

1.2.1 Intertemporal Choice: Measuring Temporal Discounting

Impulsive decision-making can be studied in situations involving so-called *intertemporal choices*. Intertemporal choices describe decisions with a trade-off between the size of a reward and the time until the reward materialises (Frederick et al., 2002). Typically, these decisions reflect choices between a smaller reward available sooner and a larger reward available later. Reading these definitions, psychologists might be reminded of the *delay of gratification* framework by Walter Mischel (Mischel et al., 1989). Indeed, typical operationalisations to assess delay of gratification, such as choosing between one marshmallow now and two marshmallows later (Mischel, 2014), are examples of intertemporal choices. However, intertemporal choices are only related to, yet distinct from, the typical delay of gratification setup, in which children have to sustain a choice of a larger reward to be expected at a non-specified timepoint in the future in lieu of a smaller reward continually present (Reynolds & Schiffbauer, 2005). That is, delay of gratification explicitly focuses on self-control or willpower, which has to be exerted over an unknown but usually short time period, thereby reflecting a recursive intertemporal choice process. Other examples of intertemporal choices that do not necessarily focus on constructs such as self-control may illustrate that intertemporal choices reflect a broader concept. A typical example in everyday life is choosing between spending money on a night out or saving it for an overseas holiday (example from **Review I**). While this decision may occur recursively as well (e.g., "Should I stay or should I go?"), people usually commit to one option at a point in time (e.g., "I won't go out tonight."). Importantly, higher gratification can theoretically also be gained by a night out, so staying is not necessarily profitable. Another example of an intertemporal choice is the decision between eating a doughnut or an apple. Since we might eat the doughnut at the same time as we would have eaten the apple, this scenario exemplifies that intertemporal decision-making is not only about the time point of *receiving* the reward itself but also about the *payoffs*, or *utilities*, associated with it. That is, a doughnut may satisfy our desire to enjoy eating some high-calorie food right now, but – especially when choosing the doughnut repeatedly – it might be at the expense of our health compared to choosing an apple.

A phenomenon stemming from intertemporal choices is the tendency of *temporal discounting* or *delay discounting*. Temporal discounting is defined as subjectively devaluing a future reward as a function of delay until receipt (Frederick et al., 2002). This is typically measured with tasks in which individuals make a range of choices between smaller-sooner and larger-later rewards, for example, "Would you prefer 69€ today or 85€ in 91 days?" (item 15 from the measure by Kirby et al., 1999; see Section 2.3). While there are animal models and task variations with different outcome types (e.g., food, drugs, sexual outcomes), temporal discounting in humans is most commonly assessed using monetary outcomes (Hamilton et al., 2015; Odum et al., 2020). However, the task design may vary. For instance, tasks may use predefined choice alternatives (Kirby et al., 1999) or a titration procedure adjusting amounts of presented choice alternatives based on

previous choices (Du et al., 2002). Additionally, tasks may be experiential (Reynolds & Schiffbauer, 2004), i.e., all consequences of decisions are realised during the experiment in real-time, or not. Similarly, rewards may be entirely hypothetical, partly hypothetical (e.g., a random choice among all choices is selected and realised) or real. However, this does not seem to influence task results (Brañas-Garza et al., 2023). Notwithstanding that the concrete task design can be manifold, studies usually derive indices of impulsive decision-making based on the choices. Prominent among these indices are the percentage of choices for the smaller-sooner or larger-later reward, the area under the curve (AUC) or discount rates (Hamilton et al., 2015).

Discount rates are the most commonly used index of impulsive decision-making and have been estimated in all studies forming part of this dissertation, therefore requiring a more elaborate explanation. Historically, the discount function is rooted in the *discounted utility model* introduced by Samuelson in 1937, according to which the utility (or subjective value) U at time t of a reward r, received at time $t + d$, can be described by the following formula:

$$U(r_t, \dots, r_T; \rho) = \sum_{d=0}^{T-t} D(d; \rho) u(r_{t+d}) \quad (1)$$

In this formula, the total utility U at time t is given by the sum of utilities u of the rewards r at some delay d (from time point t), discounted by the exponential discount function $D(d; \rho) = 1/(1 + \rho)^d$. Accordingly, $D(d; \rho)$ depends on the delay d and the individual's discount rate ρ. Higher delays and higher discount rates lead to a higher devaluation of future rewards. Thus, on the one hand, higher delays are undesired and therefore devalue a future reward. On the other hand, higher discount rates indicate steeper temporal discounting, i.e., an individual's higher preference for smaller-sooner rewards. In Samuelson's (1937) discounted utility model, the discount rate was assumed to have an exponential form. To simplify the formula above, one may assume that $t = 0$, so $T = d$ (because future rewards are usually evaluated at the current time). In this case, the formula becomes:

$$U(r_d; \rho) = D(d; \rho) u(r_d) \quad (2)$$

The exponential discount function still takes the form $D(d; \rho) = 1/(1 + \rho)^d$. Notably, the discounted utility function reflects a vast simplification, conflating all potential psychological motives relevant to intertemporal choices into a single parameter, the discount rate ρ, and the utility function u. Nevertheless, due to its simplicity, it was quickly accepted in economics (Frederick et al., 2002). However, later studies showed that actual choices often do not confirm with this, revealing various anomalies (Loewenstein & Thaler, 1989; Thaler, 1981). Building upon these anomalies, a significant number of alternatives to the classical exponential models have been proposed (Doyle, 2013). For example, hyperbolic models have been introduced, accounting for the phenomenon that the discount rate declines over time (Thaler, 1981); an example of a hyperbolic discount function is $D(d;\ \rho) = 1/(1 + \rho d)$ (Mazur, 1987). It should be noted that in hyperbolic models, the discount rate is often referred to as k. Moreover, the quasi-hyperbolic model explicitly

models the *present bias*, i.e., the phenomenon that rewards nearer to the present are weighted relatively stronger; it has the discount function $D(d;\rho) = \beta\delta$, where β corresponds to the extent of the present bias, and δ includes the discount factor varying by time, $\delta = 1/(1+\rho)^d$ (Laibson, 1997). It should be noted that in empirical studies of intertemporal choices, it is commonly assumed that the utility function u in Samuelson's formula is linear (Andersen et al., 2008; **Review I**). Fixing a discount function, discount rates are then estimated from choice data. Traditionally, discount rates have been fitted for individual participants separately (Kirby et al., 1999; Wileyto et al., 2004). Newer approaches, such as hierarchical Bayesian modelling, can be used to estimate group- and individual-level parameters (Chávez et al., 2017; Vincent, 2016). That is, information on individual discount rates is informed by the group level (Nilsson et al., 2011). As a result, the Bayesian approach entails, amongst others, the advantages that individual-level parameters may better and more robustly reflect the data and that posterior estimations retain uncertainty information on the individual level (Chávez et al., 2017; Vincent, 2016). Therefore, this approach was used in most studies (**Studies II, III and V**) of this dissertation (see Section 2.3). Figure 1A presents examples of different forms of discount functions, Figure 1B illustrates interindividual variation in hyperbolic discount rates, and Figure 1C exemplifies potential experimental manipulation effects (see Section 1.2.3).

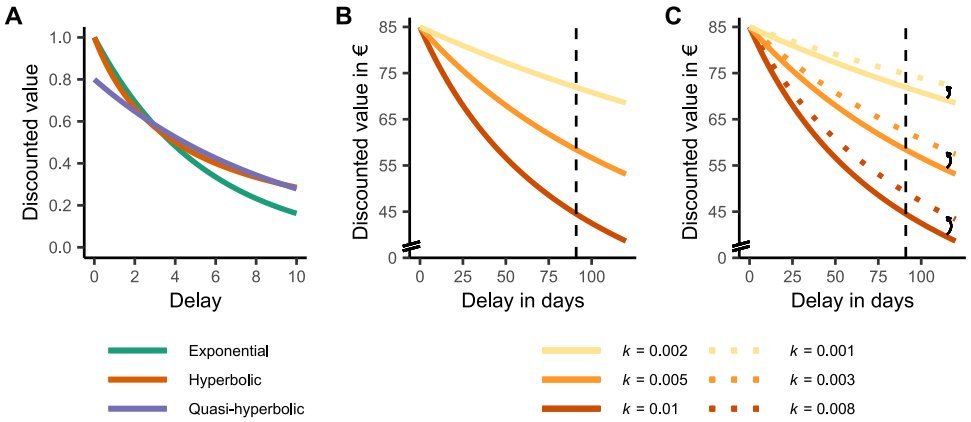


Figure 1 | Temporal discounting functions. Panel A represents examples of three different forms of temporal discounting functions with discounted values proportional to 1 and arbitrary delays. Parameters were set to $\rho = 0.2$ for the exponential model, $\rho = k = 0.25$ for the hyperbolic model and $\beta = 0.8$ and $\delta = 0.9$ for the quasi-hyperbolic model. Panel B presents hyperbolic discounting functions from three different individuals for the decision example "Would you prefer 69€ today or 85€ in 91 days?" (item 15 in Kirby et al., 1999). That is, the curves represent individual discounting functions, with more reddish curves corresponding to steeper discounting. Note that only the individual with the yellow discount curve ($k = 0.002$) is likely to choose the larger-later reward because the discounted value of 85€ after 91 days (approximately 72€ today) is higher than 69€ today. The individuals with the orange ($k = 0.005$) and red ($k = 0.01$) curves are more likely to choose the smaller-immediate reward, with discounted values of approximately 58€ and 45€ after 91 days, respectively. Panel C illustrates potential state effects within an individual, reducing the hyperbolic discount rate, for example, due to a different framing of choice options (e.g., date/delay effect; LeBoeuf, 2006; Read et al., 2005).

While traditional models of temporal discounting built upon the discounted utility model, thereby assuming that people independently compute subjective values of options, compare them and choose the option with the higher value (*option-* or *alternative-based models*), a large number of alternative models have been proposed in recent years (Doyle, 2013). Importantly, in contrast to option-based models, *attribute-based models* have been introduced to account for certain anomalies of option-based models. For example, the phenomenon of *subadditivity* or *superadditivity* (i.e., reduced or increased discounting when delays are presented as a complete time period rather than as several segments of time; Read, 2001; M. Scholten & Read, 2006) cannot be explained in terms of option-based models because these effects show that intervals of several time attributes are considered, a computation for which attribute comparison is required (M. Scholten et al., 2014; M. Scholten & Read, 2010). Attribute-based models are therefore based on the assumption that, rather than integrating the reward and time of each option to compute the subjective value of an option, people compare rewards and times of options separately and then trade off these comparisons against each other (Amasino et al., 2019; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; M. Scholten & Read, 2010). An exemplary attribute-based model has been proposed by M. Scholten and Read (2010), termed the *tradeoff model*. This model contains (i) two intra-attribute weighing functions, i.e., a time d weighing function w and a reward r weighing function v, and (ii) two inter-attribute weighing functions, i.e., trade-off functions $Q_{D|R}$ and $Q_{R|D}$, weighing the difference between weighted delays d (*effective interval*) against the difference of weighted rewards r (*effective compensation*) of the larger-later option L and the smaller-sooner option S using the parameters τ and γ, respectively. Assuming that $r_L > r_S > 0$ (upper part of formula 5 in M. Scholten & Read, 2010), a person will be indifferent between a smaller-sooner option S and a larger-later option L if

$$Q_{D|R}\big(w(d_L) - w(d_S)\big) = Q_{R|D}\big(v(r_L) - v(r_S)\big). \quad (3)$$

Time weighing is represented by the logarithmic function $w(d) = (1/\tau)\log(1 + \tau d)$, whereas reward weighing is represented by the logarithmic function $v(r) = (1/\gamma)\log(1 + \gamma r)$. For further specifications of the functions and descriptions of their properties (e.g., *reference dependence*, *diminishing absolute sensitivity*, *augmenting proportional sensitivity*), the interested reader is referred to the publication by M. Scholten and Read (2010). Importantly, the trade-off functions Q capture (amongst others) a time sensitivity parameter κ, with a greater κ corresponding to higher discounting (M. Scholten et al., 2014).

Generally, it should be noted that differences between option-based and attribute-based models are not clear-cut. Instead, a continuum exists between the two model types, with option-based models at one end and attribute-based models at the other (Payne et al., 1988; M. Scholten et al., 2014). For instance, the *interval discounting model* is a hybrid model in the middle of this continuum, as reward attributes of options are evaluated separately, but

time attributes are put into relation to each other by computing a time interval between options (M. Scholten & Read, 2006).

While most current studies still estimate temporal discounting using option-based models, an increasing number of studies indicate that attribute-based models outperform option-based ones in describing intertemporal choice behaviour (Amasino et al., 2019; J. Cheng & González-Vallejo, 2016; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; M. Scholten & Read, 2010). However, further evidence is needed to determine which of the two different classes of models fits best, and two lines of research provide particularly promising pathways. First, Read et al. (2013) demonstrated that the existence and magnitude of anomalies of classical economic models largely depend on intertemporal choice task framing. Specifically, the way in which the larger-later reward attribute was framed influenced choice behaviour (see Section 1.2.3 for an introduction to framing effects in intertemporal choice) and the existence of two anomalies, namely the *magnitude effect* (i.e., reduced discounting with higher reward magnitudes but equal interest rates; Green et al., 1997) and the *delay effect* (i.e., reduced discounting with longer delays but equal interest rates; Mazur, 1987). Thus, the goodness of fit of computational models may largely depend on task framing. Second, the two different model types are potentially associated with different information sampling strategies, i.e., alternative-based models with integrative, option-wise search and attribute-based models with comparative, attribute-wise search (Figure 2), as suggested by several eye-tracking studies (Amasino et al., 2019; Fisher, 2021; Khaw et al., 2018; Reeck et al., 2017, though see Zhang et al., 2022, who found contradicting results). Therefore, **Studies II and III** of this dissertation combined the examination of a framing effect with methods to track attentional processes through eye-tracking to elucidate cognitive strategies commonly used in intertemporal choice and to enrich the debate on alternative- and attribute-based computational models of intertemporal choice.

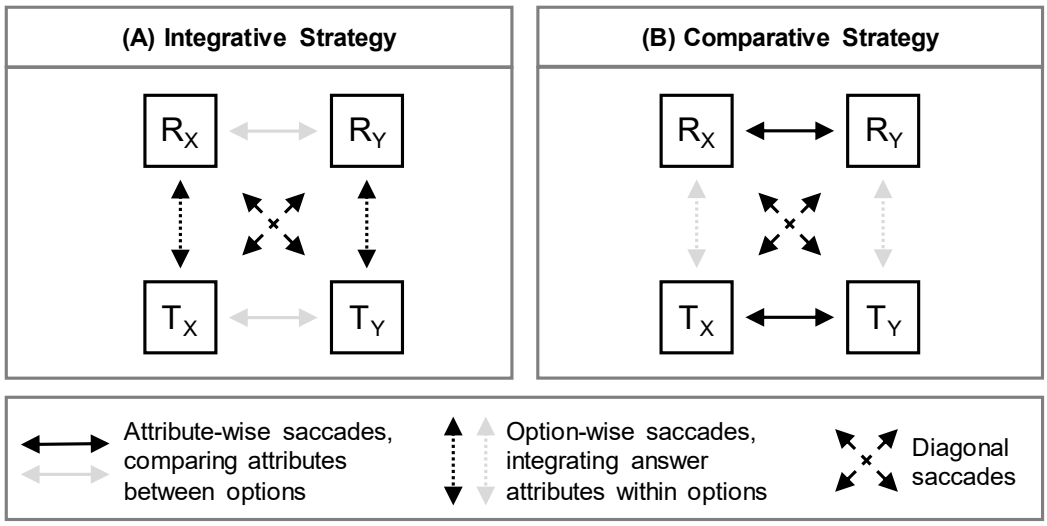


Figure 2 | Search strategies in intertemporal choice. Saccades are depicted as arrows between reward (R) and time (T) attributes of decision options X and Y. Panel A represents typical saccades used for an option-wise, integrative strategy (dashed), panel B represents typical saccades used for an attribute-wise, comparative strategy (solid). Black and grey arrows correspond to the dominant and less dominant strategy, respectively. Diagonal saccades form part of both strategies. The figure was reprinted from **Study II**. For details regarding third party copyright material, see pages 21–22.

1.2.2 Relevance of Intertemporal Choice

The examples at the beginning of the previous section illustrate that intertemporal choices are ubiquitous in everyday life. It should be noted that this spans both the group and the individual level, with the earlier examples relating to decisions made by the individual. Intertemporal decision-making on a group or societal level can be illustrated by the current challenge of limiting global warming due to climate change, such as decisions on whether to rely on fossil fuels now or spend money on renewable energy sources (Philibert, 1999; Spash & d'Arge, 1989). However, this dissertation is mainly concerned with individual- rather than group-level decision-making (with individual decisions ultimately also impacting the societal level). Therefore, the following paragraphs give an overview of aspects of everyday life that are associated with intertemporal decision-making at the individual level (also see **Review I**).

Perhaps most famously, the relevance of intertemporal choices is illustrated by the well-known longitudinal studies on delay of gratification by Mischel and colleagues (Ayduk et al., 2000; Mischel et al., 1988; Shoda et al., 1990). Potential overestimations of effect sizes notwithstanding (Watts et al., 2018), Mischel and his colleagues found that the marshmallow test had considerable predictive validity for numerous life outcomes over up to 40 years (Mischel et al., 2011). For instance, preschool children who waited longer for

the second marshmallow (i.e., chose the larger-later reward) showed higher educational attainment, better coping with stress and less vulnerability to use drugs in later life (Ayduk et al., 2000). However, as outlined in the previous section, while the marshmallow test may be interpreted as one specific form of intertemporal choice, the definition of intertemporal choices goes far beyond self-control in childhood.

Given that intertemporal choice behaviour in the current work is operationalised as choices between monetary rewards, studies examining individual differences in temporal discounting of monetary rewards (for an illustration, see Figure 1B) may serve as more refined examples. Indeed, temporal discounting has been associated with numerous health-related and non-health-related life outcomes (Bickel, 2015; Story et al., 2014; also see **Review I**). Specifically, people showing higher discount rates are less likely to engage in health prevention behaviours such as checking blood pressure (Axon et al., 2009), attending dental visits (Bradford, 2010), getting vaccinated (Bradford, 2010; Halilova et al., 2022) or abiding by social distancing measures during a pandemic (Lloyd et al., 2021). Moreover, high discounters more often show risky health behaviour, such as smoking (Audrain-McGovern et al., 2009), alcohol consumption (Fröhner et al., 2022), problematic eating (Kekic et al., 2020; Sweeney & Culcea, 2017), risky sexual behaviour (Daugherty & Brase, 2010), HIV-risk behaviour (Odum et al., 2000) or risky traffic behaviour, like not wearing a seat belt (Daugherty & Brase, 2010) or texting while driving (Hayashi et al., 2015). Importantly, temporal discounting is aberrant in many different mental disorders (Amlung et al., 2019; for a comprehensive summary, see Section 1.2.5). Regarding outcomes that are not (directly) health-related, higher temporal discounting is associated with higher credit debts (Meier & Sprenger, 2010), less creditworthiness (Meier & Sprenger, 2012) and later uptake of welfare programs (Fang & Silverman, 2006). Studies in the educational and work context found that people with higher discount rates have lower academic attainment (Freeney & O'Connell, 2010), put less effort into searching for a good job (Della Vigna & Paserman, 2005), have lower job satisfaction (de Ruijter et al., 2023) and experience lower wage growth (Munasinghe & Sicherman, 2005). Ultimately, all these behaviours and decisions reflect a preference for choosing smaller-sooner over larger-later rewards in everyday life, i.e., impulsive decision-making.

These manifestations of impulsive decision-making show that it is essential to examine determinants of steeper and shallower temporal discounting, both in clinical and non-clinical contexts. Apart from providing insights into the mechanisms of impulsive behaviour, this knowledge may help reveal pathways to modify such behavioural tendencies and avoid detrimental life outcomes. It should, of course, be noted that for many of the behaviours listed above, empirical studies were cross-sectional, i.e., the causality of the associations is not clear and variable confounds may play a role. However, in light of a number of studies revealing longitudinal effects of temporal discounting, predicting, for instance, smoking (Audrain-McGovern et al., 2009), alcohol use (Fröhner et al., 2022) and marijuana use (Kim-Spoon et al., 2019), at least a partially causal role of temporal discounting appears likely. In line with this, studies have shown that behavioural training

programs, such as an acceptance-based/mindfulness-based training, can alleviate temporal discounting (H. Scholten et al., 2019).

1.2.3 Malleability of Intertemporal Choice: The Date/Delay Effect

The finding that temporal discounting can be influenced by training programs indicates that temporal discounting, while considered a relatively stable, trait-like phenomenon (B. P. Miller et al., 2023; Odum, 2011a, 2011b), is malleable (H. Scholten et al., 2019; for an illustration, see Figure 1C). Importantly, this malleability can be revealed by simple experimental manipulations (Koffarnus et al., 2013; Lempert & Phelps, 2016; Rung & Madden, 2018; H. Scholten et al., 2019). According to Lempert and Phelps (2016), the context of intertemporal decision-making seems to be particularly relevant in that intertemporal choices can be influenced by *framing effects* (i.e., how a choice scenario is presented; see *Prospect Theory* by Tversky & Kahneman, 1981) and *incidental effects* (i.e., pre-existing states such as affect). Given that prospection-related manipulations are deemed highly effective (Lempert & Phelps, 2016; H. Scholten et al., 2019), the focus of this dissertation was on the so-called *date/delay effect* (LeBoeuf, 2006; Read et al., 2005).

The date/delay effect is a well-known framing effect in intertemporal choice. Specifically, it describes the phenomenon that temporal discounting is reduced when the delay until receipt of a reward is presented as a date (*date condition*; e.g., 30 November 2024) rather than in delay units (*delay condition*; e.g., in 91 days) (LeBoeuf, 2006; Read et al., 2005). In practice, the date/delay effect could be useful for retail, investment and credit offers or governmental policy communication regarding savings and debts (LeBoeuf, 2006; Read et al., 2005). For example, when people are presented with a potential investment, they might be more inclined to pursue it if a gain is predicted for a specific date rather than after a delay specified in years and months (Read et al., 2005). Additionally, consumers could tend to buy more long-lived and sustainable energy-efficient products or heating systems despite their higher price if advertisements focus on the date at which the energy-efficient measures will offset the initially higher cost rather than on the waiting time to recover it (LeBoeuf, 2006). In research, the date/delay effect has been replicated in several studies using various task designs (DeHart & Odum, 2015; Dshemuchadse et al., 2013; Jiang & Dai, 2021; Klapproth, 2012; Lempert et al., 2016; Naudé et al., 2018; Reyes-Huerta et al., 2023; Scherbaum et al., 2012; S. N. Sharma & Khan, 2022), with only two being unsuccessful (Lempert et al., 2016; S. N. Sharma & Khan, 2022). The effect size was medium on average (Rung & Madden, 2018).

Thus, the date/delay effect in intertemporal choice could be useful in various domains and has been found in most, though not all, studies examining it. However, the cognitive mechanisms underlying the effect are far from clear. A range of hypotheses has been proposed.

First, the *attention-focusing hypothesis* (LeBoeuf, 2006; Read et al., 2005) posits that the delay condition emphasises the duration until receipt of a larger-later reward, i.e., the waiting time, whereas the date condition emphasises the point of time at which a larger-later reward is received and the value of that reward. Thus, the date condition is thought to shift the focus of attention towards either reward rather than time attributes (Read et al., 2005) or towards the time of receipt of a larger-later reward and post-delay transactions rather than waiting time (LeBoeuf, 2006). Thereby, the reward itself becomes more vivid and accessible in the date compared to the delay condition (LeBoeuf, 2006), making the choice of a larger-later reward more likely.

Second, and related to the attention-focusing hypothesis, people may adapt the decision process, as described by the *choice strategy hypothesis* (Read et al., 2005). As outlined in Section 1.2.1, it has been assumed for a long time that participants make intertemporal choices based on an option-based process, i.e., integrating reward and time to compute subjective values of decision options, with the higher-value option most likely to be chosen (Frederick et al., 2002). However, the date condition impedes this strategy (Read et al., 2005). Specifically, while in the delay condition, both reward and time attributes are given as numeric values that can be integrated to estimate interest rates, this is not directly possible with dates. Participants would need to transform dates to delay units to use such an integrative, option-based strategy. Therefore, participants may change to a comparative, attribute-based strategy, as reflected in attribute-based models (Amasino et al., 2019; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; M. Scholten & Read, 2010). In combination with the attention-focusing hypothesis (or another internal process emphasising rewards rather than times), such a strategy could lead to a focus on the reward comparison, thereby resulting in less temporal discounting in the date compared to the delay condition.

Third, the *differential time estimation* hypothesis (LeBoeuf, 2006; Read et al., 2005) refers to the subjective experience of time, i.e., *time perception* (Matthews & Meck, 2016). Time perception is an integral part of decision-making, relevant to both the decision-making process and its consequences (see **Review II**, for a detailed discussion). With regard to the date/delay effect, the time until receipt of a reward may be underestimated in the date compared to the delay condition, ultimately resulting in reduced temporal discounting. The proposed reasons for differential time estimation are manifold. LeBoeuf (2006), for instance, suggested that this could be a consequence of attention-focusing on rewards or of the different uses of delay units and dates in daily life (i.e., dates are more often used to describe longer intervals) entailing a contrast effect (Herr, 1986), i.e., dates in the experiment appear closer to the present because they are closer to the present compared to the everyday use of dates. More generally, differential time estimation may result from the abstractness of time information (Lempert & Phelps, 2016), as suggested by *Construal Level Theory* (Trope & Liberman, 2003). Specifically, dates are more concrete and potentially have higher personal relevance than delay units, thereby representing a lower-level construal, i.e., a construal with a relatively low psychological distance. The reduced

psychological distance between the present and the date of receipt of the reward may result in the relative underestimation of the interval in the date compared to the delay condition.

Fourth, it has been proposed that dates make participants adopt a more deliberative processing mode (*deliberation hypothesis*) because dates have a higher complexity and impose higher cognitive demands on participants than delay units (Dshemuchadse et al., 2013). Thereby, date framing may result in more reflection, which could lead to more choices for larger-later rewards. Additionally, this may be an explanation for findings suggesting that the date condition leads to more exponential rather than hyperbolic discounting (Read et al., 2005; though see Reyes-Huerta et al., 2023, and DeHart & Odum, 2015, who found that hyperbolic and quasi-hyperbolic functions, respectively, fitted both conditions best), the former often being considered more rational.

Beyond these four comprehensively presented hypotheses, further explanations have been offered, which are presented in detail in **Review II**. For instance, it has been proposed that the date condition may entail a higher positive valence than the delay condition because time attributes, i.e., waiting times, are less contemplated (LeBoeuf, 2006). Moreover, the reduced discounting in the date condition may stem from higher subjective similarity of time attributes leading to differential time estimation or from higher perceived precision resulting in reduced subjective risk of not receiving the reward (Lopez-Guzman et al., 2018) in the date condition (Read et al., 2005).

As implied by the descriptions of the different hypotheses, it is highly conceivable that not a single mechanism but a combination of mechanisms ultimately causes the date/delay effect. For instance, one may hypothesise that the more complex date framing makes people underestimate time and risk and change their computational strategy to perform intertemporal choices, leading to a focus on rewards and a more positive valence because of a subjectively higher payoff. However, few studies have provided evidence in favour of or against different hypotheses. A study using mouse tracing during intertemporal choices found that reward but not time differences predicted mouse curvature (i.e., the directness of mouse movement) in a certain time period significantly more in the date condition than in the delay condition (Dshemuchadse et al., 2013), providing evidence for the attention-focusing hypothesis. While the same study found no evidence for the deliberation hypothesis because curvatures per se did not differ between conditions, a computational modelling study from the same group showed that the delay condition leads to faster accumulation of time information than the date condition (Scherbaum et al., 2012), in line with the deliberation and the attention-focusing hypotheses. Regarding the differential time estimation hypothesis, two studies using a time estimation task (i.e., a task presenting lines to estimate temporal distances) found that subjective time estimation may indeed be contracted in the date compared to the delay condition (Jiang & Dai, 2021; Zauberman et al., 2009). Finally, separate eye-tracking studies using delay units or dates indicated that participants make more comparative saccades in the date than in the delay condition (Arieli et al., 2011; Kurokawa & Ohtake, 2013), providing evidence for a different choice strategy.

However, in another study, no significant difference between conditions was found in the number of saccades between reward attributes (S. N. Sharma & Khan, 2022).

The sheer number of different hypotheses, in combination with the relatively low number of studies examining them, illustrates that more work is needed to clarify the cognitive mechanisms of the date/delay effect. Therefore, **Studies II and III** of the present dissertation aimed to examine the cognitive underpinnings of the date/delay effect. More generally, given the potential differences in computational strategies between conditions, these studies may also inform how intertemporal choices can be computationally modelled adequately (see Section 1.2.1).

1.2.4 Neural Mechanisms of Intertemporal Choice

Valuable insights into the cognitive and neural mechanisms involved in intertemporal choice and temporal discounting have been gained using a broad range of different methods, including single-unit recordings in animal models (Kalenscher et al., 2005; Kim et al., 2008), lesion studies in human patients (Bechara et al., 2000; Sellitto et al., 2010) and experimental rodent models (Cardinal et al., 2001; Fobbs & Mizumori, 2017), positron emission tomography (PET; Joutsa et al., 2015), functional magnetic resonance imaging (fMRI; Carter et al., 2010; Kable & Glimcher, 2007), electroencephalography (EEG; Blackburn et al., 2012) and neuromodulation methods such as transcranial magnetic stimulation (TMS; Figner et al., 2010; Moro et al., 2023). Building upon this literature and primarily focusing on fMRI findings, a number of reviews and meta-analyses have summarised the neural substrates of intertemporal choice (Carter et al., 2010; Frost & McNaughton, 2017; Peters & Büchel, 2011; Scheres et al., 2013; Schüller et al., 2019). Generally, these articles converge on the idea that subcortical-cortical pathways are involved in processing intertemporal choices. While different networks and underlying models have been proposed, they are not necessarily mutually exclusive (Scheres et al., 2013). The following paragraphs shall give an overview of the most important networks discussed (see Figure 3A, for a simplified representation of the main networks).

Neuroeconomic researchers have assumed for a long time that the brain represents values of different choice options using a "common currency" (Levy & Glimcher, 2012). That is, different features of options (e.g., reward and delay in the case of intertemporal choice) are integrated and the resulting values are compared based on a common scale (see option-based models in Section 1.2.1). Building upon this framework, the *valuation network*, in which different kinds of reinforcers are represented, is arguably the most rigorously investigated neural network in intertemporal choice and has been considered in all reviews and meta-analyses mentioned above.

Generally, two different approaches have been proposed to neurally map valuation in intertemporal choices. In the first fMRI study of temporal discounting, a *dual valuation*

model was used, i.e., the β-δ model (McClure et al., 2004). The β-δ model, consistent with quasi-hyperbolic discounting, distinguishes between two valuation systems. In line with the larger literature on dual-systems approaches to cognition (Evans, 2008; Metcalfe & Mischel, 1999; Salehinejad et al., 2021), it posits that intertemporal choice behaviour is guided by (i) a "hot" visceral β-system processing immediate rewards, associated with activity in ventral striatum (vS), medial orbitofrontal cortex (mOFC), medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC), and (ii) a "cold" deliberative δ-system processing both immediate and delayed rewards and associated with activity in dorsolateral prefrontal cortex (dlPFC), ventrolateral prefrontal cortex (vlPFC), lateral orbitofrontal cortex (lOFC) and intraparietal cortex (McClure et al., 2004). It should be noted, however, that the most recent meta-analysis only confirmed the association between the β-system and activation in mPFC (Schüller et al., 2019). A few years after the first fMRI study of temporal discounting, an alternative model was proposed, the *single valuation model* (Kable & Glimcher, 2007, 2010). This model, which is consistent with one-parameter behavioural models such as hyperbolic discounting, posits that subjective values of both immediate and delayed rewards are represented in a unitary system. Specifically, subjective values of choice options are associated with activity in vS, ventromedial prefrontal cortex (vmPFC) and PCC (Bartra et al., 2013). Comparing the two models, the majority of reviews favour the idea of a single valuation model rather than a dual valuation model (Peters & Büchel, 2011; Schüller et al., 2019) since a hyperbolic model seems to reflect fMRI data better than a quasi-hyperbolic model (Kable & Glimcher, 2010). Finally, while most research so far has built on the common currency hypothesis, it should be noted that more recent research challenges the notion of neural representations of a common currency (Hayden & Niv, 2021), with attribute-based models providing an appealing alternative. Indeed, one study also revealed distinct activation patterns depending on the magnitude of rewards and length of delays (Ballard & Knutson, 2009), and its findings could therefore be interpreted in terms of attribute-based models.

A second network that is often examined is the *cognitive control network* (Peters & Büchel, 2011; Schüller et al., 2019). The cognitive control network is believed to comprise brain areas involved in conflict monitoring and strategy adaptation (Peters & Büchel, 2011) and self-control, i.e., resisting an immediate temptation which may initially be valued more highly at a valuation stage (Figner et al., 2010; Schüller et al., 2019). It is assumed that the cognitive control network is particularly involved when choice difficulty is high, i.e., when subjective values of choice options are close to each other (Jimura et al., 2018; Marco-Pallarés et al., 2010; Pine et al., 2009) or, more generally, when participants choose larger-later over smaller-sooner rewards (Wittmann et al., 2007; Ye & Wang, 2023). While higher choice difficulty is associated with increased activity in mPFC and anterior cingulate cortex (ACC), choosing delayed over immediate rewards is represented in the inferior frontal gyrus and the mid-cingulate gyrus (Schüller et al., 2019). Regions of the δ-system, such as dlPFC, may also be more involved in the cognitive control rather than the valuation network, as suggested by a TMS study (Figner et al., 2010).

Based on studies showing that memory-related regions are involved in intertemporal choice (Cheung & Cardinal, 2005; Peters & Büchel, 2010), some reviews also emphasise the existence of a *memory and prospection network* (Carter et al., 2010; Frost & McNaughton, 2017; Peters & Büchel, 2011). Carter et al. (2010) interpreted this network rather broadly and referred to it as *core network*, reflecting a broad range of prospective and self-directed processes (e.g., autobiographical memory, theory of mind, planning). Their broad network encompasses inferior prefrontal cortex, mPFC, temporal-parietal cortex and peri-splenial posterior cingulate. However, the medial temporal lobe network proposed by Peters and Büchel (2011), which is largely compatible with the memory-related system proposed by Frost and McNaughton (2017), is narrower. It comprises regions associated with the representation of past reward and delay experiences and imagination of future events (e.g., receiving a later reward), such as hippocampus and amygdala, extending to vmPFC, mOFC and PCC, i.e., areas involved in valuation.

Finally, some studies and models address the early and late stages of intertemporal decision-making, i.e., processing sensory information and producing and suppressing motor responses (Frost & McNaughton, 2017; McClure et al., 2004). Specifically, processing sensory information is associated with activity in thalamus and primary sensory cortices, producing motor responses is associated with activity in premotor cortex, cerebellum and basal ganglia, and suppressing motor responses is associated with activity in cognitive control regions (Frost & McNaughton, 2017).

As becomes clear by this summary, the proposed networks are not distinct and comprise partly overlapping regions, especially in prefrontal cortex. While different networks have often been opposed, with studies providing mixed evidence and supporting all networks to some extent (Scheres et al., 2013), the large overlaps may also indicate that intertemporal decisions result from recurrent subcortical-cortical feedback loops spanning different networks (Frost & McNaughton, 2017). Interestingly, based on their summary of neural findings, Frost and McNaughton (2017) formulated a five-stage model of cognitive processing during intertemporal choice and related these processes to neural activity, thereby integrating the different networks into a single account. In short, these five stages comprise object representation (sensory areas), memory (prospection-related areas), valuation (valuation areas), comparison of options (areas involved in difficult choices, i.e., cognitive control areas) and motor response (premotor and motor areas). Figure 3B illustrates how information may be transmitted through the brain during intertemporal choices.

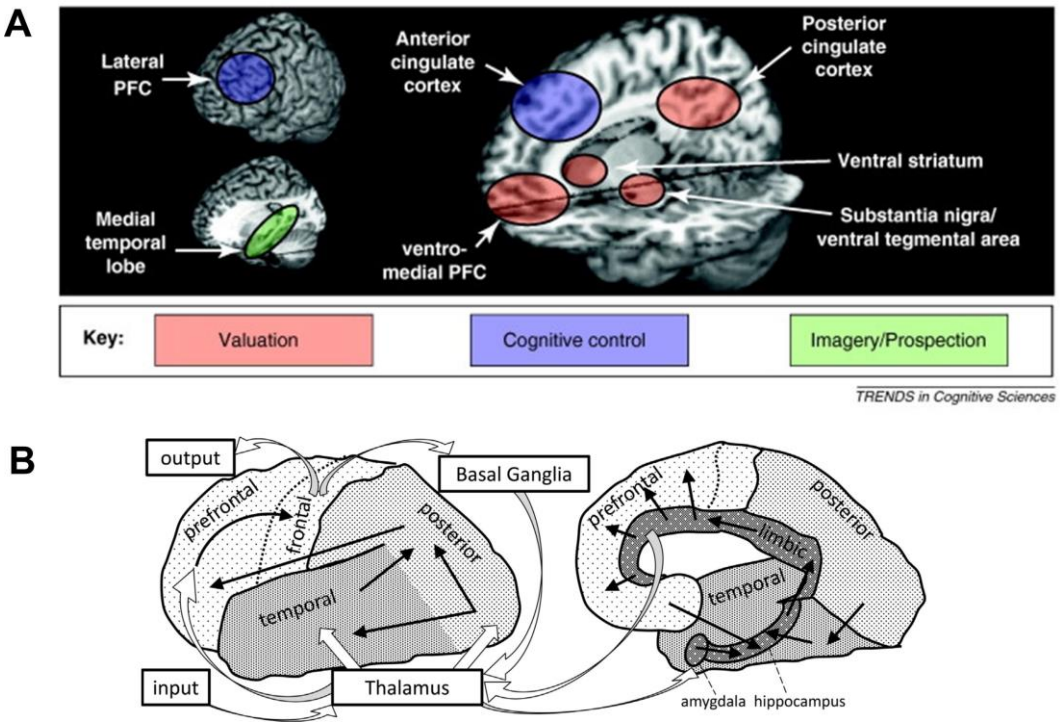


Figure 3 | Neural mechanisms of intertemporal choice. Panel A represents three proposed neural networks involved in intertemporal decision-making, i.e., valuation (red), cognitive control (blue) and imagery/prospection (green). The ventromedial prefrontal cortex (vmPFC) and posterior cingulate cortex (PCC) are thought to be involved in both valuation and prospection. Panel B presents a suggestion of subcortical-cortical feedback loops involved in intertemporal choices. The left part of the figure is the lateral surface of the brain, and the right part is the medial part. Panel A was reprinted from Peters and Büchel (2011), and panel B was reprinted from Frost and McNaughton (2017). For details regarding third party copyright material, see pages 21–22.

While the reviews and meta-analyses showed that numerous brain regions are involved in intertemporal choices, the exact roles of specific regions are so far not fully understood (Frost & McNaughton, 2017). One possibility to elucidate this is to use experimental manipulations targeting only specific parameters of the decision process. For instance, an fMRI study manipulated *episodic future thinking* (i.e., the propensity to simulate future experiences; Atance & O'Neill, 2001) by presenting intertemporal choices with or without participant-generated future event tags, finding a tag-induced reduction of temporal discounting (*tag effect*; Peters & Büchel, 2010). Compared to the condition without cues, the tag condition was associated with higher activity in imagery-related brain regions (e.g., mPFC, PCC; Schacter et al., 2007). Moreover, the individual extent of reduction of temporal discounting was predicted by valuation signals in ACC and its coupling with memory-related areas. According to the authors, these findings suggest that in intertemporal choices, the ACC has a function to dynamically adapt to different decision contexts (e.g., episodic cues), and its coupling with memory-related areas may represent a

modulation of prefrontal areas through episodic thinking and imagery. Thus, by using a simple experimental manipulation, this study helped uncover the roles of specific brain regions in intertemporal choice. However, despite the predominantly unspecified functions of brain regions in intertemporal choice, studies like this are scarce. Therefore, the combined fMRI and eye-tracking **Study III** of this dissertation may not only elucidate the mechanisms of the date/delay effect itself but also inform the neural basis of intertemporal choice in general.

1.2.5 Impulsive Decision-Making as a Transdiagnostic Marker

Temporal discounting has been associated with a broad range of mental disorders. Specifically, steeper temporal discounting has been observed in behavioural addictions (Amlung et al., 2017; Y.-S. Cheng et al., 2021; Weinsztok et al., 2021), substance use disorders (Amlung et al., 2017; MacKillop et al., 2011; Strickland et al., 2021), ADHD (J. N. S. Jackson & MacKillop, 2016; Marx et al., 2021; Mostert et al., 2015), depression (Amlung et al., 2019; Imhoff et al., 2014; Pulcu et al., 2014), bipolar disorder (Ahn et al., 2011; Amlung et al., 2019; H. E. Brown et al., 2018), borderline personality disorder (Amlung et al., 2019; Berenson et al., 2016; Paret et al., 2017) and bulimia nervosa (Amlung et al., 2019; Kekic et al., 2016; McClelland et al., 2016), whereas decreased temporal discounting was found in anorexia nervosa (Amlung et al., 2019; McClelland et al., 2016; Steinglass et al., 2012). Since temporal discounting is aberrant in so many mental disorders, it has been discussed as a transdiagnostic marker, i.e., a behaviour that is altered in various mental disorders and may therefore provide valuable insights into common underlying mechanisms (Amlung et al., 2019; Bailey et al., 2021; Bickel et al., 2019; Lempert et al., 2019; Levitt et al., 2023). However, most studies investigating the associations between temporal discounting and mental disorders so far have applied case-control designs, and research aiming to elucidate which transdiagnostic factors are responsible for these associations is scant. This is likely due to problems inherent in the current classification systems of psychopathology.

Current classification systems such as the *Diagnostic and Statistical Manual of Mental Disorders* (DSM, currently in its fifth edition; American Psychiatric Association, 2013) and the *International Classification of Diseases* (ICD; currently in its eleventh edition; World Health Organization, 2019) organise mental health issues in taxonomic systems, differentiating between numerous diagnoses. These categorical diagnoses are based on binary judgments concerning the presence or absence of a number of symptoms (Regier et al., 2013). While from a historical perspective, the introduction of these systems facilitated communication between patients, clinicians and researchers, provided new developments in assessment and treatment and led to a reduction of stigma associated with mental health issues, concerns regarding the taxonomic approach have also been raised in the last decades (see Dalgleish et al., 2020, for an overview). Major issues relate, for instance, to high

comorbidity of different disorders (Caspi et al., 2020; Kessler, Chiu, et al., 2005; Maj, 2005), high heterogeneity within disorders (Allsopp et al., 2019; Fried, 2015; Fried & Nesse, 2015; Galatzer-Levy & Bryant, 2013; Olbert et al., 2014; Zimmerman et al., 2015), large overlaps of symptoms between disorders (Allsopp et al., 2019; Forbes, 2023; Hindley et al., 2022) and artificial binarisation of underlying mechanisms that are continuous in nature (Kendler, 2012). Notably, converging evidence suggests that many symptoms are dimensional, with expressions extending from non-clinical to clinical populations (Haslam et al., 2012, 2020; Markon et al., 2011). Therefore, initiatives like the *Research Domain Criteria* (RDoC; Cuthbert, 2014, 2022; Insel et al., 2010) and the *Hierarchical Taxonomy of Psychopathology* (HiTOP; Kotov et al., 2017, 2021) challenged the categorical nature of mental health problems. Specifically, these frameworks conceptualise mental health problems as dimensional rather than categorical phenomena, thereby aiming to elucidate biobehavioural mechanisms underlying different mental health issues (RDoC) and to systematically describe psychopathologically relevant phenotypes at different hierarchical levels (HiTOP). By doing so, they seek to achieve a better understanding and classification of psychopathology and more valid and reliable measurements of mental health issues, ultimately improving prevention, assessment and treatment (Conway et al., 2019; Cuthbert, 2022; Insel et al., 2010; Kotov et al., 2017, 2021; Krueger et al., 2018; see Michelini et al., 2021, for an approach integrating RDoC and HiTOP).

Importantly, the dimensional approach to psychopathology offers new pathways to transdiagnostic research. This becomes evident by the novel distinction between *soft* and *hard transdiagnostic approaches* (Dalgleish et al., 2020; Gillan & Seow, 2020). Soft transdiagnostic approaches compare different mental disorders following the traditional classifications given in DSM and ICD to examine commonalities of the mechanisms across disorders. Like case-control studies, however, such case-case studies are restricted not only by the limited number of diagnostic groups and sample sizes but also by limitations of categorical approaches in general, such as a high heterogeneity within and a lack of distinction between disorders (see above; Gillan & Seow, 2020). Moreover, it is difficult to control for treatment confounds (Yu et al., 2017). In the context of temporal discounting, these issues make it challenging to isolate transdiagnostic factors responsible for associations between temporal discounting and psychopathology.

On the other hand, hard transdiagnostic approaches discard classification systems completely and replace them with alternative formulations, i.e., dimensional approaches. For instance, large-scale assessments in general population samples may be used to reveal associations between cognitive processes and factor analytically derived *transdiagnostic dimensions* (Wise et al., 2023; see Section 2.4). These transdiagnostic dimensions may reflect both symptoms and maladaptive personality traits, i.e., traits where high levels constitute a risk of psychopathology (DeYoung et al., 2022; Kotov et al., 2017). Specifically, in the HiTOP framework, it has been proposed to consider time frame as the major difference between traits and symptoms, i.e., traits are persistent, whilst symptoms manifest during a specific time period (DeYoung et al., 2022). Thus, assessing dimensional

symptoms or traits related to psychopathology in large-scale general population samples may help to target the question of whether temporal discounting is a transdiagnostic marker by revealing which transdiagnostic dimensions are associated with it. To be consistent with previous literature (Benwell et al., 2022; Daniel-Watanabe et al., 2022; Hoven et al., 2023; Rouault et al., 2018; Seow & Gillan, 2020; Suzuki et al., 2021), the term *symptom patterns* will be used in the following and in **Study V** of this work to cover both stable traits and time-limited symptoms as indicators of dimensional psychopathology in a general population sample, while the term *transdiagnostic dimensions* will be used for factor analytically derived higher-order dimensions (Wise et al., 2023).

To illustrate the idea that hard transdiagnostic approaches based on dimensional conceptions may inform associations between mental health issues and temporal discounting, the highly heterogeneous findings from case-control studies regarding aberrant temporal discounting in schizophrenia may serve as an example. Specifically, while many studies found increased temporal discounting in schizophrenia compared to control groups (Ahn et al., 2011; Bartolomeo et al., 2021; H. E. Brown et al., 2018; Heerey et al., 2007, 2011; Weller et al., 2014; Yu et al., 2017), others found mixed (Horan et al., 2017) or no evidence (MacKillop & Tidey, 2011; Wing et al., 2012), and one found decreased discounting in schizophrenia (Wang et al., 2018). A meta-analysis did not find significantly increased temporal discounting in schizophrenia (Amlung, 2023; Amlung et al., 2019). Elucidating which factors relevant to schizophrenia are associated with temporal discounting may explain these findings, and transdiagnostic research in large-scale general population studies of the construct *schizotypy* could provide substantial insights.

Schizotypy describes a set of personality traits phenomenologically resembling schizophrenia symptoms on a subclinical level and representing a liability for schizophrenia (Ettinger et al., 2014; Grant et al., 2018). Typically, positive, negative and disorganised schizotypy traits are distinguished (Bentall et al., 1989; Chen et al., 1997; Raine et al., 1994), largely resembling the respective symptom dimensions of schizophrenia (Grube et al., 1998; Lenzenweger & Dworkin, 1996; Liddle, 1987; Peralta et al., 1992; see Thomas et al., 2019, for a direct comparison of schizotypy and schizophrenia). Positive schizotypy involves disruptions of perception and thought contents (e.g., odd beliefs, unusual experiences, paranoia), negative schizotypy involves a decrease in experiences (e.g., anhedonia, reduced affect, social disinterest), and disorganised schizotypy involves disruptions in the ability to organise thoughts, behaviour and communication (Kwapil & Barrantes-Vidal, 2015). The role of a fourth dimension, impulsive nonconformity, involving anti-social and eccentric behaviour, is currently discussed (Lin et al., 2013; Mason et al., 1995; Polner et al., 2019).

Interestingly, the degree of dimensionality in schizotypy and schizophrenia has been debated for a long time, as demonstrated by the proposal of *quasi-dimensional* and *fully-dimensional approaches* (Grant et al., 2018; Nelson et al., 2013). Meehl's quasi-dimensional approach to schizotypy assumes a taxonomic distinction between non-schizotypes and schizotypes, with the latter carrying a genetic factor responsible for a

neural defect termed *schizotaxia* (Meehl, 1962, 1990). The prevalence of schizotypy is believed to be approximately 10% in the general population, with 10% of them decompensating into schizophrenia (Meehl, 1990). Crucially, the risk of developing schizophrenia (i.e., the level of schizotypy, if present) is proposed to increase gradually along with the occurrence of other genetic and environmental factors (Meehl, 1962, 1990). Thus, Meehl's approach is considered quasi-dimensional because, while making a clear separation between non-schizotypes and schizotypes based on a neural defect, it assumes dimensionally varying risk levels within the latter. On the other hand, Claridge's *fully-dimensional approach* does not make a categorical distinction (Claridge, 1987, 1997, 2018; Claridge & Beech, 1995; Rawlings et al., 2008). Rather, in line with and building upon personality models (H. J. Eysenck, 1947, 1952, 1953), it assumes that schizotypy reflects several personality traits normally distributed in the general population and results from gene-environment interactions. Thus, expressions range from low schizotypy to high schizotypy. According to the fully-dimensional approach, high schizotypy values are necessary but not sufficient to develop schizophrenia, i.e., people are only considered at risk when high schizotypy values are combined with other risk factors (Grant et al., 2018; Nelson et al., 2013). While the debate on quasi-dimensional versus fully-dimensional approaches has not been resolved yet, substantial overlaps between schizotypal personality and schizophrenia provide evidence for the fully-dimensional model (Debbané et al., 2015; Ettinger et al., 2014; Nelson et al., 2013; van Os et al., 2009).

The fully-dimensional approach is consistent with the so-called *continuum hypothesis* of psychosis, positing that different genetic and environmental risk factors interact and result "in a gradation of exposure and associated range of different expressions from normal through to clinical psychosis" (Allardyce et al., 2007, p. 35). In other words, as proposed more generally by dimensional frameworks such as RDoC (Cuthbert, 2014, 2022; Insel et al., 2010) and HiTOP (Kotov et al., 2017, 2020, 2021), different biobehavioural dimensions may play a role in the development of schizophrenia, and these may be reflected in schizotypy traits in the general population. Building upon this idea, general population studies of schizotypy could help generate knowledge about schizophrenia while controlling for problems of categorical approaches such as treatment confounds. However, so far, only few studies have examined the associations between schizotypy and temporal discounting, overall providing mixed results (Cai et al., 2019; Li et al., 2016; Terenzi et al., 2019; Weatherly, 2012).

In sum, hard transdiagnostic approaches based on novel dimensional frameworks of psychopathology may help elucidate the transdiagnostic role of temporal discounting. Specifically, large-scale general population studies can address the caveats of traditional categorical approaches. Thereby, they could help identify symptom patterns responsible for associations with temporal discounting, explaining the hitherto inconsistent results regarding associations between temporal discounting and schizophrenia (Amlung, 2023), but also between temporal discounting and other disorders such as obsessive-compulsive disorder (OCD; Amlung et al., 2019) and autism (Carlisi et al., 2017; Chantiluke et al.,

2014; Demurie et al., 2012; Warnell et al., 2019). Beyond such specific associations, large-scale studies assessing a broad range of questionnaires related to psychopathology and factor analytically deriving transdiagnostic dimensions (Wise et al., 2023) may reveal which transdiagnostic dimensions are associated with aberrant temporal discounting and thereby provide information about intervention targets more generally. In this context, including experimental manipulations targeting episodic and time processing could be valuable since previous studies have shown that manipulations such as the date/delay effect (Klapproth, 2012) and the tag effect (Jia et al., 2020; Stein et al., 2017; Sze et al., 2017) may be particularly effective in vulnerable populations.

However, while studies applying hard transdiagnostic approaches have begun to spread in domains such as meta-cognition (Benwell et al., 2022; Hoven et al., 2023; Rouault et al., 2018; Seow & Gillan, 2020) and reward processing (Daniel-Watanabe et al., 2022; Suzuki et al., 2021), such studies are scarce in intertemporal decision-making (Levitt et al., 2023). To fill this gap in the literature, **Studies IV and V** of the current dissertation aimed to investigate temporal discounting and the date/delay effect in large general population samples, examining their associations with schizotypy traits (**Study IV**) and a broad range of symptom patterns and transdiagnostic dimensions (**Study V**).

1.3 Open Questions and Goals of the Present Thesis

As outlined in the previous sections, impulsivity is a highly heterogeneous umbrella term subsuming many different, albeit related constructs. Given the need to focus on specific constructs (Moeller, 2012; Strickland & Johnson, 2021), the current dissertation will primarily address trait impulsivity and impulsive decision-making. However, even when narrowing down the number of constructs in focus, numerous open research questions remain regarding their structure, malleability and transdiagnostic significance.

First, related to the heterogeneous nature of impulsivity, previous studies have challenged the structure of the UPPS-P trait measure by questioning the separability of lack of premeditation and lack of perseverance on the one hand and positive and negative urgency on the other (Berg et al., 2015; Goh et al., 2020; Sperry et al., 2018). Furthermore, in light of the many phenomena subsumed under the term impulsivity, one may ask what lies at its definitory core, with a cognitive factor such as lack of premeditation being a promising candidate (L. Sharma et al., 2014). Therefore, **Study I** aimed to elucidate the structure of trait impulsivity and its relation to impulsive decision-making in an intertemporal choice task. Specifically, the study used both traditional confirmatory approaches to ensure comparability to previous studies and novel network approaches to broaden the view to alternative conceptions of personality traits. Importantly, all studies and both reviews of this thesis addressed the association between trait impulsivity and impulsive decision-making (**Studies I–V, Reviews I–II**).

Second, impulsive decision-making, while trait-like (B. P. Miller et al., 2023; Odum, 2011a, 2011b), is malleable (H. Scholten et al., 2019). It can be influenced by experimental manipulations such as framing effects (Koffarnus et al., 2013; Lempert & Phelps, 2016; Rung & Madden, 2018; H. Scholten et al., 2019). In this context, several studies have revealed the date/delay effect, i.e., reduced temporal discounting when time until receipt of rewards is presented in terms of dates rather than delay units (LeBoeuf, 2006; Read et al., 2005). However, while several hypotheses have been proposed to explain the date/delay effect (Dshemuchadse et al., 2013; LeBoeuf, 2006; Read et al., 2005), its cognitive and neural mechanisms remain largely unknown. Therefore, while the replicability of the date/delay effect itself was examined in **Studies II–V** of this dissertation, **Studies II and III** used an eye-tracking and a combined eye-tracking and fMRI approach, respectively, to elucidate the attentional and neural basis of the date/delay effect.

Third, impulsivity forms part of diagnostic criteria for a range of mental disorders (American Psychiatric Association, 2013; World Health Organization, 2019). Previous findings suggest that aberrant intertemporal decision-making (i.e., increased or decreased temporal discounting) is associated with various mental disorders (Amlung et al., 2017, 2019; Y.-S. Cheng et al., 2021; J. N. S. Jackson & MacKillop, 2016; MacKillop et al., 2011; Strickland et al., 2021; Weinsztok et al., 2021), initiating a debate on its transdiagnostic relevance (Amlung et al., 2019; Bailey et al., 2021; Bickel et al., 2019; Lempert et al., 2019; Levitt et al., 2023). However, transdiagnostic research regarding aberrant intertemporal decision-making is scarce. Therefore, **Study IV** looked deeper into the associations between schizotypy, i.e., a set of traits representing the subclinical expression of schizophrenia, and temporal discounting to inform the hitherto inconsistent association between temporal discounting and schizophrenia (Amlung, 2023; Amlung et al., 2019) on a dimensional level. Furthermore, using novel methods (Wise et al., 2023) built upon dimensional views of psychopathology such as the RDoC (Cuthbert, 2014, 2022; Insel et al., 2010) or the HiTOP (Kotov et al., 2017, 2021), **Study V** aimed to uncover symptom patterns and transdiagnostic dimensions related to temporal discounting. Importantly, since previous studies pointed towards an even higher effectivity of experimental manipulations targeted at time processing in vulnerable populations (Jia et al., 2020; Klapproth, 2012; Stein et al., 2017; Sze et al., 2017), both studies examined whether the date/delay effect covaries with psychopathological dimensions. Ultimately, this could provide valuable information on which mechanisms should be targeted in therapeutic contexts.

In addition to the empirical studies, the two narrative reviews presented in this dissertation provided more detailed overviews of topics mentioned in Sections 1.2.2 and 1.2.3, i.e., individual differences and time perception in intertemporal choice. Specifically, **Review I** summarises how temporal discounting is related to socio-demographic, psychological, neuroimaging and genetic variables, and **Review II** elaborates on how the subjective experience of time influences intertemporal decision-making and impulsivity more broadly. In total, the two reviews provide important background information for the findings of the five empirical studies of this dissertation.

Finally, given the findings on non-replicability in psychological research uncovered in recent years (Nosek et al., 2022; Open Science Collaboration, 2015) and the critical role of researchers in this crisis (Simmons et al., 2011), I would like to highlight that a major personal goal of this thesis was to follow state-of-the-art Open Science standards. Therefore, to be as transparent as possible regarding my research, all empirical studies forming part of this dissertation were preregistered in a publicly accessible repository, the Open Science Framework (OSF; https://osf.io/). Moreover, all materials, data (if not restricted by ethical regulations) and analysis scripts were uploaded in the same location to ensure easy access for reanalysis and replication.

2 Methodology

2.1 Psychometric Questionnaires

As outlined in the introduction, the present dissertation assessed personality traits and clinically relevant symptoms. In clinical populations, these phenomena are usually assessed using multiple methods such as unstructured and structured diagnostic interviews, psychological tests and questionnaires to determine diagnostic criteria and symptom severity according to DSM or ICD. In the studies of this dissertation, however, only general population (i.e., mostly healthy, subclinical) samples were recruited. Therefore, traits and symptoms were measured using only questionnaires, as they allow the measurement of different constructs in large-scale general population samples at a high benefit-cost ratio. First, to elucidate the heterogeneous nature of impulsivity, all studies (**Studies I–V**) of the present dissertation included a self-report measure of trait impulsivity. Second, adding to the growing transdiagnostic literature, **Studies IV and V** assessed symptom patterns, i.e., traits (e.g., impulsivity, schizotypy) and symptoms (e.g., depression, anxiety), with the main demarcation point between the two being their temporal frame (DeYoung et al., 2022).

2.1.1 Impulsivity

Impulsivity is a highly heterogeneous term involving different constructs that can be assessed in different ways (see Section 1.1.2). Trait impulsivity is usually assessed with self-report questionnaires such as the UPPS-P/sUPPS-P (Cyders et al., 2014; Lynam et al., 2006; Whiteside & Lynam, 2001). The UPPS-P is a 59-item questionnaire measuring the impulsivity constructs positive urgency (14 items), negative urgency (12 items), sensation seeking (12 items), lack of premeditation (11 items) and lack of perseverance (10 items). Its 20-item version, the sUPPS-P (Cyders et al., 2014), measures the same constructs (4 items each). Usually, participants answer items using a 4-point Likert scale (*strongly disagree*, *rather disagree*, *rather agree*, *strongly agree*), with some studies using a 5-point Likert scale with a *neutral* anchor as midpoint (Kämpfe & Mitte, 2009). Examples of items are presented in Table 1. The UPPS-P and the sUPPS-P have good reliabilities (Hook et al., 2021) and high construct validity, reflected in associations between trait impulsivity constructs (Cyders et al., 2014; MacKillop et al., 2016) and associations with criteria such as mental disorders and daily behaviours (Berg et al., 2015; Bø et al., 2016; Sperry et al., 2016, 2018). Here, the sUPPS-P was used in **Studies I and V**, and the UPPS-P in **Studies II and III**. Where appropriate (**Studies I–III**), German translations were used (translations

based on Schmidt et al., 2008, positive urgency items were self-translated). In **Study IV**, the impulsive nonconformity scale of a schizotypy questionnaire (Mason et al., 2005) served as a trait impulsivity measure (see Section 2.1.2).

Table 1 | Example items for the UPPS-P/sUPPS-P scales

Scale	Item
Positive urgency	I tend to lose control when I am in a great mood.
Negative urgency	When I feel rejected, I will often say things that I later regret.
Sensation seeking	I would like to learn to fly an airplane.
Lack of premeditation	I usually think carefully before doing anything. (*reverse*)
Lack of perseverance	I finish what I start. (*reverse*)

2.1.2 Schizotypy

Schizotypy describes a set of personality traits resembling schizophrenia symptoms on a subclinical level (Ettinger et al., 2014; Grant et al., 2018). Many interview and psychometric questionnaire measures have been published to assess schizotypy (Mason, 2015). A comprehensive self-report measure that is based on the fully-dimensional approach to schizotypy is the *Oxford-Liverpool Inventory of Feelings and Experiences* (O-LIFE; Mason et al., 1995). The short version of the O-LIFE (sO-LIFE; Mason et al., 2005) comprises 43 dichotomous items (*no*/*yes*). It assesses four schizotypy constructs: unusual experiences (12 items), introvertive anhedonia (10 items), cognitive disorganisation (11 items) and impulsive nonconformity (10 items). The former three constructs refer to the distinction of positive, negative and disorganised schizotypy, respectively, while impulsive nonconformity assesses anti-social and eccentric behaviour (Mason et al., 1995). Examples of items are presented in Table 2. Both the O-LIFE and the sO-LIFE have good reliabilities (Mason, 2015) and high construct validity, as reflected in convergent and discriminant correlations with other schizotypy scales (Fonseca-Pedrero, Ortuño-Sierra, Mason, et al., 2015; Mason, 2015) and associations with proneness to and symptoms of psychopathology (Grant et al., 2013; Lin et al., 2013; Nettle, 2006), although the role of impulsive nonconformity is debated (Lin et al., 2013; Polner et al., 2019). Here, the sO-LIFE was used in **Studies IV and V**. Specifically, **Study IV** included the sO-LIFE in a German version (Grant et al., 2013). **Study V** included all scales but the impulsive nonconformity scale, given the coverage of impulsivity by the sUPPS-P.

Table 2 | Example items for the sO-LIFE scales

Scale	Item
Unusual experiences	Are your thoughts sometimes so strong that you can almost hear them?
Introvertive anhedonia	Are there very few things that you have ever enjoyed doing?
Cognitive disorganisation	Are you easily confused if too much happens at the same time?
Impulsive nonconformity	Do you ever have the urge to break or smash things?

2.1.3 Symptom Questionnaires

Besides the sUPPS-P and the sO-LIFE, various questionnaires were used in **Study V** to capture a broad range of different symptom patterns in the general population.

First, the *Depression Anxiety Stress Scales 21* (DASS-21; Lovibond & Lovibond, 1995) is a 21-item questionnaire comprising the subscales depression, anxiety and stress (7 items each). The DASS-21 scale has good to excellent reliability (Antony et al., 1998; Henry & Crawford, 2005; Lovibond & Lovibond, 1995; Norton, 2007). Moreover, it has high construct validity, as reflected in convergent correlations with other affect and depression scales in clinical and non-clinical samples (Antony et al., 1998; Henry & Crawford, 2005; Lovibond & Lovibond, 1995; Norton, 2007) and differential scorings in various patient groups (Antony et al., 1998).

Second, the *State-Trait Anxiety Inventory* (Spielberger et al., 1983) is a 40-item questionnaire measuring trait (STAI-T) and state (STAI-S) anxiety (20 items each). In **Study V**, only the STAI-T was used. The STAI-T scale has good reliability (Barnes et al., 2002) and substantial construct validity, reflected in convergent correlations with other anxiety scales and high scores across different anxiety disorders (Knowles & Olatunji, 2020). However, the STAI-T has been shown to be related not only to anxiety but also to depression (Bados et al., 2010; Bieling et al., 1998; Knowles & Olatunji, 2020), which indicates that it captures negative affectivity more generally rather than mere trait anxiety.

Third, the *Obsessive-Compulsive Inventory–Revised* (OCI-R; Foa et al., 2002) is an 18-item questionnaire measuring obsessive-compulsive behaviours on the subscales washing, checking, ordering, obsessing, hoarding and neutralising (3 items each). The OCI-R scale has good to excellent reliability (Abramovitch et al., 2020; Foa et al., 2002; Hajcak et al., 2004). Its construct validity was demonstrated by convergent correlations with other scales

assessing obsessive-compulsive behaviours and discriminant correlations with scales assessing depression, found in both clinical (Foa et al., 2002; though see Abramowitz & Deacon, 2006, who found weak discriminant validity) and non-clinical populations (Hajcak et al., 2004). Moreover, the OCI-R differentiates well between OCD and other disorders (Abramowitz & Deacon, 2006; Foa et al., 2002) as well as between different severity levels of OCD (Abramovitch et al., 2020).

Fourth, the *Three-Factor Eating Questionnaire-R18* (TFEQ-R18; Karlsson et al., 2000) is an 18-item questionnaire measuring eating behaviour on the three subscales uncontrolled eating (9 items), cognitive restraint (6 items) and emotional eating (3 items). The three TFEQ-R18 subscales have acceptable to good reliabilities (de Lauzon et al., 2004; Karlsson et al., 2000). Construct validity was supported by correlations between emotional eating and mood scores in an obese sample (Karlsson et al., 2000) and differential subscale scores depending on eating patterns (i.e., reported food and energy intake) in a general population sample (de Lauzon et al., 2004). Differences between different genders and age groups should be taken into account (de Lauzon et al., 2004).

Fifth, the *Autism-Spectrum Quotient Short* (AQ-Short; Hoekstra et al., 2011) is a 29-item questionnaire (short version of the instrument by Baron-Cohen et al., 2001), measuring autistic behaviours on the five subscales social skills (8 items), routine (4 items), switching (4 items), imagination (8 items) and numbers/patterns (5 items). The subscales can be subsumed under two higher-order factors, i.e., a social behaviour factor (social skills, routine, switching, imagination) and a numbers/patterns factor (Hoekstra et al., 2011). The full scale has acceptable to excellent reliabilities (Chee et al., 2024; Hoekstra et al., 2011). Construct validity was supported by high correlations between scores in the AQ-Short and those in the original version of the autism-spectrum quotient, sex differences in expected directions and high accuracies in distinguishing clinical and control samples (Hoekstra et al., 2011; Murray et al., 2017).

Sixth, the *Adult ADHD Self-Report Scale V1.1* (ASRS; Kessler, Adler, et al., 2005) is an 18-item questionnaire measuring ADHD symptoms (9 inattention items, 9 impulsivity/hyperactivity items). The ASRS has good reliability in both clinical and non-clinical populations (Adler et al., 2006; Somma et al., 2019). While there is little data on the validity of the 18-item ASRS, construct validity of a 6-item screener, which forms part of the 18-item version, was confirmed by its high diagnostic accuracy in identifying ADHD cases, as determined by overlaps with diagnoses based on structured interviews (Kessler, Adler, et al., 2005; van de Glind et al., 2013). The 6-item version appears to have even higher sensitivity and specificity than the 18-item version (Kessler, Adler, et al., 2005). Nevertheless, in **Study V**, the full version was used so that the ADHD symptom group was reflected by a sufficient number of items (i.e., comparable to other symptom groups).

2.2 Approaches to Examine Questionnaire Structures

Different approaches can be used to examine the structure of psychological constructs and psychometric questionnaires. Factor analysis is arguably the most common statistical method to develop psychometric questionnaires and validate their structures (Gorsuch, 2014). Factor analytical approaches assume that measurable variables can be reduced to a smaller number of latent variables, i.e., factors that capture variance of measured items and thereby provide a dimensional reduction of item information (Bartholomew et al., 2011; Gorsuch, 2014; Harman, 1967). Conceptually, factors are interpreted as indicators of psychological constructs (e.g., intelligence, personality traits) causing measurable variables such as item responses. To identify factors within the data, different factor analytical methods can be used, primarily depending on the researcher's aims (Tinsley & Tinsley, 1987). The most important distinction lies between exploratory and confirmatory methods. While the former are typically used to explore data without a priori hypotheses (e.g., aiming to deduce the structure underlying a large number of items), the latter are used to test specific hypotheses (e.g., aiming to confirm a specific structure of factors in a questionnaire). Beyond factor analyses, network approaches have recently been applied to psychometric questionnaire data (Costantini et al., 2015; Costantini & Perugini, 2018; Cramer et al., 2012). Specifically, often contrasted with factor analytical approaches, network approaches do not necessarily assume the existence of latent variables but propose that psychological phenomena arise through interplays of their components (Borsboom & Cramer, 2013). In this dissertation, both exploratory (**Study V**) and confirmatory (**Study I**) factor analyses as well as network analyses (**Study I**) were used.

2.2.1 Exploratory Factor Analysis

Exploratory factor analysis is a method to identify a number of latent variables, i.e., factors reflecting psychological constructs underlying measured variables of a dataset, based on the covariance (or correlation) matrix of the measured variables. Specifically, factors are extracted from the covariance matrix to parsimoniously explain the variance shared between different variables, such as questionnaire items (Bartholomew et al., 2011; Gorsuch, 2014; Harman, 1967). In contrast to *full component models* such as PCA, *common factor models* do not only assume contributions of the factors to explain the variance of the variables but also a unique term that is not explained by the factors, comprising both systematic and unsystematic (i.e., error) variance (Gorsuch, 2014). This unique term ensures that variables in the diagonal of the reproduced covariance matrix are not equal to one but contain the explained variance of variables (*communalities*). This prevents the strength of the associations between measured variables and factors (*factor loadings*) from being inflated as in PCA (Snook & Gorsuch, 1989; Widaman, 1993). Moreover, common

factor models allow inferences regarding underlying constructs instead of merely summarising and structuring data (Bartholomew et al., 2011; Fabrigar et al., 1999). Within common factor models, different non-statistical (e.g., iterative principal axis factoring; Thomson, 1934) and statistical estimation methods (e.g., maximum likelihood procedures; Lawley, 1940) can be used to estimate parameters of the factor solution, such as factor loadings and communalities (Gorsuch, 2014; Schmitt, 2011). The number of extracted factors can be determined using a variety of methods (Fabrigar et al., 1999; Zwick & Velicer, 1986). One example is the Cartell-Nelson-Gorsuch test (CNG test), which determines the number of extracted factors based on the scree plot (Cattell, 1966; Gorsuch & Nelson, 1981). Moreover, factors are usually rotated (Browne, 2001) to approximate a *simple structure*, i.e., higher loadings of a variable on one factor are accompanied by lower loadings of this variable on other factors (Thurstone, 1931). This rotation procedure can be done either assuming factors to be uncorrelated, requiring an orthogonal rotation (e.g., varimax; Kaiser, 1958), or correlated, requiring oblique rotation (e.g., oblimin; J. E. Jackson, 2014). It should be noted that in most cases in psychology, orthogonal factors can be considered unrealistic (Cattell & Dickman, 1962; Fabrigar et al., 1999; Schmitt, 2011).

Exploratory factor analysis has been widely used in psychology, for instance, to identify structures underlying specific constructs such as intelligence (Reeve & Blacksmith, 2009; Spearman, 1904a; Thurstone, 1947) or to identify personality constructs and create corresponding questionnaires (Cattell, 1945; H. J. Eysenck, 1953). For example, while the UPPS (see Section 2.1.1) was based on PCA results (Whiteside & Lynam, 2001), the O-LIFE (see Section 2.1.2) was constructed using a common factor model (Mason et al., 1995). In addition, exploratory factor analysis has also been used for constructing clinical assessment instruments (Floyd & Widaman, 1995).

2.2.2 Confirmatory Factor Analysis

Confirmatory factor analysis is a method to verify a factor structure which is formulated based on a given theory. Thus, in contrast to exploratory factor analysis, a factor model explaining covariation between observable variables is assumed *a priori* and the model's fit with the measured data is examined (Jöreskog, 1969). Accordingly, confirmatory factor analysis reflects a specific type of structural equation modelling, namely the measurement part, as it examines the relations between factors and observed variables (T. A. Brown & Moore, 2012). Typically, maximum likelihood methods are used to estimate parameters of a specified model based on the covariance matrix and assuming predefined parameters. That is, factor loadings, inter-factor correlations and unique variances can be defined as equal to a specific value or to each other (Gorsuch, 2014; Schermelleh-Engel et al., 2003). Thus, the covariance matrix of the measured variables is reconstructed as closely as possible by estimating the parameters most likely to occur given the predefined model.

Importantly, the model fit, i.e., the consistency of the empirical data with the hypothesised model, can be evaluated using different goodness-of-fit indices (Schermelleh-Engel et al., 2003). A widely used fit index is the χ^2 statistic, which describes the difference between the empirical covariance matrix and the model-implied covariance matrix. The significance of this difference can be tested inferentially. However, χ^2 is largely influenced by model complexity and sample size, with less saturated models and higher sample sizes increasing χ^2 (Schermelleh-Engel et al., 2003). Alternative, entirely descriptive goodness-of-fit indices have been developed, such as (i) the root mean square error of approximation (RMSEA; Steiger, 1990), which quantifies the discrepancy between the population and the model-implied covariance matrix, (ii) the standardised root mean square residual (SRMR; Bentler, 1995), which reflects the magnitude of the standardised residual covariances between the empirical and the model-implied covariance matrices, (iii) the comparative fit index (CFI; Bentler, 1990) or (iv) the Tucker-Lewis index (TLI; Bentler & Bonett, 1980; Tucker & Lewis, 1973), which use different computations to quantify the superiority of the hypothesised model over the independence (baseline) model, i.e., a model in which error variances are zero, factor loadings equal one and variables are uncorrelated. For these goodness-of-fit indices, cut-off values to determine model adequacy have been proposed (L. T. Hu & Bentler, 1999; Schermelleh-Engel et al., 2003). Additionally, model fits can be compared based on these indices. While χ^2 values of different models can be compared using the χ^2 difference test, this inferential test has the same drawbacks as the χ^2 statistic itself. Comparison of the other fit indices may therefore be more appropriate. Moreover, goodness-of-fit indices such as the Akaike information criterion (AIC; Akaike, 1974) account for the parsimony of models.

In psychology, confirmatory factor analysis has widely been used to test hypothesised factorial structures and analyse scale validity (Gorsuch, 2014). This, for instance, applies to the questionnaires used in this dissertation (see Section 2.1).

Specifically, with regard to the UPPS-P, numerous studies involving confirmatory factor analyses have been conducted to validate different versions and language adaptations (Billieux et al., 2012; Bteich et al., 2017; Cándido et al., 2012; Cyders et al., 2014; Cyders & Smith, 2007; Pilatti et al., 2015; Schmidt et al., 2008; Teese et al., 2021; Zsila et al., 2020). In sum, these studies reveal acceptable fits of both a five-factor solution with correlated factors and a hierarchical factor solution, with an overall urgency factor and a lack of conscientiousness factor specified at a higher level (see Section 1.1.3). The fit of different models proposed for the sUPPS-P/UPPS-P was also examined for the German version of the sUPPS-P in **Study I** of this dissertation.

Moreover, confirmatory factor analyses were used to examine the sO-LIFE structure (Fonseca-Pedrero, Ortuño-Sierra, Mason, et al., 2015; Fonseca-Pedrero, Ortuño-Sierra, Sierro, et al., 2015; Sierro et al., 2016). Overall, studies revealed acceptable model fits of both a three-factor solution (positive schizotypy, negative schizotypy, cognitive disorganisation) and a four-factor solution (additionally including an impulsive nonconformity factor). Thus, these results reflect the controversial debate on whether

impulsive nonconformity should be considered a component of schizotypy or not (Lin et al., 2013; Mason et al., 1995; Polner et al., 2019).

Finally, confirmatory factor analyses were also used to confirm (i) the three-factor model of the DASS-21 (Lovibond & Lovibond, 1995; Norton, 2007; although see Henry & Crawford, 2005, who found evidence for a bifactor model as well), (ii) the six-factor model of the OCI-R (Abramovitch et al., 2020; Abramowitz & Deacon, 2006; Foa et al., 2002; Hajcak et al., 2004), (iii) the three-factor model of the TFEQ-R18 (Malkki-Keinänen et al., 2024; Wrzecionkowska & Rivera Aragón, 2021) and (iv) the hierarchical factor model of the AQ-Short (Chee et al., 2024; Grove et al., 2017; Hoekstra et al., 2011; Kuenssberg et al., 2014). For the STAI-T, confirmatory factor analyses revealed that hierarchical or bifactor models accounting for both depression and anxiety provide better model fits than models postulating a single anxiety factor (Bados et al., 2010; Bieling et al., 1998). For the ASRS, a bifactor model with one general ADHD factor and three specific factors (inattention, motor hyperactivity/impulsivity, verbal hyperactivity/impulsivity) provided the best fit (Stanton et al., 2018). Overall, these examples illustrate the relevance of confirmatory factor analyses to test and compare predefined factor structures. The latter examples also exemplify the need to modify theoretically postulated models in case of poor model fits.

2.2.3 Network Analysis in Psychology

Networks describe complex systems in terms of their constituent elements and the associations of those elements with each other (Barrat et al., 2008). The tools of *network science* stem from graph theory and allow to analyse the structure and dynamics of such systems (Boccaletti et al., 2006). Typically, elements are referred to as *nodes*, and their respective associations are referred to as *edges*. Edges can be directed or undirected (i.e., have a specified direction from one element to another or not) and weighted or unweighted (i.e., have values representing the strength of the association or not).

While analysing complex systems by using network approaches is relevant to various scientific fields (Barabási, 2012; Boccaletti et al., 2006), such as sociology (Wasserman & Faust, 1994), information technology (Thelwall, 2004) or biology (Pavlopoulos et al., 2011), here, the focus will lie specifically on psychological networks. In psychological networks, nodes represent observed psychological variables, such as symptoms, thoughts, emotions or behaviours (Borsboom et al., 2021; Costantini et al., 2015, 2021; Costantini & Perugini, 2018; Fried & Cramer, 2017; Robinaugh et al., 2020). The analysis of psychological networks (*network analysis*) typically involves at least two steps (Borsboom et al., 2021; Epskamp, Borsboom, et al., 2018): First, a specific statistical network model is estimated based on observed data. Second, the estimated network model is analysed in terms of measures based on graph theory, such as centrality measures. Finally, given a

lively debate on the reliability and replicability of psychological network models (Borsboom et al., 2017; Forbes et al., 2017a, 2017b; Jones et al., 2021; Steinley et al., 2017), it is recommended to assess the accuracy of the estimated network in a third step (Epskamp, Borsboom, et al., 2018).

Different mathematical models can be used to estimate networks (Boccaletti et al., 2006). For estimating psychological networks, the *Gaussian graphical model* (Epskamp, Waldorp, et al., 2018), which is an undirected network (i.e., a pairwise Markov random field) representing partial correlations of continuous data as weights, has become increasingly popular (Robinaugh et al., 2020). Gaussian graphical models can be estimated for cross-sectional and repeated-measure data (Epskamp, Waldorp, et al., 2018). Similar to the latent variable models described above, the starting point of a Gaussian graphical model is an estimated covariance matrix of the observed variables (Epskamp, Waldorp, et al., 2018; also see Bringmann & Eronen, 2018; Epskamp et al., 2016; Golino & Epskamp, 2017; Kruis & Maris, 2016, who point out overlaps of latent variable and network models and show their mathematical equivalence). The inverse of this covariance matrix is computed and standardised, resulting in a precision matrix, which represents an estimation of partial correlations between variables. Then, to obtain a sparse model (i.e., a model containing partial correlations which equal zero), a wide range of algorithmic estimation methods can be used (Isvoranu & Epskamp, 2023), like regularised algorithms such as *EBICglasso* (Epskamp & Fried, 2018) or non-regularised algorithms such as *ggmModSelect* (for both, see *qgraph* package in R; Epskamp et al., 2012). A recent simulation study (Isvoranu & Epskamp, 2023) concluded that the estimation method should be chosen depending on the research question(s). The result of this estimation is a Gaussian graphical model in which weighted edges are only present between some of the nodes.

Following the estimation procedure, psychological network models can be analysed in different ways. For instance, communities of nodes, i.e., clusters of highly connected nodes, can be identified using different community detection algorithms (Javed et al., 2018), such as the *fast-greedy optimization algorithm* (Clauset et al., 2004). Communities may reflect the existence of latent variables, revealing similarities to exploratory factor analysis (Golino & Epskamp, 2017). Beyond that, network models enable visual inspection of complex systems, which may spark new ideas and hypotheses (Bringmann & Eronen, 2018). Additionally, network models allow the calculation of *centrality indicators* (Freeman, 1978), which give insights into the importance of the elements of a network. The most widely used centrality indicators are strength or degree, closeness and betweenness (Barrat et al., 2008; Bringmann et al., 2019). The *degree* of a node is defined as the sum of edges that directly connect the node with other nodes, while *strength* is used in a weighted network and defined as the absolute sum of weights of the edges adjacent to a node. *Closeness* is defined as a low distance of a node to all others within the network, thereby reflecting both close direct and indirect associations. In weighted networks, the inverse edge weights between nodes are used to derive the shortest paths (*geodesics*) between nodes. *Betweenness* is defined as the number of shortest paths between two nodes that pass

through a specific node. Thus, a node with high betweenness has an important intermediary or bridge function. Figure 4 presents a hypothetical example of an undirected weighted network, illustrating the three centrality measures described for weighted networks. Generally, centrality indicators correlate moderately with each other (Valente et al., 2008), and high values in centrality may reflect that a node has a strong influence on other nodes or is a common effect of them (Bringmann et al., 2019).

In psychology, network approaches have so far predominantly been used to examine how different psychological symptoms influence each other (Contreras et al., 2019; Robinaugh et al., 2020). This follows the idea of psychological network theory that mental disorders do not (only) emerge as a result of a common cause, such as depression, but as a result of an interplay of different symptoms (Borsboom, 2017; Borsboom & Cramer, 2013). For instance, studies investigating mental disorders may reveal strong associations between specific symptoms and identify highly influential symptoms by means of centrality indices (Contreras et al., 2019; Robinaugh et al., 2020), with the latter potentially providing information on effective intervention targets (Robinaugh et al., 2016). Importantly, a similar approach has been proposed for personality traits (Costantini et al., 2015, 2021; Costantini & Perugini, 2018; Cramer et al., 2012). That is, traits are not necessarily caused by a latent trait variable (*correspondence view*) but could be the result of interactions between different thoughts, emotions and behaviours (*emergence view*) (Baumert et al., 2017). An example of the latter view could be that within extraversion, the preference to go to a party or not is influenced by whether the person likes people or not (Cramer et al., 2012). Since network approaches therefore present an alternative approach to factor analysis, potentially resulting in novel insights regarding the structure of psychological constructs, network analyses were conducted in **Study I** of this dissertation. In these analyses, sUPPS-P items were used as nodes in one network and the subscale scores and the discount rate of an intertemporal choice task as nodes in another.

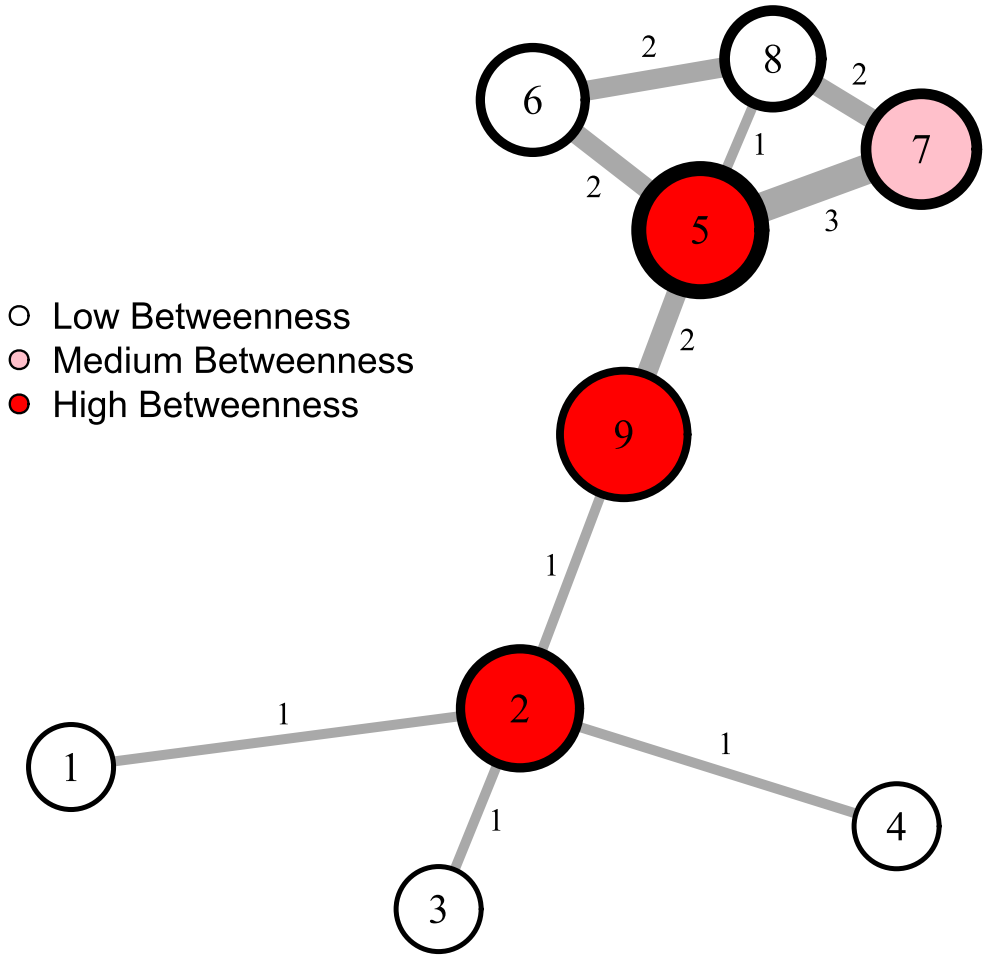


Figure 4 | Example of an undirected, weighted network. The different centrality indices are illustrated as follows. Edge width represents edge strength, with the corresponding weights noted alongside the edges. Node strength is reflected in border width, with node 5 having the highest. Node closeness is reflected in node size, with node 9 having the highest. Node betweenness is represented by colour, with node 2 having the highest. Note that while the different centrality indices correlate positively, differences between indices are possible. For example, node 9 is high on closeness and betweenness but not high on strength.

2.3 Measuring and Estimating Intertemporal Choice Behaviour

As outlined in Section 1.2.1, impulsive decision-making in intertemporal choice is usually measured by presenting participants with a range of choices between smaller-sooner and larger-later rewards and subsequently deriving indices of impulsive decision-making (temporal discounting) based on the choices. Estimates of impulsive decision-making are traditionally based on option-based models (Frederick et al., 2002). Typically, the AUC as

a non-parametric estimate or the discount rate as a parametric estimate of temporal discounting is computed (Hamilton et al., 2015). While a comprehensive theoretical account of different measures and computational models of intertemporal choice has already been provided in Section 1.2.1, this section focuses on the concrete methods used in the current dissertation. Specifically, a task used to measure temporal discounting using predefined answer options and the methods used to estimate discount rates will be presented.

The *Monetary Choice Questionnaire* (MCQ) is a widely used measure of intertemporal choice, presenting participants with 27 predefined binary choices between smaller-immediate and larger-later rewards (Kirby et al., 1999). An example of this is "Would you prefer $69 today or $85 in 91 days?" (item 15). Monetary rewards vary between $11 and $85; delays vary between 7 and 186 days. The items can be divided into three groups with nine items each based on the magnitude of the larger-later reward: small (range: $25–$35), medium (range: $50–$60) and large (range: $75–$85). This allows to account for the magnitude effect (Green et al., 1997). Items were constructed assuming a hyperbolic discounting function. Specifically, the nine items within each magnitude imply different interest rates per time unit based on a hyperbolic function. These interest rates vary within each magnitude but are the same across magnitudes. Hyperbolic discount rates are then estimated based on the decision item(s) at which a participant is indifferent between the choice options (*indifference points*; see below). Given the relatively high range of monetary rewards, the MCQ is typically implemented using hypothetical or partly hypothetical rewards, with instructions for the participants to decide as if all choices would be realised. The MCQ has a high test-retest reliability of .78 over a period of 2 years (Strickland et al., 2023) and has been used, for instance, to associate temporal discounting with other impulsivity constructs (MacKillop et al., 2016) and psychological health variables such as addictive behaviours (Amlung et al., 2017). In all studies of the current work (**Studies I–V**), the MCQ was used as a measure of temporal discounting. In most studies (**Studies I–IV)**, it was translated to a German version with € instead of $ as currency symbol. Additionally, in **Studies II–V**, the MCQ was not only conducted in the standard version with delays in form of days (delay condition; e.g., in 91 days) but also with delays in form of dates (date condition; e.g., 30 November 2024) to obtain the so-called date/delay effect.

Discount rates based on the MCQ responses can be deduced using different methods, illustrating the variety of discount rate estimation methods in general (Chávez et al., 2017; Kirby et al., 1999; Vincent, 2016; Wileyto et al., 2004; M. E. Young, 2018). As noted in Section 1.2.1, the traditional approach is to fit a discount function to the choice data of each participant, estimating the discount rate for each participant separately. This can be done, for instance, using either an algorithmic estimation method based on the original MCQ publication (Kirby et al., 1999) or using logistic regression of choice data (Wileyto et al., 2004). Alternatively, more recent approaches estimate parameters at different hierarchical levels (M. E. Young, 2018), i.e., participant and group levels, using, for example, hierarchical Bayesian modelling (Chávez et al., 2017; Vincent, 2016). The latter has,

amongst others, the advantages of more robust parameter estimates and the retention of uncertainty within posterior distributions. In this work, the algorithmic estimation method (Kirby et al., 1999) was used in **Studies I and IV** to keep the procedures as close as possible to the original instrument (Kirby et al., 1999). Building upon the estimates of **Study IV** (as priors), hierarchical Bayesian modelling (Lee, 2011) was used in studies with later start dates (**Studies II, III and V**) to obtain more robust parameter estimates.

In the algorithmic estimation method (Kirby et al., 1999), choices within an MCQ magnitude, coded as zeros (for smaller-immediate rewards) and ones (for larger-later rewards), are ordered according to their implied interest rates. Then, the consistency of choice behaviour is checked by examining to what extent the choices represent a series of zeros followed by ones (e.g., 0 0 0 0 1 1 1 1 1). If this is a perfect series of zeros and ones, the consistency is perfect (1.00), and the discount rate *k* is computed as geometric mean of the hyperbolic discount rate *k* at indifference points of the respective choices (e.g., in the example, *k* at indifference points of the fourth and fifth choice are used). If choices are not perfectly consistent (e.g., 0 0 1 0 1 1 1 1 1), the highest possible consistency is determined by inspecting the consistencies of each possible discount rate. This consistency can be highest for one or several candidate discount rates (e.g., in the example, consistency is highest either after the first two choices or after the first four choices, i.e., 0.89). In case of several possible discount rates, their geometric mean is computed. After computing discount rates for each magnitude, an overall discount rate is reflected by the geometric mean of the three magnitude discount rates. If consistency within or across magnitudes is too low, however (i.e., < 0.70 or < 0.80), it is recommended to exclude participants because of potential careless responding (Gray et al., 2016). Generally, several easy-to-use scoring tools and syntaxes have been provided for this algorithm (Gray et al., 2016; Kaplan et al., 2016).

The hierarchical Bayesian modelling approach is an estimation approach combining statistical modelling at different hierarchical levels (e.g., group, individual and trial levels) with Bayesian methods (i.e., the incorporation of prior knowledge on likely parameter values and their variability). That is, based on Bayes' theorem, prior information and the data, posterior distributions of parameters at different hierarchical levels are estimated, typically using Markov chain Monte Carlo (MCMC) sampling (Allenby et al., 2005; Gelman et al., 2013; Kruschke, 2015; McGlothlin & Viele, 2018). In the context of intertemporal choice, hierarchical Bayesian modelling can be used to estimate discount rates. Parameter estimation and hypothesis testing can either be combined, retaining information about the uncertainty of participants' discount rates, or point estimates of discount rates can be used for a subsequent hypothesis test (Vincent, 2016). Generally, discount rate estimations can be based on different functions, i.e., exponential, hyperbolic or quasi-hyperbolic functions (see Section 1.2.1). Typically, one of these functional forms is used to derive subjective values of decision options, and a person will likely decide on the option with the higher subjective value. However, participants' decision-making is not always consistent, and hierarchical Bayesian models account for this uncertainty (Chávez

et al., 2017; Vincent, 2016). In the studies of this work, different models were estimated based on different discount functions to compare the model fits with regard to the MCQ data. The model with the best fit was then used to obtain posterior estimates of discount rate and uncertainty parameters. In these models, group and individual priors for discount rate and uncertainty parameters were set beforehand (i.e., normal distributions within a specific range based on the results from **Study IV**). A discount function was assumed, like the hyperbolic discount function $SV = V/(1 + \rho d)$, where the subjective values of smaller-immediate and larger-later rewards SV were computed by multiplying the objective reward V with the hyperbolic function comprising the parametric discount rate ρ (or k) and the delay d. Then, the probability of a choice for a larger-later reward was modelled as a softmax function (taking 0 or 1 as values) combining the comparison of subjective values of larger-later and smaller-immediate rewards $SV_{LLR} - SV_{SIR}$ with an uncertainty parameter θ:

$$p(choice\ LLR) = \frac{1}{1 + e^{-\theta(SV_{LLR} - SV_{SIR})}} \quad (4)$$

This model allowed to extract posterior distributions and point estimates of discount rate and uncertainty parameters ρ and θ. Finally, using the discount function that resulted in the best model fit, another model was estimated explicitly accounting for condition (delay vs. date) in order to extract discount rates for each condition. These parameters were used to inspect posterior distributions and obtain point estimates for further statistical analyses.

2.4 Computational Factor Modelling

As described in Section 1.2.5, previous studies have usually used case-control or case-case designs to determine whether specific constructs (e.g., impulsive decision-making) are altered in specific mental disorders. More recently, dimensional approaches to psychopathology have been introduced to address caveats of categorical approaches and to determine whether transdiagnostic variables are associated with such constructs. An example in this context is *computational factor modelling* (CFM).

CFM combines exploratory factor analysis (see Section 2.2.1) and computational modelling of behaviour (e.g., of temporal discounting; see Section 2.3) to elucidate structures underlying psychopathology (Gillan & Seow, 2020; Wise et al., 2023). Instead of using clinical interviews and questionnaires to identify people with specific categorical diagnoses, CFM uses questionnaire data to identify transdiagnostic dimensions of psychopathology. Typically, a large number of participants are recruited from the general population and complete psychopathology questionnaires and a behavioural task, for example, tapping metacognition, reward processing or uncertainty (Wise et al., 2023). The questionnaire data are then used to derive transdiagnostic dimensions by conducting an exploratory factor analysis. Crucially, associations between factor scores of the

transdiagnostic dimensions and computationally derived behavioural model parameters are examined to identify the cognitive underpinnings of psychopathology and reveal potential intervention targets. **Study V** of this dissertation applied this approach. A depiction of CFM is presented in Figure 5.

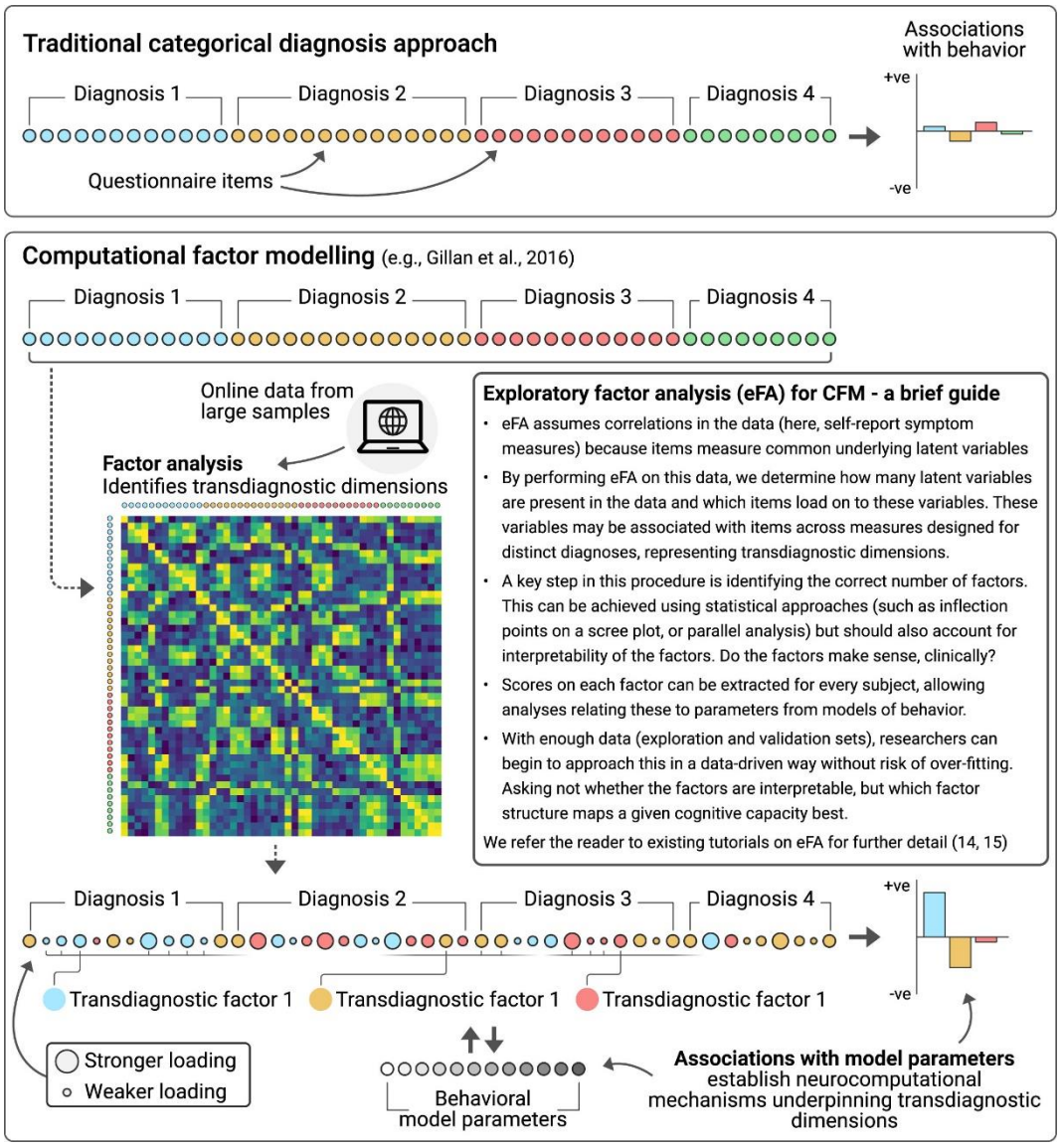


Figure 5 | Computational factor modelling. The figure opposes the traditional categorical diagnosis approach with computational factor modelling (CFM). Typical steps in CFM involve (i) exploratory factor analysis to identify transdiagnostic dimensions in large general population samples, (ii) estimating behavioural parameters using computational models and (iii) examining the relationship between transdiagnostic dimensions and behavioural parameters. References 14 and 15 in the figure correspond to Yong and Pearce (2013) and Schmitt (2011), respectively. The figure was reprinted from Wise et al. (2023). For details regarding third party copyright material, see pages 21–22.

2.5 Eye Movement Recording and Analysis

Humans move their body, head and eyes to bring objects or locations into the focus of the *fovea centralis*, the point of sharpest vision. In many cases, this process is accompanied by *visual attention*, which refers to the process of focusing the mind on specific stimuli in the field of view while ignoring others (Goldstein & Brockmole, 2017; Greenlee & Kimmig, 2019). When visual attention is accompanied by eye movements, it is referred to as *overt* visual attention (Findlay & Gilchrist, 2003; Hoffman & Subramaniam, 1995). Accordingly, overt visual attention can be examined using eye-tracking methods, yielding valuable insights into people's intentions (Tatler et al., 2010; Yarbus, 1967) and cognitive processes (Rayner, 1998, 2009).

A modern method to track participants' eye movements is video-based eye-tracking (Hansen & Ji, 2010; Hutton, 2019). Most video-based systems use the *pupil–corneal reflection (P–CR) technique*. Specifically, such eye trackers record at least one eye using a video camera and illuminate the eye, usually using infrared light. The infrared light allows to clearly separate the pupil from the rest of the eye (e.g., "dark pupil" or "bright pupil" tracking; Morimoto et al., 2000; L. R. Young & Sheena, 1975) and produces the *corneal reflection* (first Purkinje image; Cornsweet & Crane, 1973). Complex image processing algorithms implemented in the eye-tracking software are used to identify the positions of pupil and corneal reflection centres (Hutton, 2019). Importantly, when the eyes are directed to various parts of the visual field, the relative positions of pupil centre and corneal reflection differ (Duchowski, 2017; Hutton, 2019). Therefore, following calibration (and validation) procedures, the combined information of pupil centre and corneal reflection allows to determine the point of gaze, usually in terms of pixels (X and Y coordinates) on the screen (Hutton, 2019). Additionally, the difference between pupil centre and corneal reflection is relatively constant with minor head movements (Duchowski, 2017). Figure 6 illustrates the respective positions of pupil and corneal reflection when the eye is fixated on the centre, right, left, top and bottom of a target display. Finally, video-based eye-trackers may be monocular or binocular systems and stationery or mobile systems (Hutton, 2019). Importantly, some stationary systems are compatible with magnetic resonance techniques, allowing the use in magnetic resonance imaging (MRI) scanners.

Based on the position data supplied by the eye-tracker in X and Y coordinates (combined with a timestamp), various criteria are used to classify different types of eye movements, a process referred to as *event parsing* (Hutton, 2019). Typically, event parsing is based on algorithms (Hein & Zangemeister, 2017; Stuart et al., 2019). For instance, *velocity-* or *dispersion-based algorithms* are widely used to detect saccades and fixations, respectively (Salvucci & Goldberg, 2000). While the former identify saccades based on the velocity of eye movements and categorise the rest as fixations (or lost data), the latter identify fixations based on dispersion thresholds and categorise the rest as saccades (or lost data). In both cases, the specific thresholds can be set by the user. In cognitive research, for instance,

saccadic thresholds may be a minimum velocity of 30°/sec, minimum acceleration of 8000°/sec² and minimum motion of 0.15° (SR Research Ltd., 2010). Alternatively, a fixation threshold may be a maximum dispersion (i.e., distance) of 0.7–1.3° (Blignaut, 2009) within a time period of 100–200 ms (Widdel, 1984). The number and specifications of criteria used depend on the user's preferences, the research context and the software (if any) used.

Once different eye movements are classified, a broad range of metrics can be computed to examine their dynamics as well as derived perceptive, emotional and cognitive processes (Borys & Wójcik, 2017; Skaramagkas et al., 2023). Different fixation- and saccade-based metrics have been used to characterise attentional processes in decision-making (Bhatnagar & Orquin, 2022; Wedel et al., 2023). For example, the use of *areas of interest* (AOIs) is particularly important to examine visual attention within intertemporal choices. AOIs defined in terms of X and Y coordinates before or after the conduction of an experiment help reveal the number and duration of fixations within specific AOIs, which, for example, may be indicative of higher cognitive effort or task difficulty (Krajbich et al., 2010) as well as attribute weighting and choice behaviour more generally (Amasino et al., 2019; Fisher, 2021; Franco-Watkins et al., 2016; Yang & Krajbich, 2023). Moreover, patterns of saccades between different AOIs may be indicative of information search strategies (Amasino et al., 2019; He et al., 2023; Reeck et al., 2017; though see Zhang et al., 2022, challenging this notion).

Therefore, in this work, a video-based eye-tracker using the P–CR technique was used in **Studies II and III** (*EyeLink 1000* as desktop or long-range mount, respectively; SR Research Ltd., Kanata, ON, Canada) to examine attentional processes contributing to the date/delay effect. Event parsing was achieved using the default velocity-based algorithms supplied by the software Data Viewer provided by the manufacturer, and different eye-tracking metrics were computed based on predefined AOIs to draw conclusions about differences between date and delay conditions.

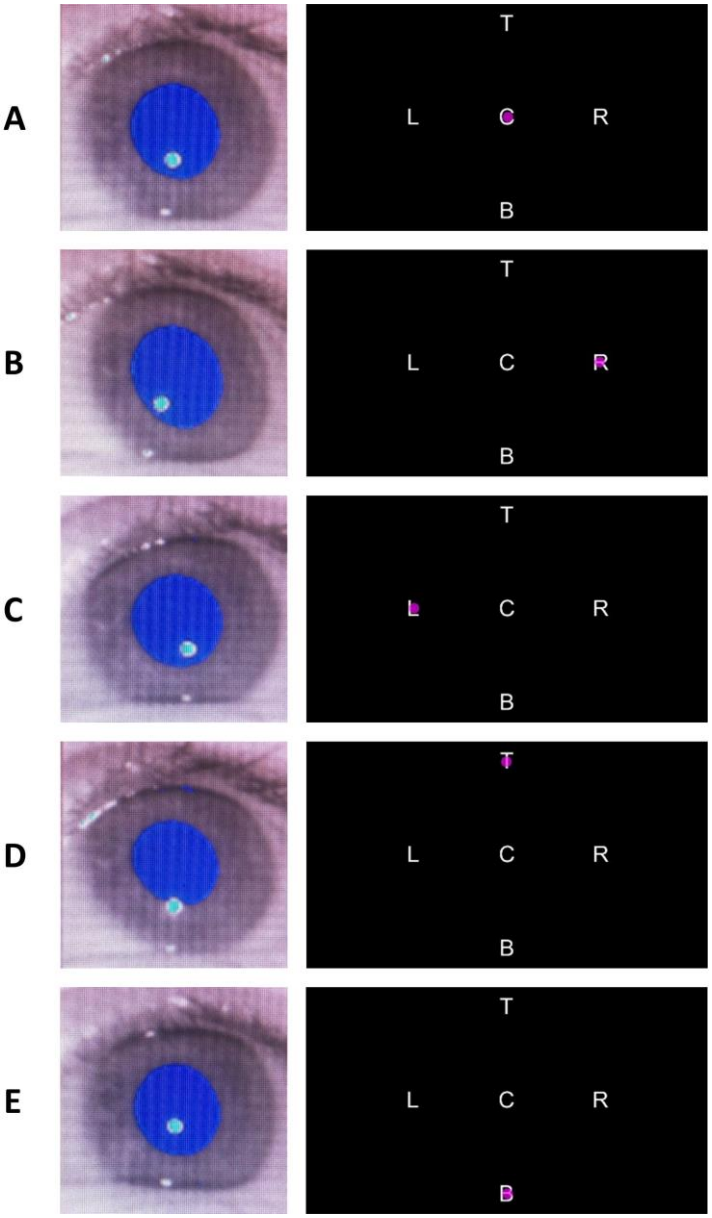


Figure 6 | Example of eye-tracking. Eye movements of the author's right eye were recorded. The subplots A–E correspond to fixations on the letters C (centre), R (right), L (left), T (top) and B (bottom), respectively. The letters outside the centre are presented at 10° of visual angle. The left column of each subplot shows the (left/right mirrored) eye with coloured thresholds for the pupil (dark blue) and the corneal reflection (light blue). The right column of each subplot presents the target display with the current fixation as pink transparent point. Note how the positions of pupil and corneal reflection relative to each other change, enabling video-based eye-tracking using the pupil–corneal reflection (P–CR) technique.

2.6 Functional Magnetic Resonance Imaging

MRI is a non-invasive imaging technique using strong magnetic fields to visualise biological tissue (R. W. Brown et al., 2014; Huettel et al., 2014). Importantly, it can be used to examine the brain's anatomical structure and neural functioning in healthy participants and patient groups (Le Bihan, 2020).

MRI relies on the magnetic properties of water molecules (R. W. Brown et al., 2014; Huettel et al., 2014; Logothetis & Wandell, 2004). Outside the MRI scanner, hydrogen nuclei spin along their axis and have a nearly random orientation so that their net magnetisation, i.e., the overall magnetic response, is very small. Within the static magnetic field generated by electromagnetic coils of the MRI scanner, hydrogen nuclei align and spin parallel (low-energy state) or antiparallel (high-energy state) to the magnetic field (Huettel et al., 2014). In the absence of excitation, more nuclei are in the parallel than in the antiparallel state, leading to a higher net magnetisation along the longitudinal axis (*equilibrium*). When a person is placed into the scanner, radiofrequency coils are used to send radiofrequency pulses with a specific resonance frequency (Larmor frequency) into the tissue, exciting some hydrogen nuclei into a state of high energy (*excitation*), i.e., more hydrogen nuclei spin antiparallel to the magnetic field. As a result, the net magnetisation changes from the longitudinal to the transverse plane. When the radiofrequency pulse ceases, some hydrogen nuclei return to their initial state, releasing energy and restoring the equilibrium (*relaxation*). The transverse magnetisation decreases, and the longitudinal magnetisation recovers. This process is measured by the radiofrequency coils (*reception*) and constitutes the magnetic resonance signal (*MR signal*). Gradient coils additionally generate magnetic gradients, causing the MR signal to become spatially controllable, and shimming coils correct for inhomogeneities in the static field (Huettel et al., 2014).

The MR signal allows to gain information about the brain tissue. Specifically, tissues differ in their relaxation process in terms of exponential changes in longitudinal recovery and transverse decay (Huettel et al., 2014; Logothetis & Wandell, 2004). While the time constant T1 reflects the growth of longitudinal net magnetisation along the static field, the time constants T2 and T2* reflect the loss of net magnetisation transverse to the static field (Serai, 2022). Measurement of T1 and T2 parameters are used to create anatomical images of the brain, whereas measurement of the T2* parameter provides an indirect measure of brain function, i.e., functional images, because it considers local field inhomogeneities. During a typical MRI measurement, multiple pulses are used to produce a series of three-dimensional brain images (Bernstein et al., 2004; E. F. Jackson et al., 1997). The pulse sequence is, amongst others, characterised by the repetition time (TR), i.e., the time between consecutive excitation pulses, and the echo time (TE), i.e., the time between the excitation pulse and the measurement.

The local inhomogeneities within the T2* images are mainly caused by changes in cerebral blood flow due to neural activity, known as the *Blood Oxygen Level Dependent* (BOLD)

contrast (Huettel et al., 2014; Logothetis & Wandell, 2004; Ogawa et al., 1990). The brain requires oxygen to produce energy, particularly in active brain regions. Therefore, oxygen is constantly transported to the brain in the blood by binding to the protein complex haemoglobin (Mairbäurl & Weber, 2012). Importantly, oxygenated haemoglobin is diamagnetic, while deoxygenated haemoglobin is parametric (Pauling & Coryell, 1936). Consequently, the T2* values change in response to changes in brain activity, and fMRI makes use of this BOLD signal (Ogawa et al., 1990). Specifically, the cerebral blood flow measured as the BOLD signal follows a haemodynamical response function (HRF). While the specific form of the HRF varies with stimulus paradigm and across participants and brain regions (Aguirre et al., 1998; Handwerker et al., 2004; Miezin et al., 2000), a prototypical shape in response to a simple stimulus is characterised by (i) a steep increase of the BOLD signal with a peak after 4–6 seconds and (ii) a decrease in the BOLD signal, slightly overshooting to a BOLD signal more negative than baseline and then returning to the baseline value (Huettel et al., 2014). Additionally, the role of an initial dip of the BOLD signal 1–2 seconds after stimulus presentation is heavily debated (X. Hu & Yacoub, 2012). Figure 7 presents examples of the HRF with and without initial dip. Specifically, Figure 7A is based on the difference of two gamma functions with default values as specified in the *spm_hrf* function of the analysis software SPM12 (Ashburner et al., 2021), resulting in an HRF without initial dip, whereas Figure 7B additionally incorporates a third negative gamma function (Kamran et al., 2018, formula 3), resulting in an HRF with initial dip.

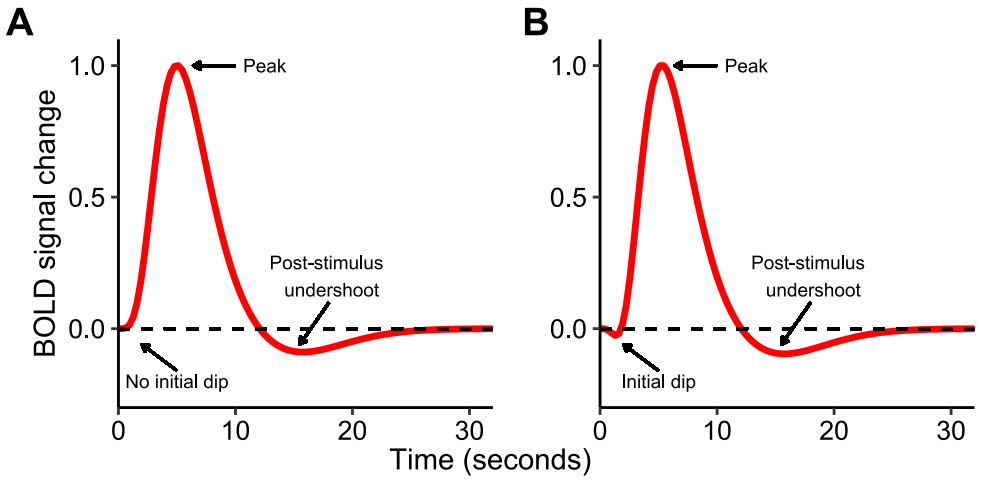


Figure 7 | Examples of the haemodynamical response function (HRF). The HRF is measured as change in blood oxygen level dependent (BOLD). Panel A presents an HRF without initial dip and is based on the difference of two gamma functions with default values specified as in the analysis software SPM12 (Ashburner et al., 2021). Panel B presents an HRF with initial dip and is based on the same gamma functions as panel A but additionally incorporates a third negative gamma function (Kamran et al., 2018, formula 3). The red line represents the HRF, while the black dashed line represents the baseline BOLD signal. The values for the BOLD signal change are arbitrary and were therefore coded as proportion of the maximum signal.

Before fMRI images can be analysed, different preprocessing steps are performed to minimise task-unrelated variability and prepare the data for statistical analysis (Huettel et al., 2014). While the used preprocessing steps may vary from study to study, the following description shall give examples of widely used preprocessing steps in event-related fMRI designs, i.e., designs in which short-duration events are presented and analysed (Huettel et al., 2014; Rosen et al., 1998), such as in **Study III**. Typically, functional images are slice-time corrected to adjust for different timings of brain slice scans within a pulse sequence. To correct for head motion, the functional images are realigned with respect to a reference image, such as the first or the mean image in the time series. Then, the functional images are mapped onto a high-resolution anatomical image to adjust for limits in resolution and contrast of functional images. To be able to compare activation across participants, images are normalised into a standard stereotaxic space. Finally, images are spatially smoothed, usually using a Gaussian kernel, so that voxel data are spread across the adjacent voxels to increase the signal-to-noise ratio. These steps enable analyses of the fMRI images on a participant and group level, commonly referred to as first and second level (Huettel et al., 2014).

In the general linear model (GLM) approach to fMRI (Friston et al., 1994; Jenkinson et al., 2020; Poline & Brett, 2012), a data matrix (comprising voxel-wise fMRI data per time point) is regressed on the product of the design matrix (comprising different regressors with data for each voxel and time point) and the parameter matrix (comprising the voxel beta values of interest) plus an error matrix (comprising the residual for each voxel). The data matrix contains the observed and preprocessed fMRI data, the design matrix is created by the researcher based on the expected effects, and the parameter and error matrices are estimated (Huettel et al., 2014). Typically, the design matrix contains regressors reflecting specific events (e.g., conditions) convolved with the HRF. Additionally, continuous parametric modulators may be specified. Such regressors, i.e., those relevant to the research question, are called *regressors of interest*. Moreover, *regressors of no interest* (nuisance regressors) may be added to the design matrix to reduce residual variation in the error matrix and improve the validity of the GLM (Huettel et al., 2014). Estimated regressor weights of the design matrix (i.e., the parameter matrix), which reflect how much voxel-wise activity a particular regressor explains, can then be compared to each other using contrasts. Specifically, contrasts are typically built on a first level, comparing regressor weights of experimental conditions against each other or against an implicit baseline (e.g., using *t*-tests). Finally, to reveal differences between conditions across participants, second level contrasts are built. Specifically, contrast images based on fixed effects on the participant level are used to infer the distributions of such effects using a random-effect analysis (e.g., one-sample *t*-test) on the second level (Huettel et al., 2014). Since the GLM approach to fMRI involves a high number of voxel comparisons, correction for multiple comparisons is essential to reduce the risk of committing a type I error (Bennett et al., 2009; Nichols, 2012).

Some shortcomings such as the correlative nature of brain activity and the relatively low temporal resolution notwithstanding, fMRI is currently the most widely used technique to map brain structure and activity during various tasks in humans (Logothetis, 2008). In this work, fMRI was used in **Study III** to examine the neural mechanisms of the date/delay effect. Preprocessing involved the steps outlined above, and different GLMs were used to compare date and delay conditions, including models with parametric regressors of subjective values at the first level and models with covariates at the second level.

3 Synopses

3.1 Empirical Studies

An overview of the five empirical studies included in this dissertation is presented in Table 3. The five studies are summarised on the following pages. The complete articles are presented in Appendices A–E.

Table 3 | Overview of empirical studies included in this dissertation

Index	Reference
Study I	Keidel, K., Ettinger, U., Murawski, C., & Polner, B. (2022). The network structure of impulsive personality and temporal discounting. *Journal of Research in Personality*, *96*, Article 104166. https://doi.org/10.1016/j.jrp.2021.104166 Preregistration: https://osf.io/qmkfc | Materials, data and scripts: https://osf.io/u6vps/
Study II	Keidel, K., Murawski, C., & Ettinger, U. (2024). Attentional mechanisms of the date/delay effect in intertemporal choice: An eye-tracking study. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. Advance Online Publication. https://doi.org/10.1037/xlm0001363 Preregistration: https://osf.io/a3u54 | Materials, data and scripts: https://osf.io/xrkuf/
Study III	Keidel, K., Schröder, R., Trautner, P., Radbruch, A., Murawski, C., & Ettinger, U. (2024). The date/delay effect in intertemporal choice: A combined fMRI and eye-tracking study. *Human Brain Mapping*, *45*(3), Article e26585. https://doi.org/10.1002/hbm.26585 Preregistration: https://osf.io/d9u74 | Materials, data and scripts: https://osf.io/td5gf/
Study IV	Keidel, K., Murawski, C., Pantelis, C., & Ettinger, U. (in press). The relationship between schizotypal personality traits and temporal discounting: The role of the date/delay effect. *Schizophrenia Bulletin*. https://doi.org/10.1093/schbul/sbad110 Preregistration: https://osf.io/7jxf9 | Materials, data and scripts: https://osf.io/xdn7c/
Study V	Keidel, K., Lu, X., Suzuki, S., Murawski, C., & Ettinger, U. (2024). Association of temporal discounting with transdiagnostic symptom dimensions. *Npj Mental Health Research*, 3, Article 13. https://doi.org/10.1038/s44184-024-00060-3 Preregistration: https://osf.io/fg9sc | Materials, data and scripts: https://osf.io/ezaup/

3.1.1 Study I: Network Approach to Impulsivity and Impulsive Decision-Making

Impulsivity is a heterogeneous umbrella term spanning multiple constructs (Evenden, 1999; Strickland & Johnson, 2021; see Section 1.1.1). So far, most studies have used factor analytical approaches to examine the associations between impulsive personality constructs, with ambiguous findings regarding the separability of positive and negative urgency as well as lack of premeditation and lack of perseverance (Berg et al., 2015; Goh et al., 2020; Sperry et al., 2018). Additionally, the construct lack of premeditation may be highly important not only to the definition of impulsivity but also to other impulsivity-related constructs, reflected in associations with personality traits (Cyders et al., 2014; Goh et al., 2020; MacKillop et al., 2016; Whiteside & Lynam, 2001) and real-world outcomes (J. Miller et al., 2003; see Section 1.1.3). Therefore, mapping the relative positions of impulsivity constructs using network analysis may yield novel insights regarding their associations and the critical role of lack of premeditation.

The structure of impulsivity was examined in N = 1,000 participants. Participants completed the sUPPS-P (Cyders et al., 2014; comprising the scales negative urgency, lack of premeditation, lack of perseverance, sensation seeking, positive urgency) as a measure of impulsive personality and the MCQ (Kirby et al., 1999; temporal discounting task) as a measure of impulsive behaviour in an online study. Data were analysed using both confirmatory factor analysis and network analysis.

Factor analysis of the sUPPS-P data showed that a model with five intercorrelated factors, a hierarchical model with urgency, sensation seeking and lack of conscientiousness as second-order factors and a bifactor model provided acceptable model fits (Figure 8A–C). An item-level network analysis with community detection yielded communities largely similar to the originally proposed constructs, but positive and negative urgency were merged into a single community (Figure 8D). Within this network, lack of premeditation items showed the highest closeness centrality (Figure 8E). Moreover, a scale-level network including the discount rate estimated based on the MCQ data revealed weak though significant associations between the MCQ discount rate and lack of premeditation and positive and negative urgency (Figure 8F). Centralities were highest for lack of premeditation as well as positive and negative urgency (Figure 8G).

In sum, this large-scale study confirmed previously observed factor solutions of the sUPPS-P (Cyders & Smith, 2007; Zsila et al., 2020) using factor and network analysis. However, the findings strengthen doubts regarding the separability of positive and negative urgency. Moreover, the closeness of lack of premeditation items to other items and the association with temporal discounting suggest that this construct may be a causal factor for, or common consequence of (Golino & Epskamp, 2017), many impulsive behaviours.

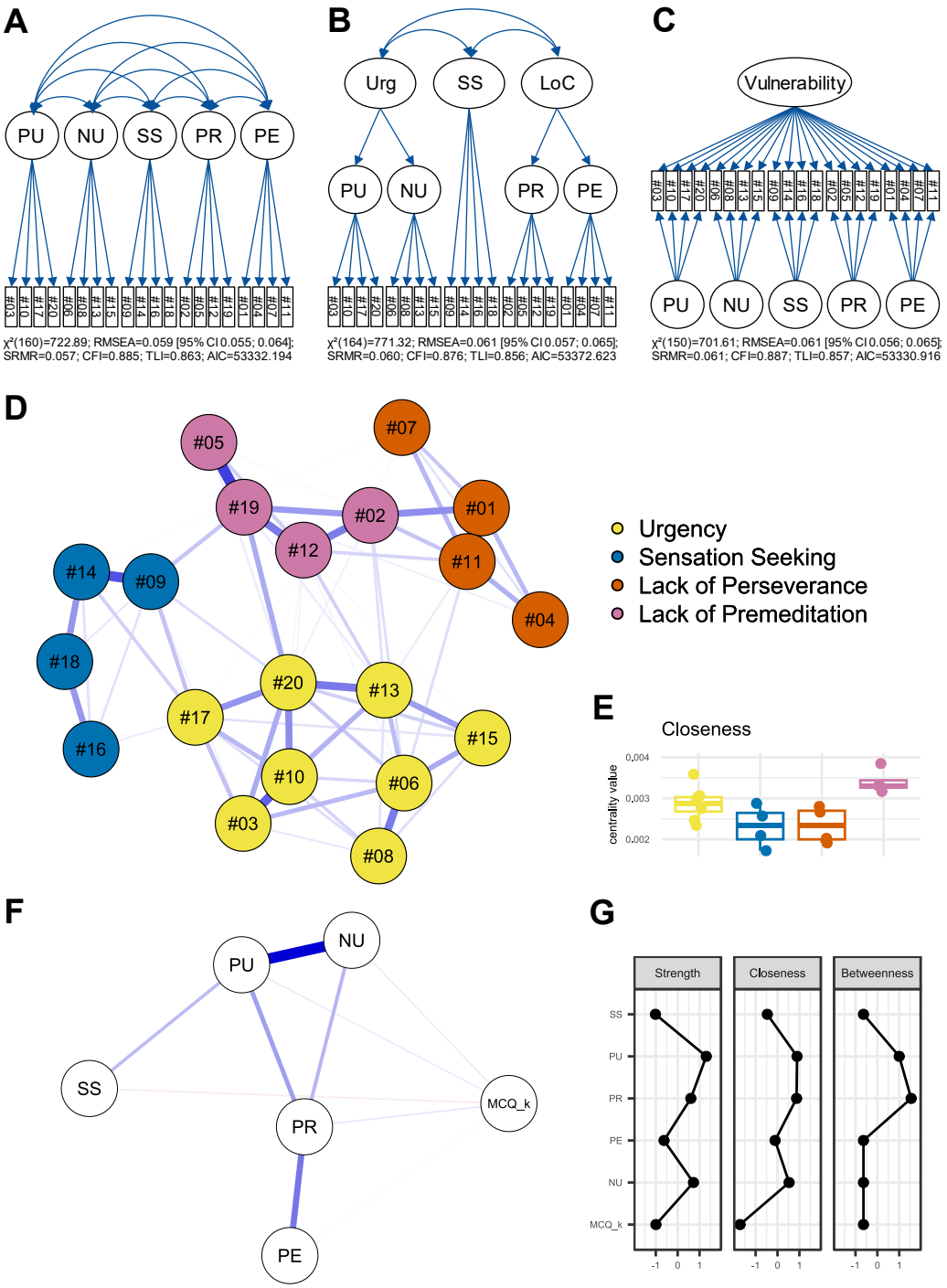


Figure 8 | Key results of Study I. Panels A–C present acceptable factor models for the sUPPS-P, panel D presents the item-level network of the sUPPS-P with closeness centralities of items per community in panel E, and panel F presents the scale-level network with centralities in panel G. PU = positive urgency, NU = negative urgency, SS = sensation seeking, PR = lack of premeditation, PE = lack of perseverance, Urg = Urgency, LoC = lack of conscientiousness, MCQ_k = log-transformed discount rate. The figure was adapted from **Study I**. For details regarding third party copyright material, see pages 21–22.

3.1.2 Study II: Mechanisms of the Date/Delay Effect I: Eye-Tracking

When time until receipt of rewards in intertemporal choice scenarios is presented in dates rather than delay units, people tend to show reduced temporal discounting, an effect known as date/delay effect (LeBoeuf, 2006; Read et al., 2005). Different hypotheses have been proposed to explain the cognitive mechanisms underlying this effect, some of which relate to attentional processes (see Section 1.2.3). Specifically, the choice strategy hypothesis posits that, consistent with attribute-based models of temporal discounting, participants shift towards a more comparative rather than integrative search strategy (Read et al., 2005), the attention-focusing hypothesis posits that participants direct their attention more towards rewards (LeBoeuf, 2006; Read et al., 2005), and the deliberation hypothesis posits that participants may adopt a more deliberate processing mode in the date compared to the delay condition (Dshemuchadse et al., 2013). Using eye-tracking to examine these hypotheses may provide novel insights regarding the date/delay effect.

Infrared oculography was used to examine overt attention in $N = 54$ participants completing intertemporal choices from the MCQ (Kirby et al., 1999) in a delay and a date condition (Figure 9A–B).

Results confirmed the date/delay effect, $p < .001$, $g_{av} = 0.48$. While participants did not experience the two conditions significantly differently (e.g., in terms of mental demand), they spent significantly more time on items in the date than the delay condition. Specifically, eye-tracking analyses revealed that participants made more saccades between (Figure 9C–D) and looked longer at (Figure 9E–F) time attributes in the date than in the delay condition. While between-participant associations of these effects with the date/delay effect were not significant, trials with a higher reward difference predicted the choice of a larger-later reward significantly more in the date than in the delay condition. Explorative correlations showed that the date/delay effect was higher in persons who showed higher discounting in the delay condition and used an integrative strategy.

Overall, this study provides tentative evidence for the choice strategy and attention-focusing hypotheses and at best partially supports the deliberation hypothesis. Participants appear to compute intervals of time attributes more often in the date than in the delay condition, in line with the choice strategy hypothesis and attribute-based models of temporal discounting. Moreover, in the date condition, overt attention may be more directed towards time than reward information, but this may be due to reading requirements (i.e., dates comprised more symbols than delay units). However, people may weight reward attributes more strongly than time attributes, speaking for a reward-weighting rather than the attention-focusing hypothesis. Finally, the date/delay manipulation may be particularly effective in people initially showing more impulsive decision-making.

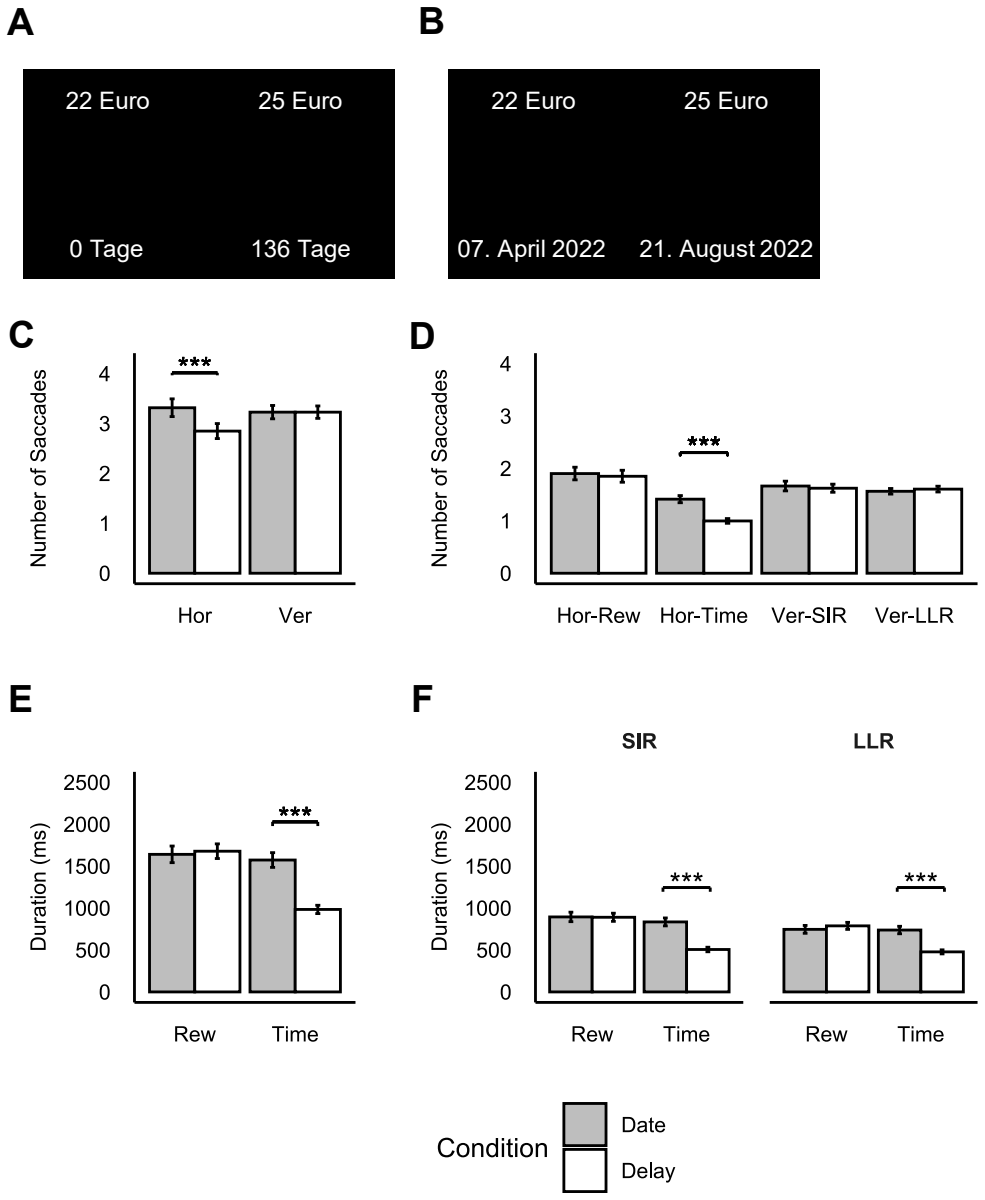


Figure 9 | Key methods and results of Study II. Panels A and B present examples of trials in the delay and date condition, respectively, with reward and time attributes in the four areas of interest (AOIs). Panels C and D represent the number of horizontal (Hor) and vertical (Ver) saccades between different AOIs. While Panel C does not differ between specific saccades, panel D specifies whether the horizontal saccade was between rewards (Rew) or delays (Time) and whether vertical saccades were between attributes of the smaller-immediate (SIR) or larger-later reward (LLR). Panels E and F represent the fixation durations on specific AOIs. While panel E summarises reward and time over both options, panel F presents the results separated by option. Errors bars represent standard errors of the mean. *** $p < .001$. Panels C–F were adapted from **Study II**. For details regarding third party copyright material, see pages 21–22.

3.1.3 Study III: Mechanisms of the Date/Delay Effect II: fMRI and Eye-Tracking

Previous studies have identified different neural networks that play a role in intertemporal choice (see Section 1.2.4). Amongst others, a memory-driven system (prospection-related areas, e.g., precuneus, medial temporal lobe), a subjective value computation system (valuation areas, e.g., mPFC, vS) and a comparator system (cognitive control areas, e.g., prefrontal cortex) can be distinguished (Frost & McNaughton, 2017). However, the exact role of specific brain regions in intertemporal choice still needs to be determined. Examining the neural mechanisms of the date/delay effect (LeBoeuf, 2006; Read et al., 2005) may therefore inform which neural processes during intertemporal choices are related to time processing. Importantly, since the neural mechanisms of the date/delay effect itself are unclear, examining the neural processes may also give important insights into the underpinnings of the effect itself (see different hypotheses in Section 1.2.3).

The cognitive and neural mechanisms of time framing were examined in a combined fMRI and eye-tracking study. Specifically, $N = 31$ completed the MCQ (Kirby et al., 1999) twice in a delay and twice in a date condition whilst brain activity and eye movements were recorded.

On a behavioural level, the date/delay effect was replicated, $p < .001$, $g_{av} = 0.54$. Moreover, eye-tracking analyses showed that participants made more saccades between and looked longer at time attributes in the date than in the delay condition. fMRI BOLD data analysis revealed that the date condition was associated with higher activity in visual areas, PCC, precuneus, middle/superior frontal gyrus (MFG/SFG) and angular gyrus (Figure 10A) than the delay condition. In this contrast, a lower date/delay effect was associated with higher activity differences in occipital areas/cerebellum, MFG/SFG, posterior medial frontal cortex (pMFC) and anterior/mid-cingulate cortex (ACC/MCC) (Figure 10B). In region of interest (ROI) analyses of the vS and vmPFC, a significantly higher subjective value signal in the vS was found in the delay compared to the date condition.

In sum, brain activation in areas associated with time processing (precuneus/PCC, angular gyrus) is higher in the date than in the delay condition, pointing towards differential processing and estimation of time (Read et al., 2005). Similar to the tag effect (Peters & Büchel, 2010; Sasse et al., 2015), the different framing cue may enhance visual imagery of the future reward. Also, higher specificity of the date cue may trigger memories and be of higher personal relevance (i.e., lower psychological distance; Trope & Liberman, 2003). Moreover, the eye-tracking results show that participants compare time attributes more often in the date condition. Given the covariation of a lower date/delay effect with cognitive control regions, people exhibiting a lower date/delay effect may transform dates to delay units, while people exhibiting a higher date/delay effect calculate relatively less and adapt their choice strategy compared to the delay condition.

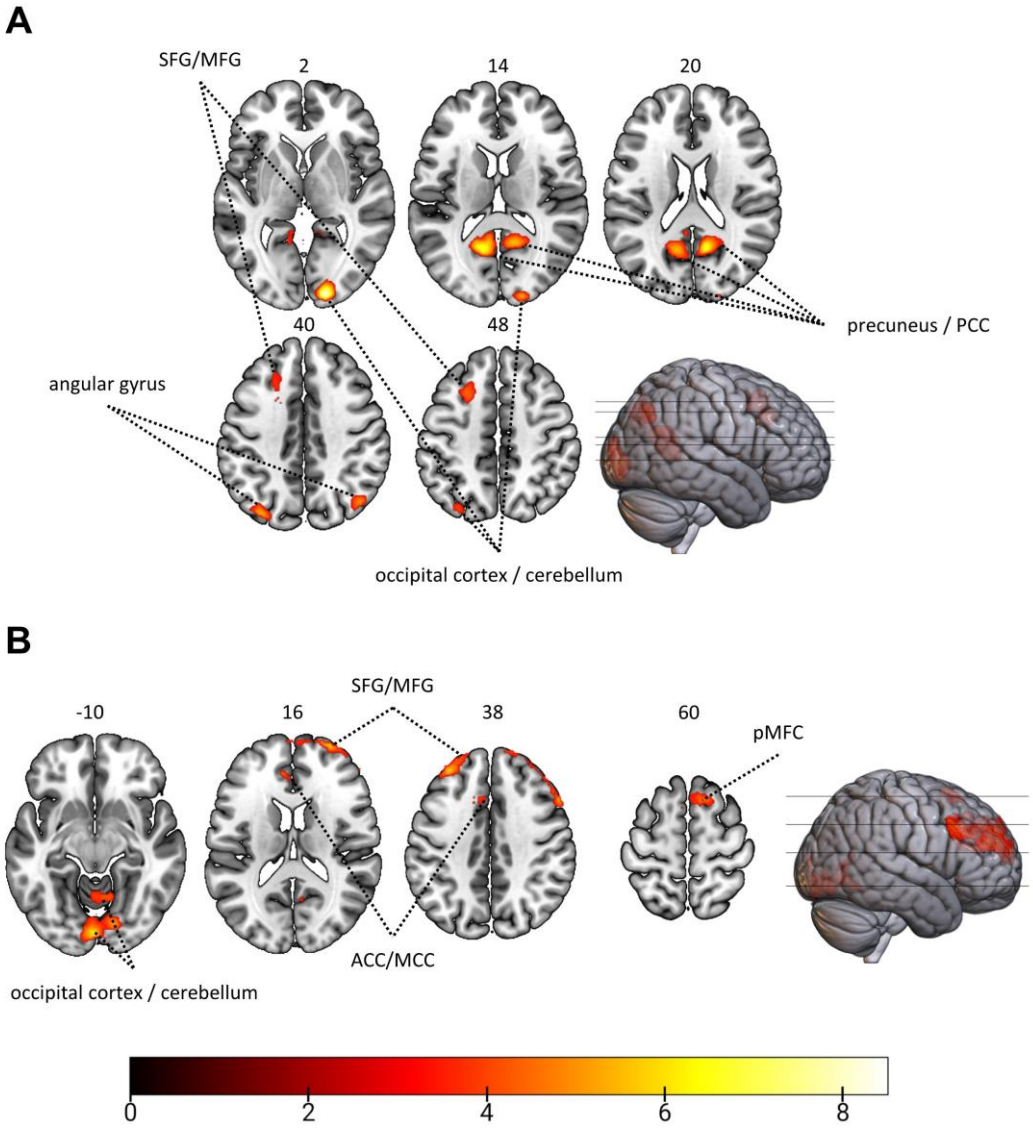


Figure 10 | Key results of Study III. Panel A presents significantly activated areas for the *t*-contrast date > delay. Panel B presents that contrast with the behavioural date/delay effect as covariate. Specifically, higher activity in these areas in the date > delay contrast correlates with a lower behavioural date/delay effect. Colour intensities reflect *t*-values. Upper labels refer to Montreal Neurological Institute (MNI) *z*-coordinates. SFG = superior frontal gyrus, MFG = middle frontal gyrus, PCC = posterior cingulate cortex, ACC = anterior cingulate cortex, MCC = mid-cingulate cortex, pMFC = posterior medial frontal cortex. The figure was adapted from **Study III**. For details regarding third party copyright material, see pages 21–22.

3.1.4 Study IV: Temporal Discounting, the Date/Delay Effect and Associations with Schizotypy

Temporal discounting is elevated in many psychiatric conditions (Amlung et al., 2019; see Section 1.2.5). Extensive research has been conducted on the association between schizophrenia and temporal discounting, yielding mixed results (Amlung, 2023). One approach to enable conclusions about the aetiology and mechanisms of schizophrenia whilst controlling for treatment confounds is to investigate dimensional schizotypy, i.e., a personality constellation resembling schizophrenia at a subclinical level (Grant et al., 2018). So far, however, few studies have examined the association between temporal discounting and schizotypy, and results are inconsistent (Cai et al., 2019; Li et al., 2016; Terenzi et al., 2019; Weatherly, 2012). Moreover, if such an association exists, its cause is largely unclear. Examining whether the magnitude of the date/delay effect (LeBoeuf, 2006; Read et al., 2005) is associated with schizotypy may help determine the role of aberrant time processing.

In this online study, the association between schizotypy and temporal discounting was examined in $N = 1{,}000$ participants. Schizotypy personality traits were assessed using the sO-LIFE (Grant et al., 2013; Mason et al., 2005), and temporal discounting was assessed using the MCQ (Kirby et al., 1999) in a delay and a date condition.

Results revealed that schizotypy traits were not significantly related to temporal discounting in the delay or the date condition after controlling for multiple comparisons (Table 4). The date/delay effect was replicated, $p < .001$, $g_{av} = 0.22$. When controlling for the other sO-LIFE subscales, higher values in the unusual experiences subscale were associated with a higher date/delay effect. This association was robust when controlling for age, education as well as alcohol and tobacco consumption (Table 5).

Overall, this study further challenges the robustness of the association between the schizophrenia spectrum and temporal discounting. Specifically, the results suggest that this association may not extend to subclinical schizotypy (or is very small in effect size), that a certain degree or constellation of symptomatology is required to reveal it or that previous schizophrenia studies may be confounded by disease chronicity or medication effects. Importantly, the association of unusual experiences with the date/delay effect points towards altered time processing in positive schizotypy and suggests that the date manipulation may alleviate impulsive decision-making in vulnerable populations.

Table 4 | Key result of Study IV: Pearson correlations

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) ln(*k*) Delay	(.93)						
(2) ln(*k*) Date	.91***	(.93)					
(3) DDE	.27***	−.15***	(.25)				
(4) UE	.06°	.04	.06	(.71)			
(5) CD	.02	.03	−.04	.40***	(.77)		
(6) IA	.02	.04	−.05	.09**	.32***	(.56)	
(7) IN	.04	.06	−.04	.40***	.39***	.10**	(.52)

Note. Values in the diagonal represent Cronbach's alphas, except for the date/delay effect (DDE) for which the reliability was estimated using formula 4 from Trafimow (Trafimow, 2015). ln(*k*) = log-transformed discount rate; UE = unusual experiences; CD = cognitive disorganisation; IA = introvertive anhedonia; IN = impulsive nonconformity. * $p < .05$, ** $p < .01$, *** $p < .001$; for columns 1 and 2 in rows 4–7, the *p*-value was corrected for multiple comparisons: ° $p < .05$ (uncorrected). The table was adapted from **Study IV**. For details regarding third party copyright material, see pages 21–22.

Table 5 | Key result of Study IV: Regression predicting the date/delay effect

Variable	*B*	95% CI for *B*		β	R^2	ΔR^2
		LL	*UL*			
Step 1					.010	.010
Constant	0.270***	0.135	0.404	–		
Age	0.004*	0.000	0.008	.07		
Education (low)	-0.067	-0.234	0.100	-.03		
Education (high)	-0.002	-0.103	0.099	.00		
Alcohol (AUDIT)	-0.009	-0.018	0.001	-.06		
Tobacco (ASSIST)	0.008	-0.001	0.018	.06		
Step 2					.019	.010*
Constant	0.323	0.145	0.501	–		
Age	0.004	-0.001	0.008	.06		
Education (low)	-0.052	-0.220	0.116	-.02		
Education (high)	0.007	-0.095	0.109	.00		
Alcohol (AUDIT)	-0.007	-0.017	0.003	-.05		
Tobacco (ASSIST)	0.008	-0.002	0.018	.06		
Unusual experiences	0.024*	0.004	0.044	.09		
Cognitive disorganisation	-0.007	-0.025	0.011	-.03		
Introvertive anhedonia	-0.019	-0.045	0.007	-.05		
Impulsive nonconformity	-0.021	-0.048	0.007	-.06		

Note. Education is reflected in two dummy variables (reference category: medium). AUDIT = Alcohol Use Disorders Identification Test (Suchtforschungsverbund Baden-Württemberg UKL Freiburg, 2017); ASSIST = Alcohol, Smoking and Substance Involvement Screening Test (Ali et al., 2002); CI = confidence interval; *LL* = lower limit; *UL* = upper limit. $N = 990$. * $p < .05$, *** $p < .001$. The table was adapted from **Study IV**. For details regarding third party copyright material, see pages 21–22.

3.1.5 Study V: Temporal Discounting, the Date/Delay Effect and Transdiagnostic Dimensions

The finding that temporal discounting is aberrant in many mental disorders has led to the proposal of temporal discounting as a transdiagnostic marker (Amlung et al., 2019; Lempert et al., 2019; see Section 1.2.5). However, owing to limitations of conventional case-control studies such as small sample sizes, heterogeneous diagnostic groups and treatment confounds, transdiagnostic research on temporal discounting is scarce. Dimensional approaches to psychopathology address these problems. Specifically, by assuming continuums of symptom patterns extending from non-clinical to clinical populations, they allow the investigation of transdiagnostic dimensions in large general population samples (Gillan & Seow, 2020; Wise et al., 2023). Therefore, dimensional approaches may reveal which transdiagnostic symptom patterns are associated with aberrant temporal discounting. Beyond that, examining whether the date/delay effect is particularly pronounced in participants with specific symptom patterns may be of therapeutic value.

The study was conducted online via a crowd-working platform. Participants completed the MCQ (Kirby et al., 1999) in a delay and a date condition, a broad range of clinical questionnaires, targeting depression/anxiety/stress, trait anxiety, OCD, schizotypy, disordered eating, autism, ADHD and impulsivity, and a proxy of cognitive abilities. Data of $N = 731$ participants were analysed by examining associations of symptom patterns and factor analytically derived transdiagnostic dimensions with temporal discounting and the date/delay effect (CFM) both without and with control of demographic variables and cognitive abilities.

Results revealed that a wide range of symptom patterns was positively and only eating-related cognitive constraint was negatively related to temporal discounting (Figure 11A). On a factor level, the transdiagnostic dimensions “Anxious-Depression” and “Inattention, Impulsivity and Overactivity” were significantly associated with steeper temporal discounting, while the transdiagnostic dimension “Compulsive Behaviour and Intrusive Thought” was not (Figure 11B). Moreover, the date/delay effect was replicated, $p < .001$, $g_{av} = 0.25$, and participants scoring higher on symptom patterns loading on the inattention/impulsivity/overactivity dimension showed a stronger date/delay effect (Figure 11C–D).

In total, consistent with previous case-control studies (Amlung et al., 2019) and one other transdiagnostic study on temporal discounting (Levitt et al., 2023), this study underlines the transdiagnostic nature of temporal discounting specifically within psychopathologies characterised by affective and impulsive symptoms. Given the particular effectiveness of the date/delay effect in persons with higher scores in inattention/impulsivity/overactivity, aberrant time processing may reflect an important mechanism underlying decision-making deficits within impulsive disorders and could therefore be a potential intervention target.

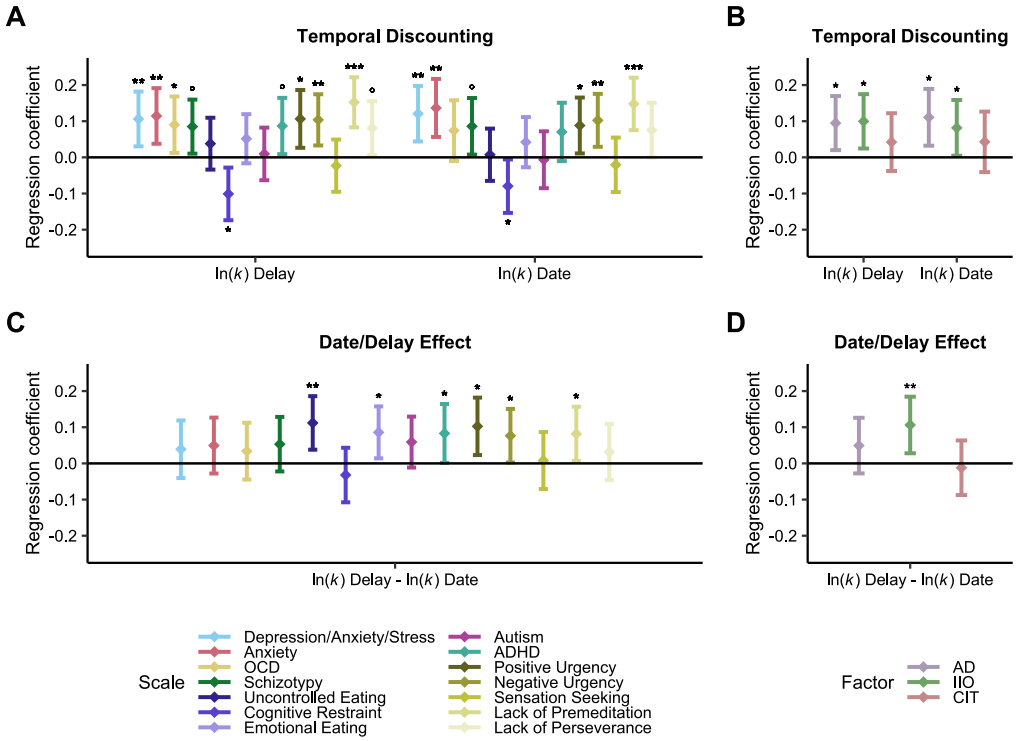


Figure 11 | Key results of Study V. All panels present several separate linear regressions controlling for gender, age and cognitive abilities. Panels A and B present regressions of the discount rates in the delay and date conditions on the different symptom patterns (questionnaire scores) and transdiagnostic dimensions (factor scores), respectively. Panels C and D present regressions of the date/delay effect on the different symptom patterns (questionnaire scores) and transdiagnostic dimensions (factor scores), respectively. Errors bars represent 95% confidence intervals. OCD = obsessive-compulsive disorder, ADHD = attention-deficit/hyperactivity disorder, AD = Anxious-Depression, IIO = Inattention, Impulsivity and Overactivity, CIT = Compulsive Behaviour and Intrusive Thought. * $p < .05$, ** $p < .01$, *** $p < .001$, in (A) and (B) Bonferroni-Holm corrected for the two dependent variables tested; ° $p < .05$, uncorrected. The figure was adapted from **Study V**. For details regarding third party copyright material, see pages 21–22.

3.2 Narrative Reviews

An overview of the two narrative reviews included in this dissertation is presented in Table 6. The two reviews are summarised on the following pages. The complete articles are presented in Appendices F–G.

Table 6 | Overview of narrative reviews included in this dissertation

Index	Reference
Review I	Keidel, K., Rramani, Q., Weber, B., Murawski, C., & Ettinger, U. (2021). Individual differences in intertemporal choice. *Frontiers in Psychology*, *12*, Article 643670. https://doi.org/10.3389/fpsyg.2021.643670
Review II	Ettinger, U., Keidel, K., & Murawski, C. (2023). Temporal cognition, impulsivity and intertemporal choice. In D. Sturma (Ed.), *Mind and Time* (pp. 151–176). Verlag Karl Alber. https://doi.org/10.5771/9783495994078-151

3.2.1 Review I: Individual Differences in Intertemporal Choice

While temporal discounting is ubiquitous in humans and other species, its expression varies substantially across individuals. These individual differences are temporarily stable (e.g., Kirby, 2009), heritable (Anokhin et al., 2011, 2015; Isen et al., 2014) and related to numerous health- and non-health-related outcomes (see Section 1.2.2). A thorough understanding of the interindividually varying determinants of individual differences in temporal discounting is important to uncover its position within the architectures of cognition and personality and to inform theories and mechanisms of impulsive decision-making. This review therefore aimed to give an overview of the current state of research on associations between temporal discounting and a broad range of variables, including socio-demographic factors, personality, cognition, brain structure and function as well as molecular genetic variation.

The current state of research can be summarised as follows (Figure 12): First, studies examining socio-demographic variables suggest that temporal discounting decreases with age from childhood to young adulthood, but findings on effects of ageing within adulthood are inconsistent. Moreover, while associations with gender are inconsistent as well, negative correlations emerge consistently between temporal discounting and educational level and income. Second, regarding personality traits, temporal discounting is positively correlated with trait impulsivity and extraversion. However, these associations are low in effect size. Third, temporal discounting is higher in persons using less future-oriented cognitive styles. Findings on the associations between temporal discounting and inhibitory control are largely inconsistent, with some studies finding a significant negative relationship. Associations between temporal discounting and intelligence are more robust, revealing that people with higher intelligence show reduced temporal discounting. Fourth, temporal discounting is related to brain structures and functions in prefrontal and limbic regions associated with valuation, cognitive control, memory and future-oriented thinking. However, effect sizes and directions of reported correlations vary largely across studies. Fifth, early candidate gene studies point towards relevance of the dopaminergic system, although it remains inconclusive which genes specifically relate to steeper discounting. More recent genome-wide association studies (GWAS) suggest that the genetic underpinnings of temporal discounting are far more complex than initially thought.

Overall, individual differences in temporal discounting are related to a range of variables spanning different domains, with small to moderate effect sizes. Future research should test a priori hypotheses in large samples to replicate effects, clarify inconsistent findings and examine potential origins, mechanisms and moderators of specific associations. In this context, latent trait modelling may serve as a promising tool to solve task impurity problems. Furthermore, combining individual differences and experimental approaches may yield novel insights into relationships between individual difference variables and temporal discounting under different conditions.

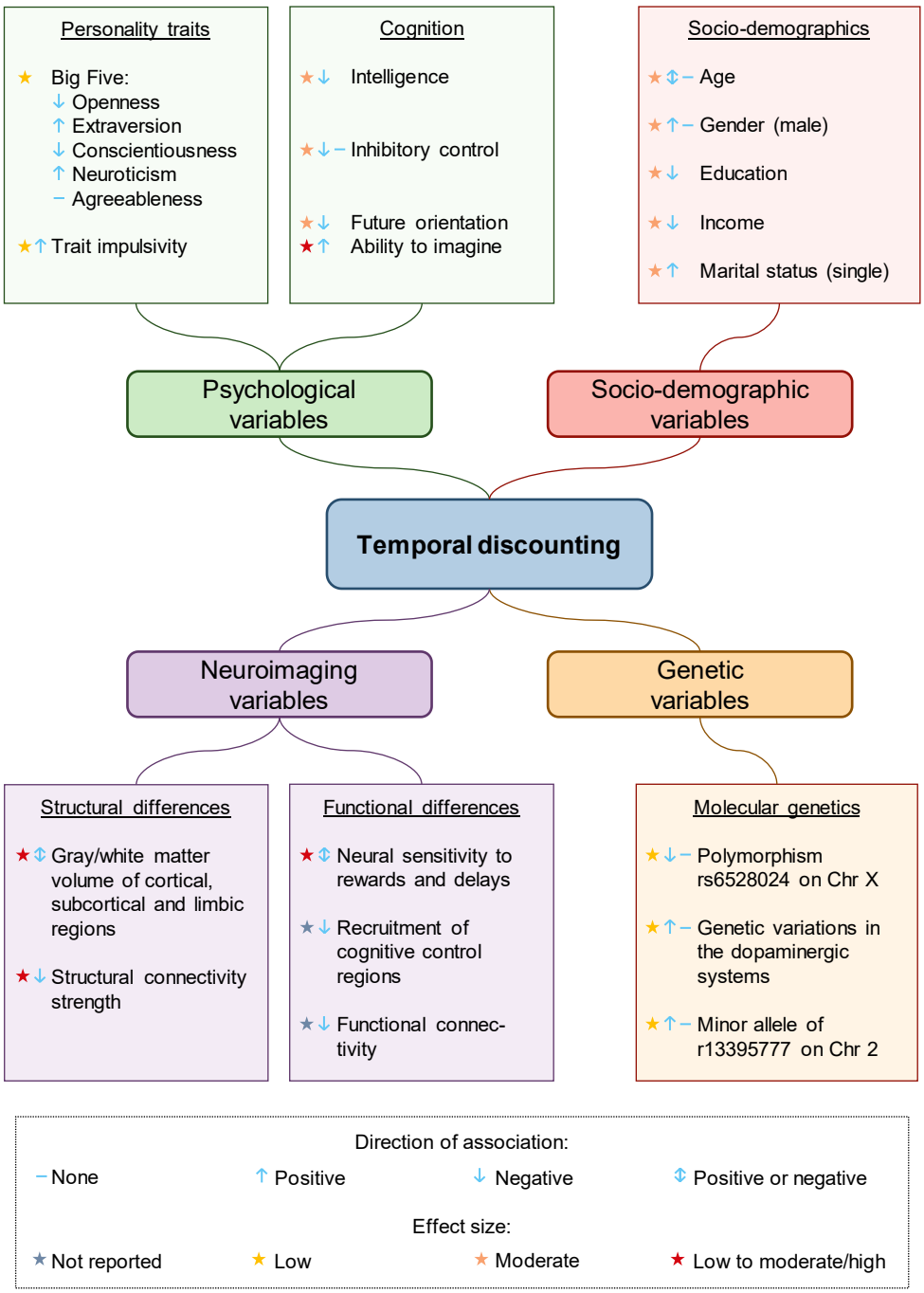


Figure 12 | Summary of Review I. The figure illustrates how temporal discounting is related to different psychological, socio-demographic, neuroimaging and genetic variables in a simplified way (not accounting for potential interactions). Low effect sizes are considered d (or r) ≤ 0.15; moderate effect sizes are considered 0.15 ≤ d (or r) ≤ 0.35; high effect sizes are considered d (or r) > 0.35. Chr = Chromosome. The figure was adapted from **Review I**. For details regarding third party copyright material, see pages 21–22.

3.2.2 Review II: Temporal Cognition, Impulsivity and Intertemporal Choice

Time is a critical dimension in human life, relevant to essential cognitive and behavioural processes such as remembering the past or planning the future. Temporal cognition, i.e., the processing of time information, and time perception, i.e., the subjective experience of time, are therefore highly relevant to different domains of human behaviour, one of which is decision-making (Matthews & Meck, 2016). Specifically, both the decision-making process itself and the consequences of one's decisions unfold over time. In this review, impulsive decision-making, i.e., intertemporal choice, is presented from a temporal cognition perspective, shedding light on the mechanistic role of time perception within the phenomenon of temporal discounting and within impulsivity in general (Figure 13).

Intertemporal decisions typically involve choices between smaller-sooner and larger-later rewards (see Section 1.2). Accordingly, next to the reward dimension, the time dimension is inherent within this type of decision, and extensive research has been concerned with modelling this reward versus time trade-off as temporal discounting (see Section 1.2.2). While different forms of temporal discounting functions have been discussed, empirical research revealed the superiority of hyperbolic over exponential discounting models, likely representing the subjective time perception of humans. Furthermore, neuroimaging studies have emphasised the relevance of brain regions associated with valuation, cognitive control, and, importantly, memory and prospection (see Section 1.2.4).

The relevance of time perception for intertemporal decisions is illustrated by experimental manipulations targeting the temporal dimension. Two examples are episodic future thinking effects (also referred to as tag effects, i.e., the reduction of temporal discounting through self-generated event tags; Peters & Büchel, 2010) and the date/delay effect (i.e., the reduction of temporal discounting through date cues; LeBoeuf, 2006; Read et al., 2005; see Sections 1.2.3–1.2.4). Both manipulations have been shown to reduce temporal discounting relatively consistently. Yet, the underlying psychological mechanisms are so far not fully understood. For episodic future thinking effects, mechanisms such as a higher concreteness of future rewards, lower sensitivity for time duration and positive mood have been discussed. Similarly, for the date/delay effect, relevant mechanisms may refer to attentional shifts towards rewards, changes in computational strategies and differential time estimation (see Section 1.2.3). Future studies on these effects may help to gain a better understanding of how aspects of time influence temporal discounting.

Another relevant finding is the relationship between intertemporal choice and trait impulsivity, albeit of small magnitude, as this association can be explained using models of time processing (Paasche et al., 2019; Wittmann & Paulus, 2008). Specifically, both impulsive decisions and impulsive actions (reflected in traits) can be interpreted as choices of smaller-sooner rewards over larger-later rewards. In line with a model of the "internal clock" proposed by Treisman (Treisman, 1963), this relationship may stem from an overestimation of time flow. That is, a highly impulsive individual may subjectively

overestimate time durations, leading to a relatively higher cost of longer delays in the reward-delay trade-off in intertemporal decisions. Reasons for differential time perception have been proposed (e.g., following Treisman's model: higher arousal and increased attention to time in more impulsive individuals), but need to be studied more thoroughly.

Overall, this review underscores the importance of temporal information processing in intertemporal choice and impulsivity. Specifically, manipulating temporal aspects of decisions has been shown to reduce temporal discounting on a group level, and interindividual variation in time sensitivity may, to some extent, explain individual differences in temporal discounting, trait impulsivity and their interaction. The characterisation of psychological and neural mechanisms of these findings reflects an important future avenue.

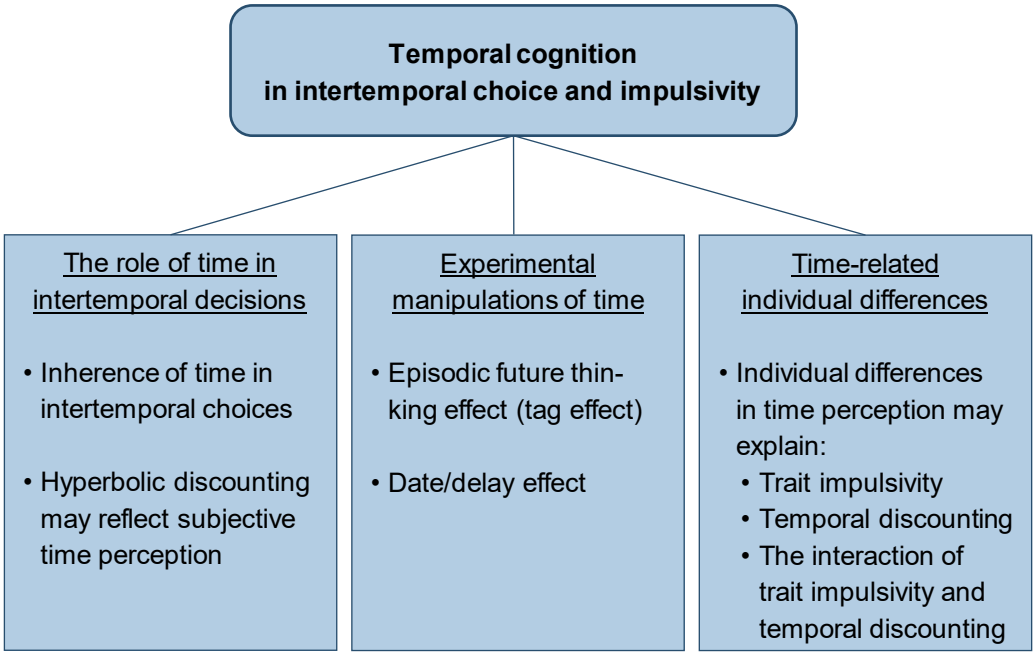


Figure 13 | Summary of Review II. The figure summarises how temporal cognition manifests in intertemporal choice and trait impulsivity. For details, see text.

4 Discussion

The five studies of this dissertation aimed to yield novel insights into impulsive decision-making, largely focusing on self-reported impulsivity and intertemporal choices. The structure of the umbrella term of impulsivity (Evenden, 1999; Strickland & Johnson, 2021) was first examined using both a personality questionnaire and an intertemporal choice task and applying confirmatory factor and network analyses (**Study I**). Moreover, to exemplify the malleability of impulsive decision-making, the date/delay effect in intertemporal choice (LeBoeuf, 2006; Read et al., 2005) was taken into focus. Investigating this effect both in large online samples and in smaller samples using eye-tracking and fMRI did not only allow to test its replicability but also to draw conclusions about its underlying cognitive and neural mechanisms (**Studies II–V**). In addition, the transdiagnostic nature of impulsive decision-making was tested using a dimensional approach to psychopathology (**Studies IV–V**). Finally, two narrative reviews provided more detailed information on the roles of individual differences and time perception in intertemporal choice (**Reviews I–II**).

4.1 Integration of Findings

4.1.1 The Structure of Impulsivity

All studies of this dissertation acknowledged the highly heterogeneous nature of impulsivity (Evenden, 1999; Strickland & Johnson, 2021) by explicitly focusing on, or dissociating between, specific constructs within the impulsivity framework. While only **Study I** comprehensively examined factor and network structures of impulsive personality, all studies assessed both trait impulsivity (using the sUPPS-P/UPPS-P in **Studies I, II, III and V** and the impulsive nonconformity subscale of the sO-LIFE in **Study IV**) and temporal discounting (using the MCQ), allowing to draw conclusions about the associations between different impulsivity constructs across studies.

Focusing on impulsive personality, **Study I** examined the sUPPS-P and revealed that a five-factor model with intercorrelated factors, a hierarchical model with factors comprising cognitive impulsivity (lack of conscientiousness), affective impulsivity (urgency) and sensation seeking as well as a bifactor model all had acceptable model fits. While the former two models confirm previous factor analytical studies (Cyders & Smith, 2007; Zsila et al., 2020), the latter suggests that a general vulnerability factor such as a *p*-factor of psychopathology (Caspi et al., 2014), which is also included in the HiTOP framework (Kotov et al., 2017, 2021), may underlie the shared variance between different impulsivity constructs.

Importantly, a network of the sUPPS-P item data was similar to the former two models but questioned the separability of positive and negative urgency. Specifically, items of the two subscales were merged into a single community, indicating a potential jangle-fallacy (Marsh, 1994). This idea is supported by the consistently significant and high correlations between positive and negative urgency in all studies of this dissertation using the sUPPS-P/UPPS-P (*r*s are equal to .59, .74, .64 and .65 in **Studies I, II, III and V**, respectively). Since, according to classical test theory, correlations between two variables are limited by the square root of their reliabilities (Spearman, 1904b), and scale reliabilities are typically around .80 (e.g., see Cyders et al., 2014, for the sUPPS-P), a correlation value of .64 would correspond to the maximal correlation (at least when assuming uncorrelated errors; see Nimon et al., 2012, for a discussion). Additionally, other network studies published at a similar time as **Study I** yielded comparable results (Billieux et al., 2021; Goh et al., 2020; though see Gustavson et al., 2020, reporting distinctiveness at the genetic level). Moreover, the real-world correlates of positive and negative urgency largely overlap (Berg et al., 2015; Sperry et al., 2018). Therefore, the conceptualisation of positive and negative urgency as two separable constructs is substantially challenged. Regarding lack of premeditation and lack of perseverance, however, whose separability had also been questioned before (Berg et al., 2015; Goh et al., 2020; Sperry et al., 2018), **Study I** did not find evidence for their separation apart from the acceptable fit of the hierarchical factor model. The descriptive correlations of these two constructs are also considerably lower than for positive and negative urgency (*r*s are equal to .32, .37, .42 and .49 in **Studies I, II, III and V**, respectively). Thus, the results on the structure of the sUPPS-P support the idea that a reconceptualisation of positive and negative urgency within the UPPS-P in favour of a general urgency construct may be necessary (Billieux et al., 2021), whereas the other three subscales assess clearly dissociable constructs.

The high heterogeneity of impulsivity is not only evident in dissociable constructs within impulsive personality but also in limited associations between impulsivity constructs measured at different levels, such as impulsive personality and impulsive task behaviour (Aichert et al., 2012; Cyders & Coskunpinar, 2011; Strickland & Johnson, 2021). In agreement with those findings, all of the studies of the current dissertation (**Studies I–V**) found low and mostly non-significant associations between impulsive traits and temporal discounting. Of note, across all studies, the highest correlation between an impulsive trait measure and a discount rate was $r = .36$ (lack of premeditation and the discount rate in the delay condition in **Study II**), and most correlations ranged between $r = .00$ and $r = .15$. This falls in the range of previous studies examining associations between impulsive traits with temporal discounting (**Review I**) and indicates large differences between the constructs. While one alternative explanation of low correlations between self-report and behavioural measures is the limited reliability of individual differences in behavioural measures (Dang et al., 2020; Hedge et al., 2018), here, this argumentation falls short for two reasons. First, the MCQ and intertemporal choice tasks in general are often conceptualised as self-report measures resembling questionnaires (Kirby et al., 1999) and not as experimental tasks of impulsivity such as, for instance, the go/no-go task as a

measure of behavioural/response inhibition (Bari & Robbins, 2013). Second, the reliabilities of both the trait impulsivity measures (Hook et al., 2021) and, importantly, temporal discounting as measured by the MCQ (Strickland et al., 2023) are relatively high, the latter also being evident in the test-retest reliability of .81 reported in **Study III**. Thus, the results support the notion that largely different constructs are measured when referring to impulsivity (Dang et al., 2020), underlining the need to be specific about which construct is investigated (Strickland & Johnson, 2021). Despite huge differences between constructs, however, the importance of the relationships between questionnaires assessing different forms of impulsivity and temporal discounting, especially for psychopathology (**Study V**), should not be underestimated (see Section 4.1.3).

In light of the converging evidence of previous literature regarding the heterogeneity of impulsivity, one aim of this dissertation was to examine which construct may lie at the definitory core of impulsivity. Based on previous findings, a cognitive factor such as lack of premeditation was identified as an important candidate (Goh et al., 2020; L. Sharma et al., 2014). Indeed, the crucial role of lack of premeditation was confirmed in **Study I** by revealing that, based on closeness centrality, lack of premeditation had a central position both in the item-level network of the sUPPS-P and the scale-level network comprising sUPPS-P subscales and the discount rate. This finding extended results of a previous study, which had found high centralities of lack of premeditation on a scale level only (Goh et al., 2020). Moreover, the close relationships between lack of premeditation and other impulsivity constructs are also illustrated by the other studies (**Studies II, III and V**), in which lack of premeditation was most consistently associated with the other sUPPS-P/UPPS-P constructs and the discount rates, aligning with previous studies (Cyders et al., 2014; Goh et al., 2020; MacKillop et al., 2016; J. Miller et al., 2003; Whiteside & Lynam, 2001). Thus, lack of premeditation appears to share features with many other impulsivity constructs. It could contribute to them by reflecting the cognitive underpinnings that play a role in other types of impulsivity (L. Sharma et al., 2014). However, as most studies, including those of this thesis, were cross-sectional, causal interpretations of the role of lack of premeditation should be made with caution.

In sum, this thesis confirmed the high heterogeneity of impulsivity and mostly confirmed the structure of impulsive personality as proposed by the UPPS-P/sUPPS-P model. However, the separability of positive and negative urgency was challenged. Beyond that, the evidence reported here suggests that lack of premeditation represents a highly important component of what is meant when people refer to impulsivity in everyday life.

4.1.2 The Date/Delay Effect in Intertemporal Choice

In intertemporal decision-making, the date/delay effect refers to the phenomenon that temporal discounting is reduced when time until receipt of rewards is framed in dates rather than in delay units such as days (LeBoeuf, 2006; Read et al., 2005; also see Section 1.2.3 and **Review II**). In this dissertation, the date/delay effect was investigated using within-subject designs in four studies (**Studies II–V**). Importantly, and consistent with previous studies (DeHart & Odum, 2015; Dshemuchadse et al., 2013; Jiang & Dai, 2021; Klapproth, 2012; Naudé et al., 2018; Reyes-Huerta et al., 2023; Scherbaum et al., 2012), all four studies successfully replicated the effect. Two of these studies (**Studies IV–V**) had by far the largest samples compared to all previously published studies. Effect sizes varied between Hedge's g_{av} = 0.22 and g_{av} = 0.48. A post-hoc random-effects meta-analysis on these effects (Figure 14) using restricted maximum likelihood estimation and Knapp-Hartung adjustments revealed an overall pooled effect size estimate of g_{av} = 0.30 (p = .013). This effect size is similar to a previous meta-analysis of six studies (g_{av} = 0.45; Rung & Madden, 2018), albeit descriptively a bit smaller. The difference could be due to several factors. First, here, within-subject designs were consistently used, while in the meta-analysis by Rung and Madden (2018), effect sizes resided from studies with between- and within-subject designs. Second, significant between-study heterogeneity, which was substantial according to the meta-analysis of the four studies reported here (I^2 = 79.5%), may contribute to differences. Third, more generally, effect sizes in psychology are often initially overestimated as a result of publication bias (Open Science Collaboration, 2015). In any case, the previous studies and the studies of this dissertation clearly show that the date/delay effect can be considered a robust phenomenon with a small to medium effect size.

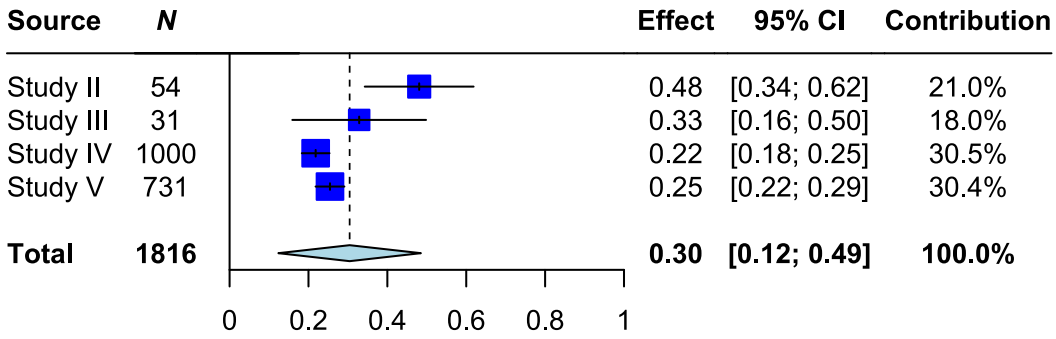


Figure 14 | Meta-analysis of the date/delay effect. The plot presents effect sizes (Hedge's g_{av}) from the four studies of this dissertation examining the date/delay effect, with error bars corresponding to 95% confidence intervals (CIs). The last row contains a pooled effect size based on a random-effects model using restricted maximum likelihood estimation and Knapp-Hartung adjustments. Sizes of (dark blue) squares relate to the relative contributions/weights of the respective studies in this model.

Apart from substantiating the robustness of the date/delay effect, a central aim of this dissertation was to elucidate its cognitive and neural mechanisms using eye-tracking and fMRI (**Studies II–III**). Despite different task constraints (e.g., different settings and different time constraints in the task), the eye-tracking results of the two studies were astoundingly consistent (see Figure 9 for **Study II** and Figure 2 in **Study III** in Appendix C). Specifically, both studies found that participants fixated time attributes longer and made more saccades between them in the date compared to the delay condition. However, only **Study II** found an interaction effect between condition and absolute reward difference, showing that a higher absolute reward difference predicted choice of the larger-later reward more strongly in the date than in the delay condition. Moreover, **Study III** revealed that brain areas associated with episodic thinking were more active in the date than in the delay condition and that participants with a smaller date/delay effect showed higher activity in prefrontal areas in the date than in the delay condition.

An important question is how these findings can be interpreted with regard to the previously formulated hypotheses regarding the mechanisms of the date/delay effect, i.e., the differential time estimation, choice strategy, attention-focusing and deliberation hypotheses (Dshemuchadse et al., 2013; LeBoeuf, 2006; Read et al., 2005; see Section 1.2.3). First, the findings of higher consideration of time information and higher activity in brain areas related to episodic thinking in the date condition are in line with previous findings of differential time estimations, i.e., durations appear to be subjectively lower when presented in terms of date intervals rather than as delay units (Jiang & Dai, 2021; Zauberman et al., 2009). Specifically, due to the higher specificity or concreteness of dates, participants may experience more memory retrievals of past reward experiences or more vivid imagery of future rewards. Thus, similar to the tag effect (Peters & Büchel, 2010; Sasse et al., 2015), the date condition is likely to result in a lower psychological distance of future rewards (Trope & Liberman, 2003). Second, findings confirmed that people compare attributes more often in the date than in the delay condition (Arieli et al., 2011; Kurokawa & Ohtake, 2013), but this only applied to time information. This finding is generally in line with the choice strategy hypothesis and consistent with a more attribute-based rather than a fully alternative-based model of temporal discounting (Amasino et al., 2019; J. Cheng & González-Vallejo, 2016; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; M. Scholten & Read, 2010). Especially the hybrid interval discounting model (M. Scholten & Read, 2006) seems promising in the context of the date/delay effect because in this model, options are evaluated separately, but time attributes are put into relation to each other. However, it remains unclear whether the choice strategy effect contributes to differential time estimation or is its consequence. For example, the finding that people with a smaller date/delay effect show higher activity in cognitive control regions in the date compared to the delay condition may reflect an adaptation in strategy use (e.g., more arithmetic operations) made by some people (see below) in reaction to the different time attributes (e.g., to avoid changes in discounting behaviour). If so, maintaining

rather than changing the strategy would result in a higher date/delay effect. Third, robust overt attentional changes were found in both studies only in the processing of time but not of reward attributes. Therefore, the results initially speak against the attention-focusing hypothesis (i.e., a higher reward focus in the date condition; Read et al., 2005). However, the finding that absolute reward difference predicted the choice of the larger-later reward more strongly in the date than in the delay condition (**Study II**) may indicate that ultimate reward-*weighting* is higher in the date condition, which is not captured in overt attention (LeBoeuf, 2006). Fourth, given the different reading requirements in the two conditions (see Section 4.2), it is difficult to draw definite conclusions regarding the deliberation hypothesis. While the higher reaction times and the higher consideration of time attributes are in favour of it (**Studies II–III**), no differences between conditions in subjectively reported mental demand as well as negative between-subject correlations between the date/delay effect and means and variations of reaction times (**Study II**) speak against it. Overall, this dissertation thus provided substantial evidence for the differential time estimation hypothesis as an essential factor in the date/delay effect, underlining the importance of time perception in intertemporal decision-making (**Review II**). Moreover, it points towards differences in choice strategy use between conditions, challenging once more the dominant role of alternative-based models of intertemporal choice (Amasino et al., 2019; J. Cheng & González-Vallejo, 2016; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; M. Scholten & Read, 2010). Rather than the attention-focusing hypothesis, a reward-weighting hypothesis may be more applicable. Results for the deliberation hypothesis were ambiguous.

It should be mentioned that it is not unlikely that the different explanations of the date/delay effect apply to different persons to different degrees. Specifically, between-person differences may explain differences in the magnitude of the date/delay effect. Interestingly, findings of all studies examining the date/delay effect (**Studies II–V**) suggest substantial interindividual variability, which may be due to differences in temporal discounting itself. That is, the date manipulation may be more effective in more impulsive persons, i.e., those showing higher discount rates in the standard delay condition (**Studies II–V**) or those having higher scores on clinical patterns associated with deficits in time perception, such as impulsivity (Wittmann & Paulus, 2008; also see **Study V** and **Review II**). This could be related, for instance, to strategy use. An integrative strategy is more often used by more impulsive decision-makers (Amasino et al., 2019; Reeck et al., 2017), which is why they may particularly profit from a date framing. This may especially be the case when they do not compute intervals (i.e., use arithmetic operations to adapt their strategy) in the date condition but rather weight the reward comparison more highly. However, it should be noted that in light of the restricted sample sizes in **Studies II and III**, interpretations involving between-person correlations (e.g., in strategy use) are quite speculative. Clearly, large-scale replications and more elaborate experimental studies (e.g., manipulating attentional processes; Reeck et al., 2017) are needed to substantiate these interpretations. If the between-participant effects reported in **Studies II and III** are corroborated, however, the beneficial effects may be of importance for clinical contexts.

4.1.3 The Transdiagnostic Dimensions of Intertemporal Choice

Temporal discounting is aberrant in a broad range of mental disorders (Amlung et al., 2017, 2019; Y.-S. Cheng et al., 2021; J. N. S. Jackson & MacKillop, 2016; MacKillop et al., 2011; Strickland et al., 2021; Weinsztok et al., 2021). Therefore, there is currently a lively debate on whether temporal discounting can be considered a transdiagnostic marker (Amlung et al., 2019; Bailey et al., 2021; Bickel et al., 2019; Lempert et al., 2019; Levitt et al., 2023). This dissertation aimed to elucidate the transdiagnostic role of temporal discounting using a dimensional approach to psychopathology. Specifically, in **Studies IV and V**, associations between temporal discounting and clinical symptom patterns were investigated in large general population samples. Moreover, the date/delay effect was examined to investigate whether the date manipulation has particularly strong or weak effects in vulnerable populations. While **Study IV** focused on schizotypy, **Study V** employed a broad range of clinical questionnaires, including those assessing depression, anxiety, OCD, schizotypy, disordered eating, autism, ADHD and impulsivity.

Findings on the association between temporal discounting and the schizophrenia spectrum have hitherto been inconsistent (Ahn et al., 2011; Bartolomeo et al., 2021; H. E. Brown et al., 2018; Heerey et al., 2007, 2011; Li et al., 2016; Terenzi et al., 2019; Weatherly, 2012; Weller et al., 2014; Yu et al., 2017). Therefore, **Study IV** aimed to elucidate whether specific schizotypy dimensions from the sO-LIFE (Mason et al., 2005) were related to temporal discounting. **Study V** assessed three scales of the sO-LIFE as well, allowing to address the same question. Results of **Study IV** yielded a significant positive association between temporal discounting and positive schizotypy, which did not, however, survive correction for multiple comparisons. In contrast, **Study V** found a significant association between temporal discounting and schizotypy collapsed over positive, negative and disorganised symptom patterns. Post-hoc inspection of the latter (data not shown) revealed that the association was due to small yet significant associations with the positive and disorganised dimensions (*r*s between .10 and .15). Moreover, the date/delay effect was particularly effective in people scoring higher in positive schizotypy when controlling for the other schizotypy subscales in **Study IV**, but no such effect was found in **Study V** – neither in the collapsed score nor, as post-hoc analyses revealed (data not shown), for the three sO-LIFE subscales. Overall, the two studies add to the heterogeneous picture of associations between temporal discounting and the schizophrenia spectrum referred to above. Aligning with the only other previous study examining schizotypy on a dimensional basis (Weatherly, 2012), associations between temporal discounting and schizotypy seem to be either very small or non-existent. The differences in the results of **Studies IV and V** could be due to the small size of effects, whose statistical significance is more susceptible to sampling errors. Future research should therefore investigate them in samples on an even larger scale or in meta-analyses. Notably, the studies of this dissertation show that when examining aberrant intertemporal choice behaviour in schizophrenia spectrum populations, research should not solely focus on reward-related mechanisms in relation to negative

symptoms, as has been the case to date (Gold et al., 2008; Kring & Barch, 2014; Strauss et al., 2014). Instead, future research should also consider associations between time processing deficits and positive (and disorganised) symptoms (Reed & Randell, 2014; Ueda et al., 2018), as implied by the association between positive/disorganised schizotypy and temporal discounting in **Study V** and the covariation of positive schizotypy and the date/delay effect in **Study IV**. In total, the differentiation between different symptom patterns appears to be crucial to elucidate mechanisms underlying potentially aberrant intertemporal choice.

Study V built upon this notion and aimed to identify associations on a broader basis by examining psychopathology-related differences in temporal discounting using a CFM approach (Gillan & Seow, 2020; Wise et al., 2023). Results revealed that temporal discounting increased with higher levels of symptom patterns loading on the anxiety/depression and inattention/impulsivity/overactivity dimensions, extending previous case-control findings using a dimensional approach (Amlung et al., 2019; J. N. S. Jackson & MacKillop, 2016). Interestingly, and consistent with previous results on anorexia nervosa (Amlung et al., 2019; McClelland et al., 2016; Steinglass et al., 2012), the only negative association with temporal discounting was observed for the eating-related cognitive restraint subscale. Furthermore, the date/delay effect was particularly pronounced in people scoring higher on the inattention/impulsivity/overactivity dimension. In sum, these results confirm the transdiagnostic relevance of temporal discounting independent of medication or treatment confounds (Levitt et al., 2023) and, more generally, support the validity of dimensional approaches such as RDoC (Cuthbert, 2014, 2022; Insel et al., 2010) and HiTOP (Kotov et al., 2017, 2021). The particular effectiveness of the date manipulation in people with higher scores on an overarching inattention/impulsivity/overactivity factor is of high importance. Specifically, this effect gives insights into the mechanisms underlying aberrant temporal discounting in psychopathology. Consistent with previous findings showing that impulsive individuals may be more sensitive to the passage of time (**Review II**), **Study V** suggests that psychopathologies characterised by inattention/impulsivity/overactivity entail deficits in future-oriented cognition and time sensitivity, which a date framing can alleviate. Thus, similar to the results discussed in Section 4.1.2, these findings lead to the conclusion that the date manipulation is particularly effective in vulnerable populations. In this context, one may even speculate that the association between the date/delay effect and positive schizotypy (**Study IV)** can be traced back to an underlying inattention/impulsivity/overactivity dimension. Specifically, the unusual experience scale has been shown to covary with impulsive nonconformity to a moderate degree (Mason et al., 1995), and such overlaps may contribute to the observed effect (although impulsive nonconformity itself was not significantly related to the date/delay effect). Concerning practical use, interventions targeting aberrant time processing could be highly beneficial to alleviate impaired decision-making in therapeutic contexts.

4.2 Limitations

The results and interpretations of this dissertation are subject to several limitations. First, all empirical studies reported here were cross-sectional and relied at least partially on correlative results. Specifically, only the date/delay effect was experimentally manipulated, whereas the network analyses in **Study I** and associations with transdiagnostic symptom patterns and dimensions in **Studies IV and V** were largely correlational. As a consequence, causal inferences regarding the directions of relations between impulsivity constructs and those between intertemporal choice and transdiagnostic dimensions should be made with caution. Future research should substantiate the reported findings using longitudinal (e.g., Goh et al., 2020, for a longitudinal network analysis on impulsivity) and experimental (e.g., Reeck et al., 2017, for an experimental manipulation of search strategies in intertemporal choice) designs.

A second yet related limitation in those studies examining the mechanisms of the date/delay effect (**Studies II–III**) is the use of indirect measures of (overt) attention and neural activity, which makes inferences about cognitive mechanisms subject to interpretations. Eye-tracking analyses, for instance, allow to deduce attentional mechanisms only to a limited degree. Specifically, overt attention can but does not necessarily have to correspond to which intertemporal choice attributes are processed and weighted more strongly (Zhang et al., 2022). An example is the potential reading confound in **Studies II and III**. That is, date notations (e.g., 30 November 2024) typically comprise more symbols than delay unit notations (e.g., 91 days), making it difficult to differentiate whether differences in eye-tracking (and neural) measures relating to time attributes were due to attentional or mere perceptual processes. While interpretations were made with caution, future research should consider displaying delay and date notations with similar numbers of symbols to make the two conditions even more comparable (e.g., 30/11/24 vs. 3m/0w/1d, with m corresponding to months, w to weeks and d to days). Like eye-tracking as an indirect measure of overt attention, the fMRI BOLD signal is an indirect measure of brain activity and thus subject to interpretations as well (Logothetis, 2008). Specifically, conclusions about mental processes were drawn based on brain activity, although brain areas may serve several distinct purposes, a problem known as *reverse inference* (Poldrack, 2011). For example, the precuneus has been associated with a broad range of cognitive functions ranging from visual imagery and episodic memory retrieval to self-referential processing and consciousness (Cavanna & Trimble, 2006). The idea that in **Study III**, higher activity in the precuneus in the date compared to the delay condition reflects deeper episodic processing is therefore only one possible interpretation, albeit one that fits well with both the literature on precuneus activity and the date/delay effect. However, to be sure about such an association, neural stimulation techniques such as TMS would be required.

Third, **Studies IV and V** aimed to answer clinical research questions based on a dimensional approach but did not collect data on clinical diagnoses. Therefore,

interpretations regarding categorically diagnosed clinical populations should be made with caution. Importantly, transdiagnostic research studies in clinical populations should aim to replicate the results reported here. Moreover, potential comorbidities should be controlled for (Levitt et al., 2023).

Fourth, a statement on the constraints on generality (COG) is essential to accurately communicate the generalisability of findings (Simons et al., 2017). Here, the focus lies on the sample characteristics and task stimuli of the conducted studies. Regarding sample characteristics, **Studies I, IV and V** presented results of several hundred participants, who were at least partially representative of the German/U.S. populations (for details, see the respective publications in the Appendices). However, samples in **Studies II and III** were small and demographically homogenous due to the methodology used. Thus, although the eye-tracking results were broadly consistent across the two studies, their generalisability has yet to be confirmed. Highly powered replication studies are particularly needed to examine differential mechanisms (see Section 4.1.2). More generally, all studies of this dissertation examined so-called WEIRD (Western, educated, industrialised, rich, democratic) societies (Henrich et al., 2010). Further generalisation is clearly needed, especially regarding cultural differences (Triandis & Suh, 2002) in the individual difference effects investigated in **Studies I, IV and V**. Moreover, generalisability is also limited with regard to the measures used. As outlined in Section 1.2.1, there are numerous measures to assess intertemporal choice behaviour. Here, only a prototypical task operationalising options as (hypothetical or partly hypothetical) monetary rewards was used (Kirby et al., 1999). While the hypotheticality of rewards has been shown not to influence task results (Brañas-Garza et al., 2023), the type of reward (Odum et al., 2020) and – as this dissertation showed – the framing may do so. It is, for instance, conceivable that aberrant temporal discounting in some psychopathological dimensions (such as disordered eating) is only measurable with food stimuli (Amlung et al., 2019). Moreover, as outlined in **Study III**, it may be particularly important to vary the times of the smaller-immediate rewards to ensure that people need to look at all attributes. Also, systematic variation of reward and time attributes more generally would allow to evaluate the influences of the values of reward and time attributes (and subjective values) on choices more independently.

Finally, it should be noted that the current dissertation does not provide a conclusive answer regarding the complex structure of impulsivity, an overall explanation of the mechanisms of the date/delay effect or definite mechanisms of and treatment approaches for aberrant intertemporal decision-making. Instead, it gives important insights into these topics. Further research is needed to confirm and extend these results, ultimately providing a more comprehensive picture of the structure, malleability and transdiagnostic role of impulsivity and impulsive decision-making.

4.3 Future Avenues

In the previous sections (Sections 4.1 and 4.2), specific suggestions have already been made to address limitations and extend the findings of this dissertation. In this section, more general future avenues will be presented, building upon the central contributions of the dissertation.

First, this dissertation provided valuable insights into the structure of trait and behavioural impulsivity. In **Study I**, the separability of positive and negative urgency was questioned, and lack of premeditation was identified as a candidate core feature. Moreover, network analysis was used for the first time to examine the weak relationships between trait and behavioural impulsivity. However, the structure of impulsivity still needs to be more comprehensively analysed. Future research will need to build upon this and further studies on the structure of impulsivity (Billieux et al., 2021; Cyders et al., 2014; Goh et al., 2020; MacKillop et al., 2016; J. Miller et al., 2003; Teese et al., 2021; Whiteside & Lynam, 2001; Zsila et al., 2020) to establish a more general framework and a better understanding of the umbrella of impulsivity. For instance, more studies on the separability of positive and negative urgency are needed, especially in light of diverging results on psychometric (Billieux et al., 2021; Goh et al., 2020; **Study I**) and genetic (Gustavson et al., 2020) levels. Moreover, key constructs such as lack of premeditation and their assessment should be taken into focus (Strickland & Johnson, 2021). Network analyses may help in this endeavour. Specifically, given that high centralities in cross-sectional networks can reflect that a construct is a causal factor or a common consequence of others (Golino & Epskamp, 2017), future studies should use longitudinal designs to identify the causal role of lack of premeditation more conclusively. More generally, large-scale studies and further meta-analyses combining personality and behavioural measures as well as real-life outcomes may provide clarifications about potential jingle/jangle-fallacies and generate a better overall picture of impulsivity, especially in light of the lack of consensus regarding the classification of behavioural constructs (see Section 1.1.2).

Second, this dissertation (**Studies II–V**) corroborated the robustness of the date/delay effect in intertemporal choice (LeBoeuf, 2006; Read et al., 2005). Moreover, **Studies II and III** yielded important insights into its cognitive and neural mechanisms. Future research should particularly pursue the ideas of differential time estimation, reward weighting and choice strategies. Specifically, future studies on the date/delay effect should include a task of subjective time estimation (Jiang & Dai, 2021; Zauberman et al., 2009). Additionally, experimental manipulations of reward focus (Reeck et al., 2017) may be useful to determine whether rewards need to be considered or weighted more in the date condition to yield the date/delay effect. Furthermore, to provide information not only about the date/delay effect but about intertemporal choice strategies in general, different alterative-based, attribute-based and hybrid models (Doyle, 2013) should be explicitly compared, potentially accounting for interindividual differences in the date/delay effect.

More broadly, the malleability of intertemporal decision-making should be examined in clinical populations such as patients with ADHD, bulimia nervosa or substance use disorders, given that the date/delay effect has been shown to be particularly effective on a psychopathological dimension characterised by inattention/impulsivity/overactivity.

Third, regarding psychopathology, this dissertation used two state-of-the-art research approaches (Eaton et al., 2023; Roefs et al., 2022): network analysis (**Study I**) and transdiagnostic dimensional approaches (**Studies IV–V**). **Study I** yielded different acceptable models of trait impulsivity, one of which was a bifactor model. The common factor in this model may reflect the *p*-factor of psychopathology, which has been discussed to reflect impulsivity (Southward et al., 2023). In combination with **Study V**, which confirmed the critical role of impulsivity in psychopathology as well, this idea should be investigated in future research. Moreover, focusing on intertemporal choice specifically, **Studies IV and V** showed that aberrant intertemporal decision-making is prevalent in many but not all psychopathology dimensions. Future studies should examine whether the transdiagnostic findings in the general population indeed translate to clinical populations. Moreover, a vital task for future studies will be to more rigorously investigate the neurobiological basis of temporal discounting and the date/delay effect both in clinical and non-clinical populations. In accordance with dimensional approaches such as RDoC (Cuthbert, 2014, 2022; Insel et al., 2010) and HiTOP (Kotov et al., 2017, 2021), this may ultimately contribute to describing common psychopathology dimensions more thoroughly and identify intervention targets for aberrant decision-making in psychopathology.

Finally, by replicating the date/delay effect in four studies, this dissertation has illustrated the value of replications. Replications are a cornerstone of science, which has become evident not least in view of the current reproducibility crisis (Nosek et al., 2022; Open Science Collaboration, 2015). At the same time, it is therefore important to highlight that many other findings of this dissertation should be replicated by independent research groups. Specifically, while all studies were preregistered, some of the reported data analyses were non-preregistered and explorative (as disclosed explicitly in the articles). Future studies could therefore benefit from the publicly shared materials, data and analysis scripts to conduct replication studies associated with the research studies reported here to provide additional empirical evidence of the conclusions presented in this dissertation.

4.4 Conclusion

This dissertation provided new insights into impulsivity in general and, more specifically, impulsive decision-making. Illustrating the scope of open research questions in these topics, the studies examined their heterogeneity, malleability and transdiagnostic relevance using psychometric, experimental and neuroimaging approaches. Specifically, **Study I** broadly confirmed the heterogeneous nature of impulsivity itself, questioned the

separability of positive and negative urgency and revealed the importance of lack of premeditation for the umbrella of impulsivity. **Studies II and III** focused on the cognitive and neural mechanisms of the date/delay effect in intertemporal choice, suggesting that the effect may be caused by differential time estimations, reward weightings and choice strategies. **Studies IV and V** used dimensional approaches to psychopathology, revealing that intertemporal decision-making is aberrant in a broad range of symptom patterns but may be alleviated by manipulations targeting time processing, especially in persons showing higher scores on an impulsivity dimension. Future research may profit from the work reported here to obtain a clearer conceptualisation of impulsivity as well as a better understanding of the malleability and determinants of intertemporal choice. Overall, the umbrella of impulsivity is far from being closed.

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Appendix A | Study I

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The network structure of impulsive personality and temporal discounting

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ABSTRACT

Impulsivity is an ill-defined umbrella term. Therefore, in addition to factor-analytic models, network models that characterize the relative positions of their components can offer novel insights. Here, we investigated the structure of impulsivity in 1000 participants using the Short UPPS-P Impulsive Behavior Scale and a temporal discounting task. Our results revealed an acceptable fit of a five-factor solution of the Short UPPS-P but question the separability of Positive and Negative Urgency. Additionally, Lack of Premeditation showed high closeness centrality and was – like Positive and Negative Urgency – significantly yet weakly related to temporal discounting. It remains to be investigated further to what extent Lack of Premeditation is a common cause or consequence of other impulsivity components.

1. Introduction[1]

Impulsivity has been defined as "a predisposition toward rapid, unplanned reactions to internal or external stimuli without regard to the negative consequences of these reactions to the impulsive individual or to others" (Moeller et al., 2001, p. 1784). Despite its relevance in personality (Whiteside & Lynam, 2001), psychopathology (American Psychiatric Association, 2013), and daily behavior (Sperry et al., 2016, 2018), impulsivity represents an ill-defined umbrella term subsuming various phenomena (Evenden, 1999; Strickland & Johnson, 2021). While recent studies have shown that different constructs referred to as impulsivity are barely related to each other (Creswell et al., 2019; Cyders & Coskunpinar, 2011; MacKillop et al., 2016; Sharma et al., 2014), knowledge of the relation between the different concepts that have been referred to as impulsivity is sparse. Only few studies have used network analysis to study impulsive personality (e.g., Goh et al., 2020)[2]. In the present study, we aim to contribute to the debate on the "varieties of impulsivity" (Evenden, 1999, p. 348) by applying network analysis techniques that have recently opened new directions in psychopathology (Contreras et al., 2019; Fried & Cramer, 2017; Robinaugh et al., 2020) and personality research (Costantini et al., 2015, 2021; Cramer et al., 2012). Specifically, our aim is to examine the mutual relations between different constructs subsumed under the term impulsivity. Importantly, we include both a self-report measure of impulsivity and a behavioral measure of impulsive decision making, i.e., an intertemporal choice task.

1.1. Measurement and core features of impulsivity

Impulsivity is frequently assessed with either personality inventories or behavioral tasks (Aichert et al., 2012; MacKillop et al., 2016; Sharma et al., 2014). Both measurement types have been shown to correlate with daily behavior (Sharma et al., 2014), and in two recent studies, self-report measures were found to outperform behavioral tasks in predicting real life outcomes (Creswell et al., 2019; Eisenberg et al., 2019). Whilst attempts to develop theoretical models of behavioral tasks in the context of impulsivity (e.g., go/no-go tasks, gambling tasks, or temporal discounting tasks) have not reached a consensus to this point (Eisenberg et al., 2019; Fineberg et al., 2014; Stahl et al., 2014; Strickland & Johnson, 2021), personality research has been more successful in establishing a widely accepted model of impulsive personality.

Specifically, Whiteside and Lynam (2001) constructed the *UPPS*

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[1] The hypotheses, methods, and analysis plan of this study were preregistered at https://osf.io/qmkfc on 22nd June 2020. Study materials, data and analysis scripts used for this article as well as supplemental material can be accessed at https://osf.io/u6vps/.

[2] That study was published after preregistration of our study, i.e., during our data collection. Additionally, after submission of our manuscript, another paper has examined the network of impulsive personality with a focus on the conceptualization of Positive and Negative Urgency (Billieux et al., 2021).

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Impulsive Behavior Scale by factor-analyzing personality inventories connected to impulsivity, resulting in four distinct but related constructs: *Negative Urgency* (tendency to act rashly when experiencing intense negative affect), *Lack of Premeditation* (tendency to act without thinking), *Lack of Perseverance* (tendency to get distracted and give up on a boring or difficult task), and *Sensation Seeking* (tendency to seek new and exciting experiences). Subsequently, Lynam et al. (2006) added *Positive Urgency* (tendency to act rashly when experiencing intense positive affect), resulting in the *UPPS-P Impulsive Behavior Scale*. Validation studies in different samples and languages have confirmed the five-factor structure of the UPPS-P (e.g., English: Cyders & Smith, 2007; Teese et al., 2021; Spanish: Verdejo-García et al., 2010) and its short versions (e.g., English: Cyders et al., 2014; Hungarian: Zsila et al., 2020). While weak to moderate correlations between most scales (Cyders et al., 2014; MacKillop et al., 2016) as well as their often differential associations with affective, cognitive, and behavioral outcomes (Smith et al., 2007; Sperry et al., 2016, 2018) and psychopathologies (Berg et al., 2015) provide evidence for their construct validity and indicate that they represent largely separable constructs, factor analytic studies have also shown overlaps between some of them. Specifically, hierarchical models with three second-order factors also achieve reasonably good fits (Cyders & Smith, 2007; Teese et al., 2021; Zsila et al., 2020). These models include an Urgency factor comprising Positive and Negative Urgency, a Sensation Seeking factor, and a Lack of Conscientiousness factor comprising Lack of Premeditation and Lack of Perseverance. Thus, the structure of, and relations between, impulsigenic personality constructs are far from clear, and especially the separations of Positive vs. Negative Urgency and Lack of Premeditation vs. Lack of Perseverance are debatable (Goh et al., 2020; Sperry et al., 2018).

Lack of Premeditation is not only central to the definition of impulsivity (see Moeller et al., 2001, quoted above) but it is correlated with all other lower-level impulsivity-related constructs (Cyders et al., 2014; MacKillop et al., 2016; Miller et al., 2003; Whiteside & Lynam, 2001) and has predictive validity with respect to real world outcomes (e.g., substance use; Miller et al., 2003); therefore, one may reason that Lack of Premeditation is a core feature of impulsivity. In line with this, Sharma et al. (2014) argued that their purely cognitive factor (disinhibition vs. constraint) might represent "the core of impulsivity" (p. 382) because, while independent of concrete affect, it influences affective responses on a more general level. However, other studies reported low and inconsistent associations with behavioral tasks (MacKillop et al., 2016), emphasized similarities between the daily life correlates of Negative Urgency, Positive Urgency, Lack of Perseverance and Lack of Premeditation (Sperry et al., 2018), and highlighted that affective impulsivity traits are better predictors of externalizing behaviors other than substance use (e.g., aggression; Creswell et al., 2019; however, see Miller et al., 2003) and psychopathologies such as depression, anxiety, borderline, and eating disorders (Berg et al., 2015; Miller et al., 2003), thus further challenging the central role of Lack of Premeditation in impulsivity.

1.2. The network approach in psychology

The methodological tools of network science can be applied to investigate the relative importance of different (aspects of) psychological constructs, once they are represented as networks where nodes are variables (e.g., items or subscale scores) and links indicate their statistical associations (Robinaugh et al., 2020). Indeed, the application of *network models* has yielded new insights in areas such as clinical psychology (Contreras et al., 2019; Fried & Cramer, 2017; Robinaugh et al., 2020), social psychology (Dalege et al., 2017), and personality research (Costantini et al., 2015, 2021; Cramer et al., 2012) by revealing, for instance, that obsessions may cause the comorbidity between obsessive-compulsive disorder and depression (Jones, Ma, et al., 2021), changes in emotional pain and emptiness are critical in the recovery from complicated grief (Robinaugh et al., 2016), or guilt can drive sustainable consumer behavior (Zwicker et al., 2020).

The general idea of *psychological network theory* is that complex higher-level psychological phenomena, such as mental disorders, personality traits, or cognitive functions, arise through interplays between their constituent elements (Borsboom & Cramer, 2013). Network theory is often contrasted with the framework assuming common causes behind dimensions of individual differences. This is related to the concepts of *correspondence* and *emergence* in personality research (Baumert et al., 2017; Costantini et al., 2021). The correspondence view posits that individual differences in personality components are caused by stable, higher-order traits, represented by latent variables in statistical models (Borsboom et al., 2003), whereas the emergence view claims that patterns of interindividual covariation are caused by dynamic interactions of different components (Cramer et al., 2012).

Despite these conceptual differences, critiques of the network approach have highlighted that network and latent variable models may not be that different (Bringmann & Eronen, 2018), as latent variable models and network models can be mathematically equivalent (Bringmann & Eronen, 2018; Epskamp et al., 2016; Kruis & Maris, 2016) and communities of nodes in networks may be indicative of latent variables generating the observed covariation (Golino & Epskamp, 2017; see Pearl, 2009, for discussions on causality). Nevertheless, network and latent variable models differ in terms of interpretations and predictions (Christensen et al., 2020). Moreover, while the explanatory power of latent variables is weakened by modelling direct associations between indicators (i.e., residual covariances) (Bringmann & Eronen, 2018) and cross-loadings complicate interpreting the latent variables (Clark & Watson, 2019), in network models, these issues are either theoretically meaningful or do not even emerge. Therefore, network analysis may provide a novel perspective on the debated structure of impulsive personality by considering direct interactions between its components (e.g., a lower ability and preference to think carefully before acting [Lack of Premeditation] will cause someone to act more rashly under the influence of emotions [Urgency] and behave less strategically [Lack of Perseverance / impulsive decision making]) (Cramer et al., 2012).

Furthermore, network visualizations can intuitively represent highly complex structures, which may facilitate insights and spark novel hypotheses (Bringmann & Eronen, 2018). Perhaps even more importantly, once complex multivariate associations have been represented with a network, centrality indicators can be calculated which can be used to infer whether some elements of the network are more important than others (e.g., structurally suitable to causally influence multiple other elements or to be a common endpoint) (Bringmann & Eronen, 2018; Costantini et al., 2015; Opsahl et al., 2010). In the psychometric network literature, strength, closeness, and betweenness are the most frequently used indicators of centrality (Borgatti, 2005; Bringmann et al., 2019; Costantini et al., 2015; Wang et al., 2018). *Strength* is the sum of the absolute weights of the direct connections of a node, *closeness* is the reciprocal of the average distance between a node and all the other nodes in the network, and *betweenness* shows the probability that a node lies on the shortest path connecting any two other nodes in the network (for mathematical definitions, see Wang et al., 2018). Intuitively, strength indicates the importance of a node in terms of its direct connections, while closeness considers direct and indirect connections, and betweenness reflects the importance of a node in terms of forming bridges in the network (Fig. 1). In the case of impulsivity, the analysis of centralities can show if any component of impulsivity is structurally situated to have a dominant causal influence on the other aspects or to be a common effect of the other components. Such inferences would not be straightforward within confirmatory factor analysis models. It should be noted, however, that causal inferences in network models should also be made with caution, especially in those applied to cross-sectional data (Guloksuz et al., 2017; see section 4.4).

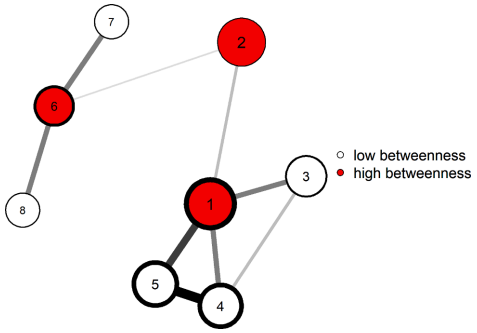


Fig. 1. *Illustration of the Centrality Indicators Used in the Study. Note.* Strength is reflected in border width, closeness is reflected in node size, while color shows betweenness. Note that centralities can diverge: #1 scores high on all of them, #2 scores high on betweenness and closeness but low on strength, and #6 only scores highly on betweenness.

1.3. The network of impulsivity

So far, only two studies have examined impulsivity using network analysis (Goh et al., 2020; Martel et al., 2017). Martel et al. (2017) demonstrated high centrality of impulsivity symptoms within a network of externalizing problems across child development, which suggests that impulsivity symptoms are probably causing many other problems, potentially making them a promising intervention target. Goh et al. (2020) administered the UPPS-P to college students repeatedly over three years, conducted network analyses where nodes represented subscale scores, and found the network of UPPS-P dimensions to be quite stable. Their analyses broadly confirmed the central position of Lack of Premeditation, which suggests that Lack of Premeditation is either causing other features related to impulsivity, or is their consequence (or both). Moreover, they, like previously mentioned studies using factor analytic approaches (Cyders & Smith, 2007; Zsila et al., 2020), also found close relations between the urgencies on one side and Lack of Premeditation/Perseverance on the other.

1.4. The current study

Goh et al.'s (2020) results are important for our study: They were the first to conduct a network analysis of impulsive personality. However, whilst their sample size was limited and subject to drop-outs ($n_1 = 525$; $n_2 = 378$; $n_3 = 333$), which, for example, made interpretations of network analyses on an item-level virtually impossible, we sought to investigate the network structure of impulsivity on a broader basis. Hence, our preregistered study features three crucial differences. First, our sample was larger ($N = 1000$) and drawn from the German general population (i.e., sampling aimed at people from different locations with varying age and levels of education and without any a priori socio-demographic exclusion criteria apart from being at least 18 years old) to enable better generalization of findings. Second, we used a short version of the UPPS-P (Cyders et al., 2014) to investigate the structure of impulsivity with both factor analysis and network analysis (not only at the level of subscales but also at item level). Third, we included an intertemporal choice questionnaire (Monetary Choice Questionnaire [MCQ]; Kirby et al., 1999) to investigate associations of self-reported impulsigenic traits with temporal discounting, i.e., impulsive decision making behavior. Temporal discounting refers to the phenomenon of devaluing a future reward as a function of time until receipt of that reward. It is generally referred to as measure of choice impulsivity (Hamilton et al., 2015) and involves several features of the definition of impulsivity given above, i.e., lack of planning, lack of regard for future consequences (Hamilton et al., 2015), and it is associated with negative consequences such as negative health-related or financial outcomes (Amlung et al., 2019; Bickel, 2015). Whilst small yet significant correlations have been observed between self-reported trait impulsivity and temporal discounting (MacKillop et al., 2016), no previous study has combined these measures in network analysis.

We expected first to replicate the five-factor structure of the Short UPPS-P found in previous factor analytic studies (e.g., Cyders et al., 2014). Specifically, like Schmidt et al. (2008), we hypothesized that a five-factor model with intercorrelated factors would provide a better fit than a general impulsivity model or a five-factor model with uncorrelated factors (hypothesis 1). Furthermore, in explorative, non-preregistered analyses we evaluated the model fit of three alternative models, all involving the same five factors on a first level: A hierarchical model with one second-order factor, a hierarchical model including three second-order factors (Urgency, Sensation Seeking, Lack of Conscientiousness) (cf. Cyders & Smith, 2007), and a bifactor model including a general vulnerability factor (i.e., a factor predisposing for behaviors termed "impulsive").

Moreover, for network models, we hypothesized that Lack of Premeditation would be a core component of impulsivity (hypothesis 2), as reflected by having the highest centrality score – not only in the item-level network (where we only exploratively examined centralities of items after community detection; not preregistered), but also within a network where nodes represent subscales (hypothesis 2a) – and showing the strongest association to the discount rate k, a variable that indicates the degree of temporal discounting (hypothesis 2b).

2. Method

2.1. Sample

To obtain a large sample from the German general population, our study was conducted through the online platform SosciSurvey (https://www.soscisurvey.de/) and advertised widely on diverse mailing lists and online forums, e.g., through various local groups on social media. As an incentive, participants were given the opportunity to take part in a lottery to win one of five Amazon-vouchers (worth €25 each). Psychology students from the University of Bonn could alternatively choose to be rewarded with course credits.

Participants had to be at least 18 years old. Furthermore, for data quality assurance purposes, participants were only included in the analysis if they (a) responded consistently to four items from Jackson's Infrequency Scale (Jackson, 1967) embedded within the Short UPPS-P (i.e., they always chose the least infrequent option), (b) indicated that they would answer / had answered the questionnaires seriously and conscientiously (one question each at the beginning and end of the study), and (c) answered the survey in a reasonable amount of time as defined by a relative speed index under 2.0 (Leiner, 2019). As an additional measure, we followed the recommendation of Gray et al. (2016) to exclude participants if they showed low consistency in their answer patterns of the MCQ (consistency within any of the different magnitudes < 0.70).

We conducted an a priori power analysis with G*Power (Faul et al., 2009) to determine the sample size. Since we wanted to examine, amongst others, the associations between temporal discounting and the Short UPPS-P subscales, which are quite low (MacKillop et al., 2016), we determined the sample size needed to reveal small effects ($r = 0.1$), given an alpha of 0.05 and a power of 90%. This analysis yielded a sample size of 1046 participants, which we rounded to 1000 participants (thus leading to a power of 88.68% to reveal an effect of $r = 0.1$). To reach this sample size, data collection was stopped after 1259 completed surveys, since 259 of them had to be excluded due to the reasons specified above. Participants (72.8% female, 26.4% male, 0.8% diverse) were between 18 and 78 years old ($M = 33.66$; $SD = 11.17$) (see

supplement A1) and had a wide range of education attainment (10.1% low level of education, 64.4% medium level of education; 25.5% high level of education). Education levels were assessed according to the German version of the *International Standard Classification of Education ISCED 2011* (United Nations Educational Scientific and Cultural Organization Institute for Statistics, 2012; https://www.datenportal.bmbf.de/portal/de/G293.html) (see supplement A2 for detailed data and comparison with education levels in the German population). Responses were coded as follows: Low level of education ranged from no school education up to completion of lower secondary education, medium level of education ranged from completed upper secondary education to completed Bachelor's degree (or equivalent), and high level of education ranged from completed Master's degree (or equivalent) to completed doctoral degree or habilitation (or equivalent).

The study was approved by the ethics committee of the Department of Psychology, University of Bonn.

2.2. Materials

After consenting to the study terms and providing demographic information, participants were asked to complete the MCQ (Kirby et al., 1999) and the Short UPPS-P (Cyders et al., 2014).

2.2.1. Short UPPS-P

The Short UPPS-P (Cyders et al., 2014) is a 20-item version of the original 59-item UPPS-P (Lynam et al., 2006) and assesses five impulsive personality constructs: Positive Urgency, Negative Urgency, Sensation Seeking, Lack of Premeditation, and Lack of Perseverance. We applied a German version, using the validated UPPS translations of Schmidt et al. (2008) for the items that corresponded to those of Cyders et al. (2014) as well as additional translations, which were needed for the four Positive Urgency items. We created them by translation (A1; German native), back-translation (A2; English-German bilingual), and analysis of potential differences between the original and the back-translated version (colleague; English native). No adjustments had to be made. The 20 translated items (supplement B) were assessed together with four items from Jackson's Infrequency Scale (Jackson, 1967) on a five-point Likert scale (1 = *completely disagree*, 2 = *rather disagree*, 3 = *neutral*, 4 = *rather agree*, 5 = *completely agree*). To generate sum scores reflecting the different impulsive personality constructs, some items were reverse coded as specified in Cyders et al. (2014) (Table 1).

2.2.2. MCQ

To assess participants' temporal discounting, we used the MCQ (Kirby et al., 1999), which asks participants to make 27 hypothetical decisions between smaller, immediate and larger, later monetary rewards (e.g., €55.00 now vs. €75.00 in 61 days). The decisions can be divided into three different monetary magnitudes (low, medium, high), each including nine items. Participants were asked to make all decisions as if they were to actually receive the rewards involved. We calculated the consistency of choices (to exclude participants, see above) as well as the discount rate *k* for the three different magnitudes according to the procedures suggested by Gray et al. (2016). We computed their geometric mean[3] and log-transformed it due to its skewness of 4.19 (*SE* = 0.08) in order to use it as single individual parameter of impulsive choice in analyses (in the following: MCQ-*k*).

[3] Please note that in our preregistration, we erroneously wrote that we would calculate an "arithmetic mean" to get an overall MCQ-*k*. However, to prevent underweighting the smaller *k* values due to hyperbolic discounting, the geometric mean is more appropriate and generally used (Gray et al., 2016). We also note that using either method does not change our results (https://osf.io/u6vps/).

Table 1
Means, Standard Deviations, and Skewness of the Short UPPS-P Items, as well as Their Original Scale and Their Community.

#	Short version of the item	*M*	*SD*	Sk	Sc	Com
01	Seeing things through the end (R)	1.65	0.75	1.22	PE	Pers
02	Careful and purposeful thinking (R)	1.96	0.81	0.79	PR	Prem
03	Problems when in great mood	2.23	1.06	0.76	PU	Urge
04	Bothered by unfinished tasks (R)	2.12	1.03	0.76	PE	Pers
05	Thinking things over (R)	2.41	0.97	0.39	PR	Prem
06	Doing later regretted things when feeling bad	2.80	1.20	0.23	NU	Urge
07	Hating to stop something (R)	2.23	0.98	0.66	PE	Pers
08	Making things worse when feeling bad	2.45	1.23	0.43	NU	Urge
09	Enjoying taking risks	2.35	0.97	0.53	SS	Sens
10	Losing control in great mood	1.83	0.91	1.12	PU	Urge
11	Finishing what is started (R)	2.00	0.85	0.93	PE	Pers
12	Rational approach to things (R)	1.96	0.82	0.74	PR	Prem
13	Acting without thinking when upset	2.73	1.05	0.26	NU	Urge
14	New and exciting experiences	3.20	1.11	−0.18	SS	Sens
15	Saying later regretted things when rejected	2.72	1.15	0.19	NU	Urge
16	Flying an airplane	2.09	1.43	0.91	SS	Sens
17	Others are shocked what I do when excited	1.76	0.99	1.33	PU	Urge
18	Skiing very fast	2.61	1.49	0.30	SS	Sens
19	Thinking carefully before acting (R)	2.18	0.87	0.51	PR	Prem
20	Acting without thinking when excited	2.33	1.08	0.55	PU	Urge

Note. (R) indicates reverse scoring. Sk = Skewness; Sc = Scale (based on the a priori defined scales in Cyders et al., 2014); Com = Community (based on the community detection algorithm applied to the item-level network model in this study); PE = Lack of Perseverance; PR = Lack of Premeditation; PU = Positive Urgency; NU = Negative Urgency; SS = Sensation Seeking; Pers = Lack of Perseverance (community); Prem = Lack of Premeditation (community); Urge = Urgency (community); Sens = Sensation Seeking (community).

2.3. Statistical analyses

All analyses described below were preregistered, unless specified otherwise, and performed in R (version 4.1.1) using RStudio (version 1.4.1717).

First, we computed Pearson correlations between the UPPS-P Short subscale scores and MCQ-*k*. Confirmatory factor analyses were then calculated using the lavaan package (Rosseel, 2012), following the reporting recommendations by Credé and Harms (2019). Due to somewhat increased skewness of some items (skewness ranging from −0.18 to 1.33; see Table 1), we used robust maximum likelihood (ML) estimators (Satorra & Bentler, 1994).

To evaluate model fit and compare the fit of different models (five-factor model with intercorrelated factors, model with one general impulsivity factor, and a five-factor model with uncorrelated factors; cf. Schmidt et al., 2008), the following fit indices were examined (Hu & Bentler, 1999; Schermelleh-Engel et al., 2003): Root Mean Square Error of Approximation (RMSEA), Standardized Root Mean Square Residual (SRMR), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), and Akaike Information Criterion (AIC). Acceptable fits are defined as RMSEA < 0.08, SRMR < 0.10, CFI ≥ 0.95, and TLI ≥ 0.95 (Schermelleh-Engel et al., 2003). AIC, which penalizes for additional parameters, served as additional index of model comparison. Moreover, χ^2 and degrees of freedom were displayed for transparency purposes, though we note that χ^2 is sensitive to small amounts of misspecification in large sample sizes such as ours (Schermelleh-Engel et al., 2003). Since consideration of plausible alternative models is needed to also consider possibly disconfirming evidence (Credé & Harms, 2015, 2019), we compared our models in an explorative analysis, which was not specified in our preregistration, to a hierarchical model with one second-order

factor (loadings between second-order and first-order factors equality constrained), to a hierarchical model with three second-order factors (Urgency, Sensation Seeking, Lack of Conscientiousness), as previously suggested (Cyders & Smith, 2007), as well as to a bifactor model including both five factors and a general vulnerability factor. Concepts of all six models are illustrated in Fig. 2.

Next, a network model of Short UPPS-P items was estimated using the qgraph package (Epskamp et al., 2012). Item-level data were nonparanormal-transformed due to their high skewness (Table 1). Specifically, we computed a Gaussian graphical model using graphical lasso. The tuning parameter was chosen based on the Extended Bayesian Information Criteria (EBIC) (Epskamp, Waldorp, et al., 2018). The network was estimated and visualized on the basis of polychoric correlations, and communities were detected using the fast-greedy modularity optimization algorithm (Clauset et al., 2004) as implemented in the igraph package (Csardi & Nepusz, 2006). After examining the emerging network communities, we did an explorative, non-preregistered analysis of their centralities using the qgraph package (Epskamp et al., 2012): Specifically, to compare distributions of strength, closeness, and betweenness centralities of items within each community, we did Kruskal-Wallis tests and, if significant, Mann-Whitney post-hoc tests. Centralities capture the importance of the components of the impulsivity network, that is, whether their position in the network is suitable to causally influence the others and/or be a common causal effect of them. Finally, in order to assess the robustness of the findings, we evaluated the precision of network model estimation as well as differences and stabilities of centralities with bootstrapping using the bootnet package (5000 bootstrap samples) (Epskamp, Borsboom, et al., 2018).

To examine associations of impulsive personality with MCQ-*k*, we computed another network model, applying the above-described analytical approach to the subscale scores of the Short UPPS-P[4] and MCQ-*k*. We note that in this network, each node reflected a summary of multiple measurements; thus, it is less likely that differences in measurement error between subscales and MCQ-*k* would confound the network model. The relative importance of the six constructs was inferred on the basis of strength, closeness, and betweenness centralities and bootstrapping was used again to evaluate the stability of the network, the differences of the edge weights, as well as the stability and differences of centralities.

3. Results

Descriptive statistics of the Short UPPS-P items are displayed in Table 1. Subscale scores and MCQ-*k* as well as their intercorrelations are displayed in Table 2.

3.1. Confirmatory factor analyses

As presented in Table 3, confirmatory factor analysis of the Short UPPS-P items showed that a five-factor model with intercorrelated factors (model 1) provided an acceptable model fit (except for CFI and TLI, which did not reach the threshold of 0.95 specified by Schermelleh-Engel et al., 2003), whereas the fits of both a general impulsivity model (model 2) and a five-factor model with uncorrelated factors (model 3) were poor. χ^2 reached significance in all of the models, probably due to the large sample size. However, model 1 showed substantially better values in all fit indices (RMSEA, SRMR, CFI, TLI, AIC) than models 2 and 3.[5]

To explore the structure of trait impulsivity further, we additionally ran confirmatory factor analyses with three non-preregistered models. First, we investigated the fit of a model with one second-order factor (model 4). This model had a poor fit. The second model included three second-order factors (model 5)[6]: (a) Urgency: Positive and Negative Urgency; (b) Sensation Seeking; (c) Lack of Conscientiousness: Lack of Premeditation and Lack of Perseverance. The model, like model 1, yielded an acceptable fit (except for CFI and TLI), with only slightly lower fit indices than model 1. Third, a bifactor model including five factors as well as a general vulnerability factor (model 6) yielded similar fit indices.[7]

Accordingly, model 1, model 5, and model 6 showed the best fit indices. Comprehensive depictions of these models, including loadings and residuals, are shown in Fig. 3. Observed and implied covariances and standardized residuals of items as well as modification indices of the models are presented in supplement C.

3.2. Item-level network analysis

Next, to examine the structure of the Short UPPS-P from a perspective which places more focus on direct associations between its components, we modelled the complex multivariate association structure between the items with a Gaussian graphical model. Then, in order to evaluate the dimensionality of the UPPS-P, we applied the fast-greedy community detection algorithm to the estimated network. As can be seen in Fig. 4A, the analysis yielded four interconnected communities, three of which accurately represented the items of the Lack of Premeditation, Lack of Perseverance, and Sensation Seeking subscales. However, Positive and Negative Urgency items were grouped into a single community (Table 1).

In order to examine whether certain components of impulsivity might be more important than others, in a non-preregistered analysis, we explored centralities of the different communities. Centrality estimates of the four communities are presented in Fig. 4B. Comparisons of the estimates with Kruskal-Wallis tests showed that strength, $\chi^2(3) = 4.38$, $p = .22$, and betweenness, $\chi^2(3) = 1.08$, $p = .78$, did not differ significantly between the nodes of the different communities, whereas closeness did, $\chi^2(3) = 10.81$, $p = .01$. Post-hoc tests revealed that nodes of the Lack of Premeditation community entailed higher closeness values compared to all other communities (Urgency: $Z = -2.19$, $p = .03$, $r = 0.07$; Sensation Seeking: $Z = -2.19$, $p = .03$, $r = 0.07$; Lack of Perseverance: $Z = -2.19$, $p = .03$, $r = 0.07$), while comparisons between nodes of other communities were non-significant (all $p > .10$). In line

[4] Since skewness of subscale scores were only moderate (< 1) and subscale scores are generally less prone to be skewed than single items, we did not apply a nonparanormal transformation in this network analysis (Table 2).

[5] χ^2-difference tests (model 1 vs. model 2; model 1 vs. model 3) were also calculated (using the method from Satorra & Bentler, 2001) and were highly significant (https://osf.io/u6vps/). However, due to sample size, the fit indices reported in Table 3 are of higher value for interpretation (cf. Schermelleh-Engel et al., 2003).

[6] This model initially yielded a Heywood case, as the error variance for the Lack of Premeditation factor was negative (−0.09). The estimation converged nevertheless, and we assumed that the negative error variance was due to sampling variability. We tested whether it differed significantly from zero, which it did not ($z = -0.56$, $p = .57$) (see Chen et al., 2001). We then reestimated the model with the error variance of the Lack of Premeditation factor set to zero. The resulting model fit was comparable to the fit of the model with Heywood case and is presented in Fig. 3B. For further details, see https://osf.io/u6vps/.

[7] Again, χ^2 for models 4, 5, and 6 were significant. χ^2-difference tests (Satorra & Bentler, 2001) were highly significant for all possible comparisons of these three models with the other models (i.e., model 4 vs. models 1, 3, 6; model 5 vs. models 1, 2, 3; model 6 vs. models 2, 3, 4; for directions see χ^2-values in Table 3; https://osf.io/u6vps/), but see Footnote 5.

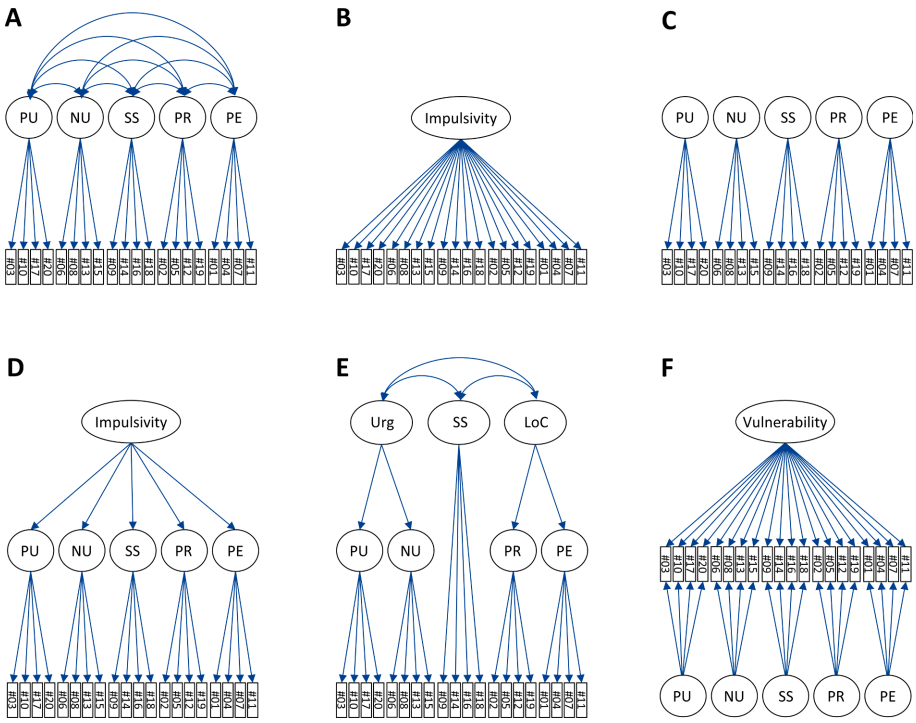


Fig. 2. *Conceptual Factor Models Investigated Within Confirmatory Factor Analyses. Note.* (A) Five-factor model with intercorrelated factors (model 1); (B) general impulsivity model (model 2); (C) five-factor model with uncorrelated factors (model 3); (D) hierarchical model with one second-order factor (model 4); (E) hierarchical model with three second-order factors (model 5); (F) bifactor model (model 6). Numbers with a preceding # represent item numbers of the Short UPPS-P (Cyders et al., 2014; see Table 1). PU = Positive Urgency; NU = Negative Urgency; SS = Sensation Seeking; PR = Lack of Premeditation; PE = Lack of Perseverance; LoC = Lack of Conscientiousness; Urg = Urgency.

Table 2
Descriptive Statistics of and Correlations between Short UPPS-P Subscales and MCQ-k.

Variable	*M*	*SD*	Sk	(1)	(2)	(3)	(4)	(5)	(6)
(1) Positive Urgency	8.16	3.08	0.74	(0.76)					
(2) Negative Urgency	10.70	3.31	0.15	0.59***	(0.68)				
(3) Sensation Seeking	10.24	3.34	0.41	0.20***	0.06*	(0.57)			
(4) Lack of Premeditation	8.52	2.57	0.50	0.36***	0.33***	0.05	(0.73)		
(5) Lack of Perseverance	8.00	2.53	0.63	0.07*	0.12***	< 0.01	0.32***	(0.64)	
(6) MCQ-*k*	−5.32	1.69	−0.11	0.12***	0.12***	−0.06*	0.11***	−0.03	(0.87, 0.86, 0.90)

Note. Values in the correlation diagonal represent Cronbach's Alphas, except for MCQ-*k*, for which parallel-test reliabilities based on the different magnitudes of the MCQ are reported (Pearson correlations between small MCQ-*k* and medium MCQ-*k*, small MCQ-*k* and large MCQ-*k*, and medium MCQ-*k* and large MCQ-*k*, respectively). Correlations: $df = 998$. $N = 1000$. Sk = Skewness; MCQ-*k* = log-transformed discount rate based on the Monetary Choice Questionnaire (Kirby et al., 1999). $^{*}p < .05$. $^{***}p < .001$

with this, bootstrapping difference tests (based on 5000 bootstrap samples) demonstrated that item #19 ("I usually think carefully before doing anything.") had significantly higher closeness relative to almost every other item (i.e., 17/19 = 89.5%) and the other Lack of Premeditation items showed higher closeness relative to 7 (#05 ["I like to stop and think things over before I do them."]: 7/16 = 43.8%) and 9 (#02 ["My thinking is usually careful and purposeful."] and #12 ["I tend to value and follow a rational, "sensible" approach to things."]: 9/16 = 56.3%) items in the other communities (supplement D1).

Furthermore, the estimation of edge weights as well as of node strength and closeness was highly accurate, as indicated by bootstrapping-based network stability analyses. On the other hand, the estimation of betweenness centralities was slightly less stable. These results can be deduced from bootstrapped distributions of centralities, also after dropping different subsets of data. Specifically, edge weights as well as strength and closeness centralities retained, with a 95% certainty, a correlation of at least 0.7 with the original parameter estimates after dropping 75%, 75%, and 67% of the sample, respectively, whereas in betweenness centrality, this correlation warranted only when dropping 59% of the sample (see supplements D2, D3).

Table 3
Fit Indices of Confirmatory Factor Analyses.

Model	χ^2	*df*	RMSEA [95% CI]	SRMR	CFI	TLI	AIC
Model 1	722.89***	160	0.059 [0.055; 0.064]	0.057	0.885	0.863	53332.194
Model 2	2318.25***	170	0.112 [0.108; 0.117]	0.102	0.560	0.508	54907.558
Model 3	1624.68***	170	0.093 [0.088; 0.097]	0.152	0.702	0.667	54213.985
Model 4	1088.57***	169	0.074 [0.070; 0.078]	0.094	0.811	0.788	53679.880
Model 5	771.32***	164	0.061 [0.057; 0.065]	0.060	0.876	0.856	53372.623
Model 6	701.61***	150	0.061 [0.056; 0.065]	0.061	0.887	0.857	53330.916

Note. Model 1 refers to a five-factor model with intercorrelated factors, model 2 to a general impulsivity model, model 3 to a five-factor model with uncorrelated factors, model 4 to a hierarchical model including one second-order factor, model 5 to a hierarchical model including three second-order factors (Urgency, Sensation Seeking, Lack of Conscientiousness), and model 6 to a bifactor model including a general vulnerability factor. RMSEA = Root Mean Square Error of Approximation, CI = Confidence Interval; SRMR = Standardized Root Mean Square Residual, CFI = Comparative Fit Index, TLI = Tucker-Lewis Index, AIC = Akaike Information Criterion.
*** $p < .001$

3.3. Scale-level network analysis including temporal discounting

Finally, we estimated a network model using the five subscale scores of the Short UPPS-P and MCQ-*k* (Fig. 5A).[8] First, it can be seen that the strongest associations emerged between the subscales of the Short UPPS-P (notably, between Positive Urgency and Negative Urgency as well as between Lack of Premeditation and Lack of Perseverance). Second, impulsive choice behavior (MCQ-*k*) was weakly and positively connected to Lack of Premeditation and the two Urgency scales, and weakly and negatively connected to Sensation Seeking. Numerically, intertemporal choice behavior had the strongest association with Lack of Premeditation. However, bootstrapped significance testing revealed that only weights of edges between subscale scores differed significantly from each other while connections between subscale scores and MCQ-*k* did not differ significantly from each other (supplements F1 to F4). Finally, we note that bootstrapping results are not recommended to be used to infer whether an edge is different from zero, as LASSO regularization already performs model selection and retains only edges that are sufficiently strong (Epskamp, Borsboom, et al., 2018).

Estimations of centralities (Fig. 5B) revealed that, descriptively, the Positive Urgency, Negative Urgency, and Lack of Premeditation subscales had the highest strength and closeness values. Additionally, Lack of Premeditation showed the highest betweenness centrality. Bootstrapping difference testing revealed that Positive Urgency showed significantly higher strength centrality than all other subscales and MCQ-*k*. In addition, there were no differences in closeness and betweenness centralities between Positive Urgency, Negative Urgency, and Lack of Premeditation, which all (except for betweenness of Negative Urgency) were higher as compared to those of the other nodes (supplement F5).

Finally, case-dropping subset bootstrapping suggested that edge weight and strength centrality estimates were stable, whereas closeness stability was slightly less stable and betweenness centrality considerably less stable. Specifically, edge weights and strength centralities retained, with a 95% certainty, a correlation of at least 0.7 with the original coefficients both after dropping 75% of the sample, respectively, whereas in closeness and betweenness, this correlation was warranted only when dropping 36% and 5%, respectively, of the sample (see supplements F6, F7).

[8] Note that in our analysis, we used MCQ-*k* as combined index of the discount parameters for the three different magnitudes within MCQ because nodes should be based on a similar number of measurements (i.e., four measurements per subscale, three estimates for the discount parameter) to ensure comparable reliabilities. Networks and centrality estimations including discount parameters of each magnitude are shown in supplement E (E1 to E3). Results show comparable findings to the reported network (strong connections only between Short UPPS-P subscales; only weak associations between Short UPPS-P subscales and MCQ-*k*).

4. Discussion

The current study ($N = 1000$) is the first large-scale study to investigate the structure of impulsivity in the German general population by applying both a factor-analytic approach and a network approach to widely used and validated measures of impulsive personality and impulsive behavior. While confirmatory factor analysis can be used to test a priori defined models about latent variables generating the data, the network approach uses data-driven methods to uncover the pattern of relationships between components of a construct and to infer their importance (Borsboom et al., 2021).

First, confirmatory factor analyses of the Short UPPS-P revealed that a model with five intercorrelated factors had a better fit than a model with a general impulsivity factor and a model with five uncorrelated factors (confirmation of hypothesis 1). However, additional analyses showed that a hierarchical model with three second-order factors (Urgency, Sensation Seeking, Lack of Conscientiousness) as well as a bifactor model reached comparable model fits, thus leaving the findings open to interpretation.

Second, a data-driven item-level network analysis with community detection largely confirmed the proposed structure of the Short UPPS-P, attributing the items of Sensation Seeking, Lack of Premeditation, and Lack of Perseverance to one community each. Unexpectedly, however, Positive and Negative Urgency formed a single community. Centrality measures showed that, while strength and betweenness centrality did not significantly differ between the four detected communities, closeness centrality was significantly higher for the Lack of Premeditation community than for all others. This suggests that components of Lack of Premeditation capture especially important features of impulsive personality: they may either exert a primary causal influence on other aspects of impulsivity or they might be a final common consequence of various sources of impulsivity. Although the present study design does not allow causal inference, it seems plausible that edges connecting nodes in different communities are likely to indicate bidirectional causal effects, while connections between nodes in the same communities may reflect the influence of latent common causes (Golino & Epskamp, 2017).

Third, a network analysis involving the five Short UPPS-P subscale scores as well as the discount rate MCQ-*k* confirmed weak to strong associations amongst the subscales and only weak associations between impulsive personality and MCQ-*k*. Of note, the strongest relationship occurred between Positive and Negative Urgency. Different centrality measures revealed high importance of Lack of Premeditation as well as of Positive and Negative Urgency (partial confirmation of hypothesis 2a). Considering MCQ-*k*, nominally, the strongest association was found for Lack of Premeditation but our bootstrapping analysis suggests that this association was not significantly higher than other comparisons (rejection of hypothesis 2b).

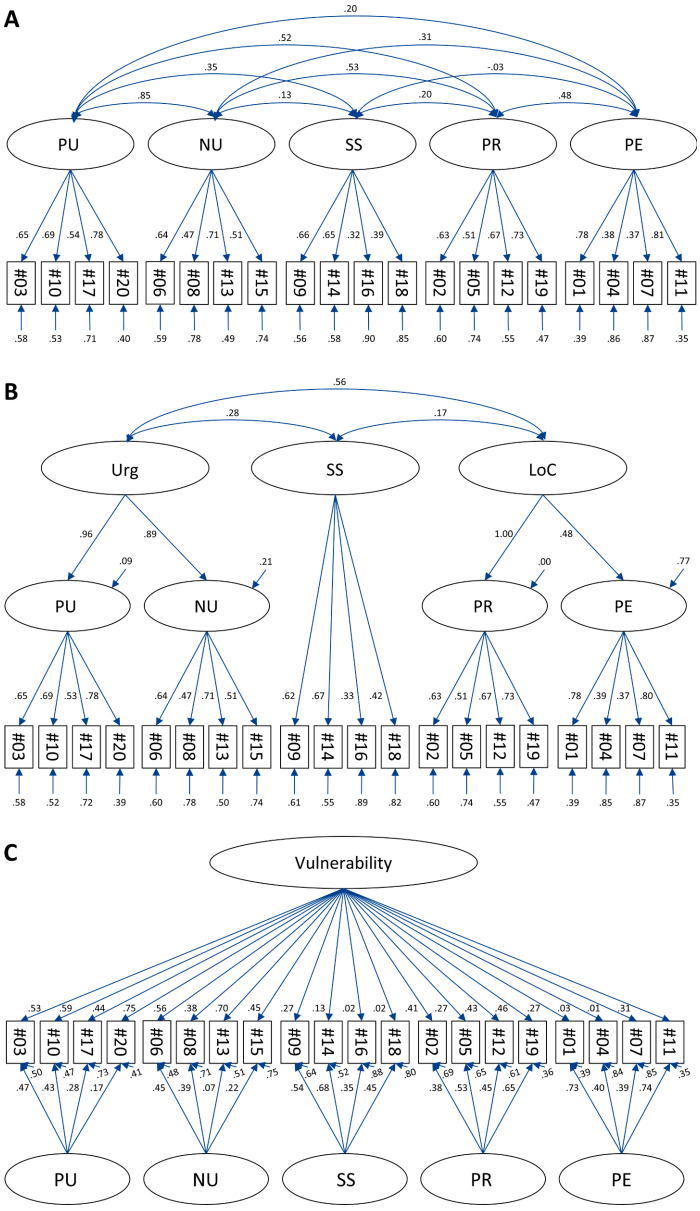


Fig. 3. *The Three Best Factor Models, Including Loadings and Residuals. Note.* (A) Five-factor model with intercorrelated factors (model 1); (B) hierarchical model with three second-order factors (model 5); (C) bifactor model (model 6). Numbers with a preceding # represent item numbers of the Short UPPS-P (Cyders et al., 2014). PU = Positive Urgency; NU = Negative Urgency; SS = Sensation Seeking; PR = Lack of Premeditation; PE = Lack of Perseverance; Urg = Urgency; LoC = Lack of Conscientiousness.

4.1. Structure of the Short UPPS-P

Like previous validation studies in different countries (Cándido et al., 2012; Cyders et al., 2014; Zsila et al., 2020), our study generally replicated the five-factor structure of a short version of the UPPS-P. However, the general model fit of models 1, 5, and 6 was at most acceptable, depending on the concrete fit index, which warrants further discussion. Specifically, several reasons for a lack in model fit should be considered: First, in comparison to Cyders et al. (2014), who used the same items as we did but found partly better model fit indices (especially CFI and TLI) with a weighted least squared mean variance (WLSMV) estimation, we applied an ML estimation, which has a relatively deteriorating impact on

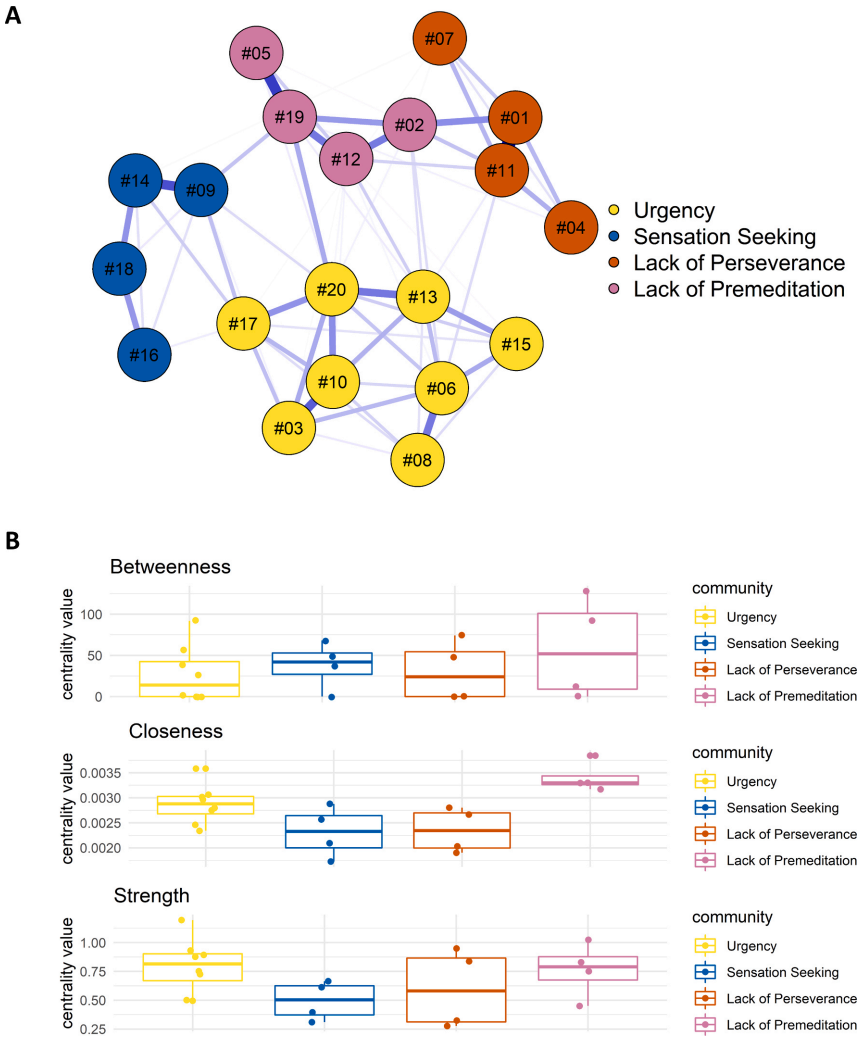


Fig. 4. *Network Model of Impulsive Personality (A) and Centrality Indices of the Detected Communities (B). Note.* Numbers with a preceding # represent item numbers of the Short UPPS-P (Cyders et al., 2014; see Table 1).

various fit indices (see, e.g., Li, 2016; Xia & Yang, 2019). Second, differences in samples concerning age and educational level could play an important role as well. Third, and independently from other studies, post-hoc inspection of the observed covariances of Short UPPS-P items (see supplement C1) revealed relatively low covariances of items reflecting Lack of Perseverance (5 of 6 covariances < 0.30) and Lack of Premeditation (3 of 6 covariances < 0.30), which might be a reason for the relatively low CFI and TLI values (in comparison to low RMSEA and SRMR values). Notably, and consistent with the network analyses, covariances of Lack of Premeditation items with other items were relatively high as compared to other between-construct covariances of items. Finally, standardized residuals and modification indices (supplements C2 to C10) revealed that some covariances are not adequately reproduced by the estimated parameters (models 1, 5, and 6). For instance, especially items #05 ("I like to stop and think things over before I do them.") and #19 ("I usually think carefully before doing anything.") seem to share much unexplained variance, which is probably due to their high similarity. A modified version or other short versions of the UPPS-P might represent a useful alternative for future studies (e.g., Zsila et al., 2020).

With regard to model comparison, however, our study is in line with several studies that found that more than one model fitted the data adequately, notably revealing acceptable to good fits of both first-order five-factor models and hierarchical models with the three higher-order

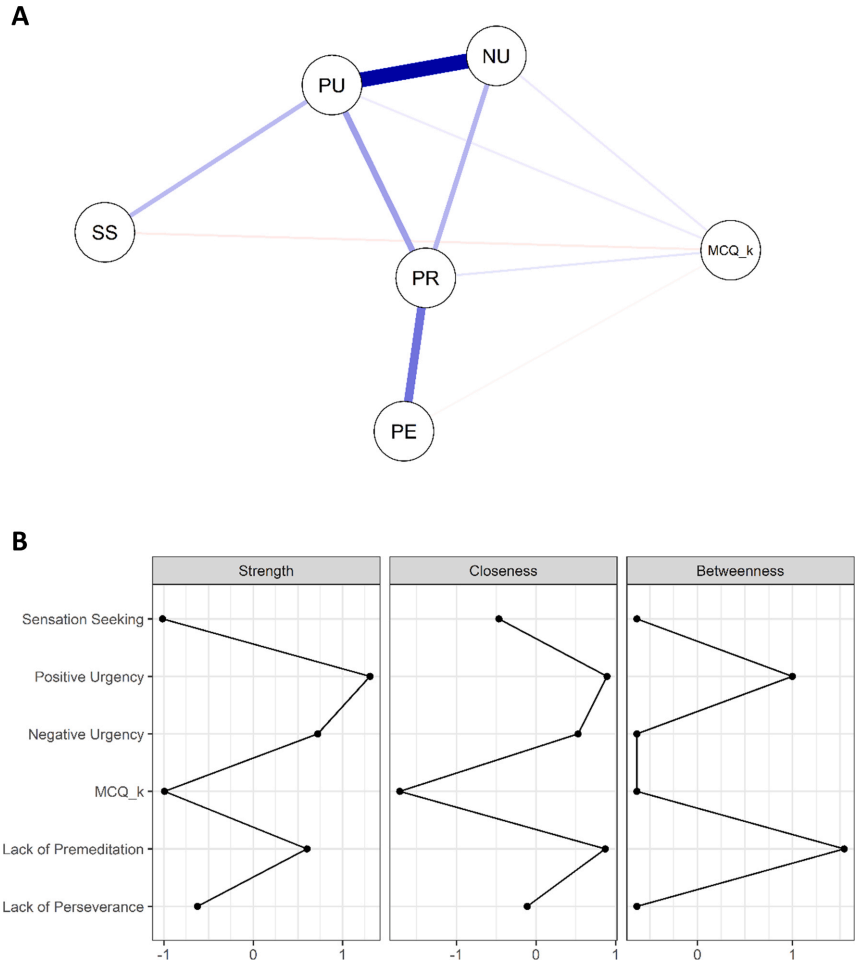


Fig. 5. *Network Model of Short UPPS-P Scales and Temporal Discounting (A) and their Centrality Indices (B). Note.* NU = Negative Urgency; PR = Lack of Premeditation; PU = Positive Urgency; PE = Lack of Perseverance; SS = Sensation Seeking; MCQ_k = log-transformed discount rate based on the Monetary Choice Questionnaire (Kirby et al., 1999).

constructs Urgency, Sensation Seeking, and Lack of Conscientiousness (Cyders et al., 2014; Zsila et al., 2020). This is also the case for the original UPPS-P (Teese et al., 2021). Thus, while the multifaceted nature of impulsive personality has been largely confirmed, some nuances in the UPPS-P model need to be reconsidered to elucidate the structure of impulsive personality constructs and relations amongst them.

Reasons for comparable model fits in different model variations are illustrated by the hierarchical factor model involving three second-order factors as well as by our item-level network analysis: First and foremost, the strong relationship between Positive and Negative Urgency items, which led to a single detected community in the network analysis, might not only indicate a common cause of the constructs (Cyders et al., 2014; Cyders & Smith, 2007), but could also suggest that they are subject to the *jangle fallacy* (two identical or nearly identical constructs are perceived as different because they are named differently; Marsh, 1994). While it has been shown that Positive and Negative Urgency differ from Lack of Premeditation and its interaction with affect (Peterson & Smith, 2019), it remains unclear whether they themselves reflect different constructs. Indeed, the strong association of the two urgencies was not only found in other psychometric studies (Adams et al., 2012; Goh et al., 2020; MacKillop et al., 2016; Settles et al., 2014), but also in their neural profiles (see Johnson et al., 2020, for a recent review). Additionally, they often showed indistinguishable associations with daily life correlates (Rose & Segrist, 2014; Sperry et al., 2018), supporting the idea of a lack of discernability between the constructs. In contrast with those findings, however, a recent genetic association study found that, despite high genetic correlations between Positive and Negative Urgency, a model in which Positive and Negative Urgency are collapsed into a single Urgency factor provided a worse fit than a five-factor model (Gustavson et al., 2020). In view of this inconsistent literature, future

large-scale studies and meta-analyses will be needed to investigate to what extent the two constructs can be differentiated psychometrically, behaviorally and neurally. If the two constructs are in fact distinct and exhibit incremental validity over each other in predicting at least some life outcomes, it might be necessary to adjust some item formulations to increase selectivity.

Furthermore, and as previously suggested (Berg et al., 2015; Cyders & Smith, 2007; Goh et al., 2020), similarities between Lack of Premeditation and Lack of Perseverance also point to crucial overlaps. However, relationships in our data were not as strong as between the two urgencies, in line with other studies (Goh et al., 2020; MacKillop et al., 2016; Teese et al., 2021). Moreover, community detection in our study resulted in separable constructs, and modification indices (supplement C) suggested that only specific items were possibly not distinct (e.g., item #02 "My thinking is usually careful and purposeful."; also see the exploratory factor analysis in Schmidt et al., 2008, Table 2, in which this item loaded comparably strong on the Lack of Perseverance and Lack of Premeditation factors). The separability is also supported by distinct daily life correlates of the two constructs (Smith et al., 2007; Sperry et al., 2018). Thus, while some ambiguous items might need reconsideration or specification, the general separation of Lack of Premeditation and Lack of Perseverance seems necessary and reasonable.

Another reason for comparable model fits might be a common-cause explanation of different constructs subsumed under the term impulsivity. Considering the *p factor* of psychopathology (Caspi et al., 2014; Caspi & Moffitt, 2018), for example, it could be argued that a general vulnerability factor, potentially represented not only in many mental disorders (American Psychiatric Association, 2013) but – to some degree – also in impulsive behaviors in the general population (see continuum assumption; Ettinger et al., 2014; Krueger et al., 2018; Krueger & Markon, 2006), might influence all impulsive actions and thus justify a bifactor model of impulsivity. In line with this, the vulnerability factor in model 6 primarily reflects variance in items assessing Positive Urgency, Negative Urgency, and Lack of Premeditation – the constructs that seem to be most central to impulsivity as well as most consistently related to psychopathology (Berg et al., 2015; Miller et al., 2003). Thus, this model would explain correlations between different impulsivity constructs – at least in part – by a (single) common cause and has, to the best of our knowledge, not been empirically investigated in the impulsivity framework yet.

Next to these common-cause explanations, it is also possible that there are interplays between impulsivity items or constructs. As in the Big Five example "You Can't Like Parties if You Don't Like People" (Cramer et al., 2012, p. 414), there might be similar causal relationships in impulsivity. Considering our item-level network analysis, for example, there might be causal relationships between items #19 and #20 (e.g., if you usually do not think carefully before doing anything, you tend to act without thinking when you are really excited) or between items #09 and #17 (e.g., if you enjoy taking risks, others are shocked or worried about the things you do when feeling excited). However, these potential causal interpretations of our network models are purely explorative and need further evidence by future experimental and longitudinal investigations.

Overall, the current study provides a high-powered replication of the structure of the Short UPPS-P in a German sample, but at the same time reinforces previously raised doubts about the separability of the Urgency constructs and raises questions about potential common causes and/or mutual influences of impulsigenic traits in general.

4.2. Lack of premeditation – The core of impulsivity?

It has been argued that Lack of Premeditation, or disinhibition vs. constraint (Sharma et al., 2014), is, not only by definition (Moeller et al., 2001), but also by its substantial correlations with both self-report and behavioral constructs the feature of impulsivity that influences other impulsivity-related constructs most strongly (Goh et al., 2020; Sharma et al., 2014). As in Goh et al. (2020), this claim is supported by the relatively high centrality indices of Lack of Premeditation in our scale-level network. The interpretation of this result, however, is, in both studies, challenged by the high centrality indices of the two urgencies, which could be overestimated due to their strong relationship to each other (see above, and Goh et al., 2020, for a discussion). Therefore, it is important to note that our study provides two additional important findings that outline the high relevance of Lack of Premeditation. First, the item-level network analysis revealed high closeness centrality of items in the Lack of Premeditation community. Note that this was the highest closeness of all communities despite the fact that the Urgency community included four more items. Thus, the average distance to other features of impulsive personality is lowest in Lack of Premeditation items, revealing a strong connection to other impulsivity-related constructs. Whether this relationship can be interpreted causally or not (see examples above), needs to be investigated in future studies using longitudinal and experimental designs. Second, the relation with the intertemporal choice parameter MCQ-*k* shows that the impact of Lack of Premeditation is not limited to self-report measures, but also plays a role in behavioral tasks. Higher Lack of Premeditation was associated with higher discount rates (though this relation is stronger than those between other constructs and MCQ-*k*, the differences between these relations were not statistically significant). Furthermore, it has to be mentioned that, like in previous studies (Cyders & Coskunpinar, 2011; MacKillop et al., 2016), the relationships between the Short UPPS-P constructs and MCQ-*k* are relatively weak, as illustrated both in Pearson correlations and network analysis. This could, in part, be caused by typical problems when comparing self-report and behavioral data, such as limitations in reliability or differing response processes in different measurement types (Dang et al., 2020). However, effect sizes in this range are not rare and important to investigate (Owens et al., 2020).

In sum, Lack of Premeditation shows the closest relationships with other self-report impulsivity measures both on item- and scale-level and a weak, but significant relationship to an impulsive decision making task. Whether this reflects that Lack of Premeditation is an important causal factor in daily life behavior and psychopathology – maybe even more important than the two urgencies – or reflects more variance of some common cause factor (like a p factor, discussed above), should be evaluated by future studies, which should consider the possible confound of Positive and Negative Urgency.

4.3. Post-hoc power considerations

As our preregistered a priori power analysis referred to the association of Short UPPS-P and temporal discounting, some a posteriori information on power in confirmatory factor analyses and network models is required. First, our sample size ($N = 1000$) as well as ratios of cases to measured variables (i.e., N:p = 1000:20 = 50:1) and of cases to free parameters (e.g., for model 1: N:q = 1000:50 = 25:1) exceeded the values recommended for confirmatory factor analyses by far (for an overview, see Kyriazos, 2018). Additionally, a posteriori power analyses (semPower package in R; Moshagen, 2020) revealed that our sample size was sufficient to reject models 1, 5, and 6 ($df_1 = 160$; $df_5 = 165$; $df_6 = 150$) with an amount of misspecification corresponding to RMSEA = 0.08 on alpha = 0.05 with a power of more than 99.99%. Second, for network analyses, the requirement to "have at least as many observations as the number of parameters" (Epskamp et al., 2017, p. 2) was also exceeded by our study, since for the (larger) item-level network a weight matrix containing 190 parameters was estimated. Furthermore, in addition to the bootstrapping-based stability estimates, we did simulations with the netSimulator function in the bootnet package (Epskamp, Borsboom, et al., 2018) to get estimates of power. The results indicated that, assuming our network to be true, future studies with $N = 1000$ would achieve correlations between our item-level network and estimated networks of about 0.95, a sensitivity of about 0.80 and a specificity of about 0.90. Correlations between the model's centralities would

all be above 0.80. A simulation of our scale-level network yielded similar results (though showing less sensitivity and less stable centrality correlation estimates). For further details, see supplement G.

4.4. Limitations

This study is subject to some limitations which should be considered.

First, data were collected online, which limited the possibility to standardize and control data quality. However, we minimized this problem by applying conservative exclusion criteria (infrequency scale, response speed, control questions).

Second, since our study is one of the first using network analysis within the broad framework of impulsivity, there was no theory about the concrete causal interactions of items and scales, rendering our network approach largely explorative. Given that the stability and generalizability of psychological network models have recently been debated (Borsboom et al., 2017; Forbes et al., 2017a, 2017b, 2021; Funkhouser et al., 2020; Jones, Williams, et al., 2021) and that network analysis in general is a data-driven approach, which often involves estimation of a large number of parameters, the risk of poor reproducibility should be considered (Forbes et al., 2017a; Fried & Cramer, 2017). We tried to counter the potential threat of low accuracy and measurement error (Forbes et al., 2017a) by using bootstrapping-based estimates of stability of network structures (Borsboom et al., 2017; Epskamp, Borsboom, et al., 2018; Jones, Williams, et al., 2021). Nevertheless, to ensure reliability on a broader basis, it is important to engage in open science practices (Borsboom et al., 2017) and replicate findings such as ours in large samples (Lin et al., 2020) and cross-sample validations (Fried et al., 2018).

Third, our design imposes strong limits on causal inference (Guloksuz et al., 2017). However, future studies could build upon studies like the one by Goh et al. (2020) (who already applied a longitudinal design in a smaller sample) and ours to deduce theoretical assumptions on the concrete causal interactions between impulsive behaviors and test them empirically.

Fourth, it should be noted that in the Short UPPS-P (Cyders et al., 2014), all items assessing Lack of Premeditation and Lack of Perseverance are reverse-scored, whereas all other items are positively scored. While our results are in line with previous studies examining correlations within the same constructs but with other UPPS-P versions that also use a few items scored differently (e.g., MacKillop et al., 2016), we cannot rule out the possibility that methodological factors also contribute to the observed structures. This, by the way, is the case for most studies examining self-report impulsivity, as the two most widely used self-report measures (UPPS-P and BIS) assess at least one construct that is mainly measured with reverse-scored items (e.g., non-planning impulsiveness in case of the BIS). This methodological issue could contribute, for instance, to the surprising strength of the association between Positive Urgency and Negative Urgency. Therefore, future studies may wish to construct impulsivity scales that use both positive and negative item wording.

With regard to generalizability, we wish to stress that, although we recruited from across Germany and the distribution of educational level points to a rather good representation of the general German population (see supplement A2), the sample does not include enough male and older participants to be entirely representative of the German population. Also, we cannot rule out that our results primarily apply to non- or subclinical populations, as mean response scores of the Short UPPS-P indicate relatively low rates of impulsivity in our sample. While the aim of this study was not to assess a perfectly representative sample of the (German) general population (e.g., we did not measure any demographic data beyond gender, age, and education), we believe that the sample size and the compatibility with previous findings (Goh et al., 2020; MacKillop et al., 2016) serve as indicators that our findings will also hold in more controlled settings and other Western culture samples. Future large-scale studies will need to apply a concise sampling strategy to ensure representativeness – especially concerning balanced age and gender distributions – and examine specific clinical populations as well. Regarding materials, the Short UPPS-P has been shown to reflect the original version well (Cyders et al., 2014), the MCQ covers different ranges of monetary values (supplement E), and previous studies have shown that discounting of hypothetical and real rewards produce very similar results (Johnson & Bickel, 2002; Matusiewicz et al., 2013). Thus, we expect that our findings will be reproducible with other versions of the UPPS-P and other monetary temporal discounting tasks (e.g., with incentivization) as well. However, given that network analyses in impulsivity research are scarce, replications could consider extending our results to other temporal discounting tasks. We have no reason to believe that the results depend on other characteristics of the participants, materials, or context.

5. Conclusion

The present study represents an important replication and extension of the findings of Goh et al. (2020) in a larger and more widespread sample. It provides new insights into the structure of commonly used measures of impulsive personality and behavior, which can be built upon to investigate common causes and causal interactions between actions termed "impulsive". Ultimately, this could not only benefit impulsivity research by bringing order into the diffuse structure of different constructs related to impulsivity (Strickland & Johnson, 2021) but also open new advances in research into the psychopathology and treatment of mental disorders by determining which features of impulsivity need to be particularly targeted.

CRediT authorship contribution statement

KK, UE, and BP conceptualized the study (conceptualization). KK collected and curated the data (investigation, data curation). KK, UE, CM, and BP analyzed the data (formal analysis), KK and BP visualized the data (visualization). All authors contributed to manuscript writing and revision and read and approved the submitted version (Writing – original draft; Writing – review & editing).

Open practices

The hypotheses, methods, and analysis plan of this study were preregistered at https://osf.io/qmkfc on 22nd June 2020. Study materials, data and analysis scripts used for this article as well as supplemental material can be accessed at https://osf.io/u6vps/.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jrp.2021.104166.

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Corrigendum

Corrigendum to "The network structure of impulsive personality and temporal discounting" [J. Res. Pers. 96 (2022) 104166]

Kristof Keidel [a,b], Ulrich Ettinger [a,*], Carsten Murawski [b], Bertalan Polner [c]

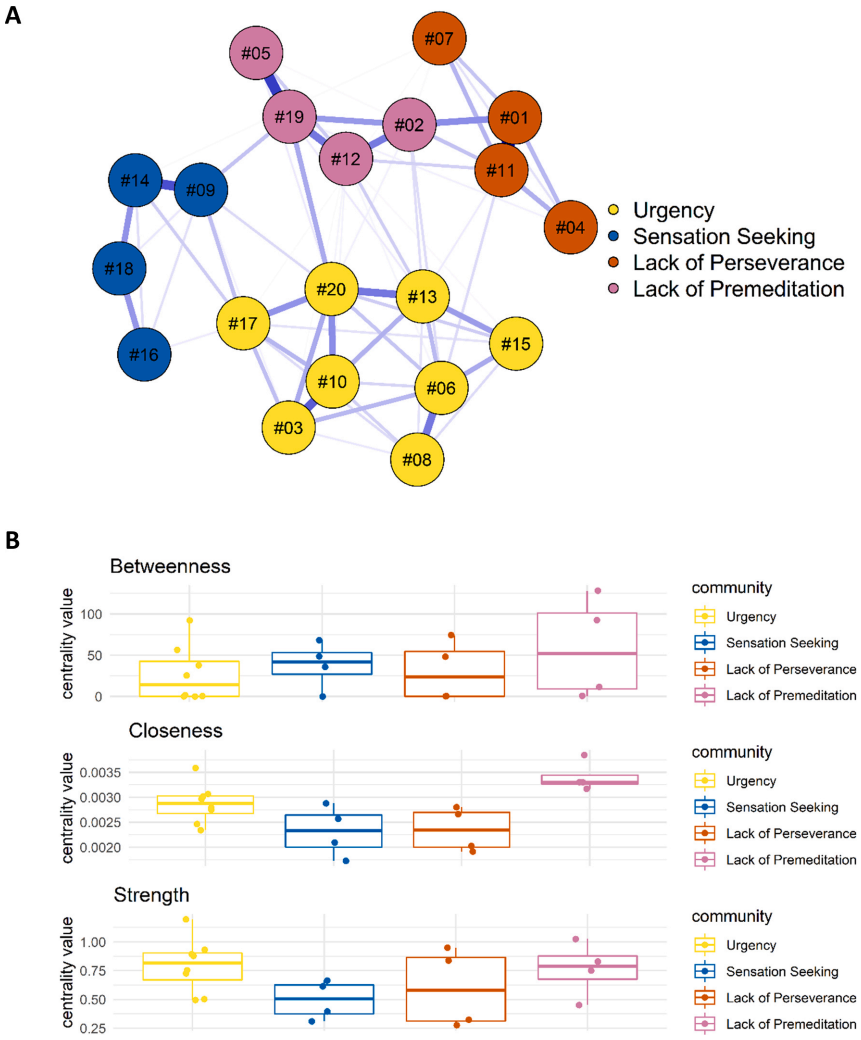
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The authors regret that an error occurred in the display of data in Fig. 4. In Fig. 4B, in the row entitled "Closeness", two additional data points were added to the figure erroneously, one to the plot corresponding to the Urgency scale and one to the plot corresponding to the Lack of Premeditation scale. This error affects only this part of the figure, not the statistics reported in the paper or any of the manuscript text. The authors would like to apologise for any inconvenience caused.

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Appendix B | Study II

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Preregistration: https://osf.io/d9u74
Materials, data and scripts: https://osf.io/td5gf/
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Attentional Mechanisms of the Date/Delay Effect in Intertemporal Choice: An Eye-Tracking Study

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Temporal discounting refers to the tendency to discount future rewards as a function of time until receipt of rewards. The discount rate can be reduced by experimentally manipulating time framing, an example being the date/delay effect: Specifically, if time until receipt of the reward is presented as a date (e.g., August 21, 2022) rather than as a delay (e.g., 136 days), temporal discounting is reduced. While this effect has been replicated several times, its underlying cognitive mechanisms are not well understood. Therefore, we used eye tracking to examine the role of attention in the date/delay effect. Participants completed both a delay and date condition of the Monetary Choice Questionnaire, while eye movements were recorded ($N = 54$). Results revealed a successful replication of the date/delay effect ($p < .001$, $g_{av} = 0.48$). Eye tracking showed that participants compared time attributes (relative to reward attributes) more and fixated them longer in the date compared to the delay condition. Moreover, the absolute difference in reward values of choice options was more predictive of choosing the delayed reward in the date compared to the delay condition. Finally, explorative correlations revealed a stronger date/delay effect in participants who paid more attention to time than reward attributes in the delay condition and who used a more integrative search strategy. Our findings suggest that the date manipulation causes participants to weight rewards more strongly in their decision process than in the delay condition, ultimately reducing temporal discounting. Computation of time intervals in the date condition could possibly reflect an adaptation lowering the date/delay effect.

Keywords: attention, date/delay effect, eye tracking, search strategies, temporal discounting

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22 euros today or 25 euros in 136 days?—Intertemporal choice tasks involving decisions between smaller-sooner and larger-later rewards are commonly used to assess the degree of temporal discounting, that is, the tendency to devalue future rewards as a function of delay until receipt of the reward. Given that temporal discounting is associated with a broad range of life outcomes (Keidel, Rramani, et al., 2021), including economic (Meier & Sprenger, 2010, 2012) as well as physical (Bickel, 2015) and mental health (Amlung et al., 2019) outcomes, it is important to understand to what extent the ways in which choices are presented affect temporal discounting (Rung & Madden, 2018; H. Scholten et al., 2019). One such way is time framing. The so-called date/delay effect refers to the finding that future rewards are discounted less strongly when time periods until receipt of rewards are presented as dates (date condition; e.g., August 21, 2022) compared to time units (delay condition; e.g., 136 days; LeBoeuf, 2006; Read et al., 2005). While the date/delay effect itself is a robust phenomenon (Rung & Madden, 2018), the cognitive mechanisms associated with it are not well understood.

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We gratefully acknowledge intramural funding of this work from the University of Bonn. Additionally, we would like to thank Anna-Luisa Harder and Annika Lingk for their invaluable help in data collection. The authors have no conflicts of interest to declare. The study was preregistered at https://osf.io/a3u54 (Keidel, Murawski, & Ettinger, 2021). Study materials, raw and processed data, analysis scripts, and supplementary materials are accessible at https://osf.io/xrkuf/ (Keidel et al., 2024).

Kristof Keidel served as lead for data curation, formal analysis, investigation, visualization, writing–original draft, and writing–review and editing and contributed equally to methodology. Carsten Murawski contributed equally to formal analysis, project administration, and supervision. Ulrich Ettinger served as lead for project administration and supervision and served in a supporting role for formal analysis. Kristof Keidel, Carsten Murawski, and Ulrich Ettinger contributed equally to conceptualization. Carsten Murawski and Ulrich Ettinger contributed equally to writing–review and editing and validation.

The data are available at https://osf.io/xrkuf/.
The experimental materials are available at https://osf.io/xrkuf/.
The preregistered design is available at https://osf.io/a3u54.

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In this study, we used a behavioral task in combination with eye tracking to examine the computational and attentional mechanisms underlying both the date and delay conditions, aiming to investigate the cognitive strategies associated with the date/delay effect and temporal discounting more generally.

Alternative-Based Versus Attribute-Based Models of Intertemporal Choice

For a long time, studies have modeled intertemporal choices assuming that decisions are based on subjective values of decision options (Frederick et al., 2002). In these alternative-based models, decision makers are assumed to compute a single subjective value for each choice option by integrating the attributes of an option, that is, reward amount r and delay t, using a discount function d (e.g., Ainslie, 1975; Samuelson, 1937). Specifically, the subjective value or utility U of a discounted future reward r_t with delay t is given by $U(r_t; k) = d(t; k)\, u(r_t)$. The discount function d incorporates a discount rate k, for which different forms have been proposed (e.g., exponential, hyperbolic, quasi-hyperbolic; Frederick et al., 2002) and which describes the degree to which the utility u of the future reward r_t is discounted per unit of delay, with higher values resulting in lower present subjective values of future rewards (i.e., more discounting of future rewards; Keidel, Rramani, et al., 2021). Decisions are then driven by the differences in subjective values of the different options, with the option with the highest subjective value being most likely to be chosen. Accordingly, a decision maker will be indifferent between two options S and L if $U_S(r_{t1}; k) = U_L(r_{t2}; k)$. Since it is assumed that values of different attributes within an option are integrated into a single currency, this framework is typically referred to as the "common currency hypothesis" (Levy & Glimcher, 2012). However, this framework has been challenged, for example by questioning the existence of signals in the brain corresponding to the "common currency" (Hayden & Niv, 2021).

An alternative view suggests that decision processes are more adequately reflected by models building upon attribute-wise comparisons (Amasino et al., 2019; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; M. Scholten & Read, 2010). In such attribute-based models, options are compared along each of their attributes (e.g., differences in rewards, differences in delays), and decisions are based on a function which trades off the relative favorability of each of these comparisons. Thus, if a reward difference between options outweighs a time difference between options, the larger-later reward is more likely to be chosen. Otherwise, if a time difference (i.e., a longer interval) between options outweighs a reward difference between options, the smaller-sooner reward is more likely to be chosen. One example of these models is the tradeoff model (M. Scholten & Read, 2010). According to the tradeoff model, differences between weighted delays (effective intervals), $w(t_L) - w(t_S)$, and differences between valued outcomes (effective compensations), $v(r_L) - v(r_S)$, of options are computed. These differences are then scaled with regards to each other and weighted against each other using a tradeoff function Q, and the decision maker will be most likely to choose the option with the higher advantage. The decision maker will be indifferent between options when $Q[w(t_L) - w(t_S)] = v(r_L) - v(r_S)$. Q incorporates among others a scaling parameter κ, with higher values reflecting higher time sensitivity (for details, see M. Scholten & Read, 2010; M. Scholten et al., 2014). While we note that there is a variety of different computational models aiming to capture intertemporal choice behavior (Doyle, 2013). Here, we will primarily address the distinction between alternative- and attribute-based models, since an investigation of the date/delay effect may specifically provide novel insights regarding these model families.

Computational and Attentional Mechanisms of the Date/Delay Effect

The date/delay effect has been replicated several times (e.g., Dshemuchadse et al., 2013; Keidel et al., in press; LeBoeuf, 2006; Naudé et al., 2018; Read et al., 2005; though see Lempert et al., 2016), with medium effect size on average (Rung & Madden, 2018). At present, there is little evidence about the cognitive mechanisms underlying the effect. Different hypotheses are based on differences in the perceived concreteness of response options (construal level theory; Kim et al., 2013; LeBoeuf, 2006; Trope & Liberman, 2003), differences in attentional strategies (Dshemuchadse et al., 2013; LeBoeuf, 2006; Read et al., 2005), influences of subjective time perception (Jiang & Dai, 2021; Zauberman et al., 2009), and the role of emotional valuation (LeBoeuf, 2006; Lempert et al., 2016). In this article, we focus on potential differences in attentional processes between intertemporal choices involving delay units and those involving dates (Dshemuchadse et al., 2013; LeBoeuf, 2006; Read et al., 2005). Specifically, a major difference between the date and the delay conditions is that in the delay condition, rewards and delay units, which are both numerical variables, can be directly integrated to compute discounted values (Ainslie, 1975), while more complex operations would be required to compute discounted values when delays are presented in terms of dates. This could result in different cognitive adjustments made by participants, as suggested by various studies.

First, Read et al. (2005) and LeBoeuf (2006) similarly proposed that while delay units direct the focus on waiting time, dates lead to a stronger focus on the time at which a reward is received and on the reward value at that time. As a consequence, participants might increase the ratio of attention focused on reward relative to time attributes in the date compared to the delay condition (attention-focusing hypothesis). While Read et al. (2005) proposed a direct attentional change (suggesting overt attentional shifts from delays to rewards when options are presented in terms of dates), LeBoeuf (2006) stated that the delay condition "directs attention to the amount of time in an interval, whereas a date condition directs attention elsewhere, such as to the interval's endpoint and to postdelay transactions" (p. 68). The latter statement implies that changes in overt attention are not necessarily observable since attentional changes might only refer to shifts in internal instead of external attention (Chun et al., 2011). In both cases, however, it is assumed that reward information becomes relatively more accessible or vivid in the date condition (LeBoeuf, 2006; Read et al., 2005), so that a higher weight is placed on the difference in rewards than on the difference in delays until receipt of rewards. This in turn leads to comparatively more choices of larger-later rewards, that is, less discounting. On a computational level, such a differing valuation of attribute types would be more directly reflected in attribute-based than alternative-based computational approaches. Specifically, an attentional shift toward and a higher weight put on rewards should lead to a relatively higher valuation of the reward comparison (e.g., reduced time sensitivity in the tradeoff model, as represented in the tradeoff function; M. Scholten & Read, 2010), ultimately residing in

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more choices of the larger-later reward. If this increased processing of rewards is accompanied by changes in overt attention, this should result in increased durations of fixations on reward compared to time attributes in the date compared to the delay condition.

Second, and relatedly, Read et al. (2005) argued that in the date condition, dates would need to be mentally transformed into delay units to apply the same strategy as in the original delay unit condition (e.g., computing discounted values). Hence, participants might use an alternative choice strategy (choice strategy hypothesis). Specifically, Read et al. (2005) proposed that in the date condition, participants might change their cognitive strategy by shifting toward a more attribute-wise (comparative) strategy rather than option-wise (integrative) saccadic strategy (Figure 1; Amasino et al., 2019; Fisher, 2021; Reeck et al., 2017) and decide on the attribute comparison that is considered more important. Thus, in combination with the attention-focusing hypothesis, stronger attentional focus on the attribute-wise reward comparison would ultimately lead to more choices of larger-later rewards, that is, a lower degree of discounting. It should be noted that, while the attention-focusing hypothesis may stand for its own (i.e., a strategy change is not necessarily required for attentional changes per se), the choice strategy hypothesis depends—if not on a change in overt attention toward rewards—at least on a higher weighting of rewards. On a computational level, mental transformations of dates into delay units would enable to follow an option-wise strategy, reflected in alternative-based models, whereas a shift of choice strategy toward a more attribute-wise strategy would be reflected in an attribute-based approach. Specifically, alternative-based strategies would better be captured by traditional approaches of discounted values (e.g., hyperbolic discounting), whereas a shift toward a comparative strategy would—in combination with a relatively higher weighting of the reward comparison (see attention-focusing hypothesis)—lead to higher weightings of the reward comparison compared to the time comparison, resulting in a better fit of attribute-based models (see above; M. Scholten & Read, 2010). Thus, in the context of our study, we would argue that a majority of eye movements between attributes of the same option would provide support of alternative-based models like the "common currency hypothesis" (integration of attributes), whereas a majority of eye movements between the same attributes (e.g., rewards, delays) across options would provide support of attribute-based models such as the tradeoff model. It is therefore of interest to examine whether participants indeed make more attribute-wise saccades in the date compared to the delay condition, thereby following attribute-based models more closely.

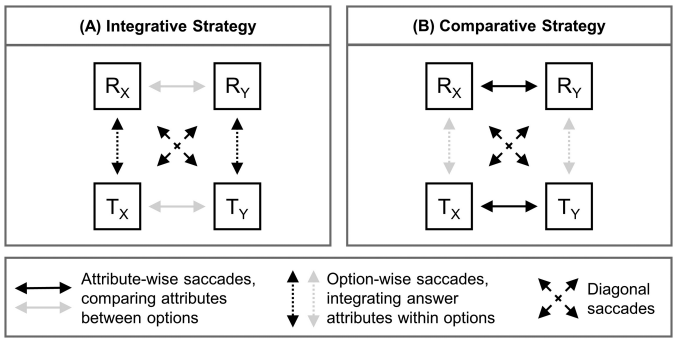
Third, Dshemuchadse et al. (2013) proposed that, due to higher cognitive demands in the date condition (i.e., dates are more complex than delay units), participants might engage in a more deliberate processing mode. That is, the need to adapt to the date format (either through calculations or compensatory strategies) could lead to more reflection time and effort spent on each choice, ultimately resulting in less discounting. Computationally, more deliberation could both be reflected in lowered discount rates or in lowered sensitivity to times, allowing no conclusions regarding alternative- versus attribute-based models.

In sum, some of the proposed attention-related hypotheses explaining effects of the date manipulation are more in line with attribute-based models, while others can also be explained in terms of alternative-based models. So far, however, studies examining attentional mechanisms of the date/delay effect, which may allow to draw conclusions about the computational mechanisms used in intertemporal choices, are scarce.

Visual Attention, Eye Tracking, and the Date/Delay Effect

Visual attention can be defined as the process of focusing on some stimuli of a visual scene while ignoring others, thereby enhancing the processing of objects in view (Goldstein & Brockmole, 2017; Greenlee & Kimmig, 2019). Eye tracking can be applied to investigate overt visual attention, that is, visual attention through eye movements (Findlay & Gilchrist, 2003; Hoffman & Subramaniam, 1995), and

Figure 1
Saccades Between Choice Attributes Used in Intertemporal Choice Tasks



Note. Saccades are represented as arrows between choice attributes, that is, reward (R) and time (T) attributes of two options indexed X and Y. (A) Saccades used in an option-wise, integrative strategy. (B) Saccades used in an attribute-wise, comparative strategy (also see Reeck et al., 2017). Black arrows represent the dominant strategy, while gray arrows represent saccades that are less likely used in the corresponding strategy.

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has been used to infer people's goals and intentions (Tatler et al., 2010; Yarbus, 1967) as well as cognitive processes involved in specific tasks (Rayner, 1998, 2009). Specifically, fixation and saccade metrics have been used to examine how people perform basic everyday tasks ranging from preparing a sandwich (Land & Hayhoe, 2001) to scanning websites (Nielsen & Pernice, 2009) but also higher-level tasks such as decision making (Orquin & Mueller Loose, 2013).

For example, Horstmann et al. (2009) examined differences in intuitive versus deliberate processing modes. They conducted two eye-tracking studies to examine oculomotor differences in instruction-induced intuitive versus deliberative processing modes. While they found no evidence for qualitative differences in information processing, they showed that deliberative processing led to more fixations as well as a more thorough and repeated information search. More recently, eye tracking has been used to explore the role of attentional mechanisms in intertemporal choice, explaining differences in choice behavior by means of longer or more fixations on (Amasino et al., 2019; Fisher, 2021; Franco-Watkins et al., 2016) and saccades between (Reeck et al., 2017; Reppert et al., 2015) specific choice attributes.

While several hypotheses about the cognitive mechanisms underlying the date/delay effect are based on attentional mechanisms (Dshemuchadse et al., 2013; LeBoeuf, 2006; Read et al., 2005), there is no comprehensive study using eye tracking so far to examine both saccades and fixations as oculomotor indices of attention to directly compare delay and date conditions.

However, some prior studies provide indirect support of the attention-focusing and choice strategy hypotheses. Specifically, Dshemuchadse et al. (2013) examined mouse trajectories during intertemporal choices in delay and date conditions. They found that in the interval of 386–648 ms of the choice period, reward value difference predicted mouse trajectory angle more strongly in the date than in the delay condition, indicating that it had a higher impact on choices in the date condition. While this finding is in favor of the attention-focusing hypothesis, there was no evidence for stronger deliberation since curvatures of mouse trajectories did not differ between conditions. Other studies showed that both use of a comparative strategy and fixation times on beneficial attributes in the choice process (i.e., stronger focus on amounts of larger-later options, weaker focus on timings of smaller-sooner options) are predictive of choices of larger-later rewards (Amasino et al., 2019; Fisher, 2021). Thus, ultimately, both a change in search strategy toward attribute-wise comparisons and an attentional shift toward specific attributes appear to accompany reduced temporal discounting.

Focusing on the date/delay effect, Kurokawa and Ohtake (2013) used their findings on saccade trajectories in an intertemporal choice task involving delay units to compare them to the results of Arieli et al. (2011), who had used dates. In accordance with both the choice strategy and the attention-focusing hypothesis, they reported that the date condition leads to a more comparative than integrative strategy as compared to the delay condition. The data reported in their Table 1 suggest that this difference is primarily due to more saccades between the time attributes in the date than in the delay condition. This is in line with a recent secondary finding by S. N. Sharma and Khan (2022)[1] who also did not find a difference between date and delay conditions in the number of saccades made between reward attributes. However, Kurokawa and Ohtake (2013) compared the two conditions using two different studies and S. N. Sharma and Khan (2022) did not find the date/delay effect itself, which is why a replication of the attentional effect is needed. Furthermore, none of these studies focused on how much time was spent looking at the relative attributes in the two conditions (though see Table 3 in S. N. Sharma & Khan, 2022). Most importantly, it is largely unclear whether the proposed mechanisms are associated with lower discount rates in the date compared to the delay condition.

Our Study

In the present study, we aimed to replicate the date/delay effect in intertemporal choice (Read et al., 2005) and examine its attentional mechanisms using eye tracking. Our preregistered hypotheses were as follows.

Generally, we hypothesized that we would observe lower discount rates, that is, less discounting of larger-later rewards, in the date compared to the delay condition (Hypothesis 1).

Moreover, based on the candidate explanations of the date/delay effect in the literature, we made a number of predictions about (oculomotor) behavior: First, if participants indeed adopt a more deliberative processing mode due to the higher cognitive demands in the date compared to the delay condition (i.e., dates are more complex than delay units), this should be observable in reaction times (RTs) as well as in the number of saccades and fixations (Horstmann et al., 2009). Particularly, we expected that in the date condition, participants would show higher RTs and, consequently, a higher total number of saccades and fixations compared to the delay condition (Hypothesis 2a). We also explored (a) whether participants showed a higher extent of information search (i.e., a higher number of saccades within or between areas of interest [AOIs] around choice attributes; Horstmann et al., 2009) and (b) whether increased time spent in the date condition was due to relatively more time spent on all or on specific AOIs. Second, if the date condition leads to a more comparative (rather than integrative) search strategy, as reflected in attribute-based (rather than alternative-based) computational models (Amasino et al., 2019; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; M. Scholten & Read, 2010), the proportion of attribute-wise, horizontal saccades made to compare reward or time information separately (relative to option-wise, vertical saccades made to integrate reward and time information) should be higher in the date condition compared to the delay condition (Hypothesis 2b). We also explored whether this difference depended on the type of horizontal saccade (i.e., between reward or time attributes; Kurokawa & Ohtake, 2013). Third, if there is a change in attentional allocation toward more focus on a specific type of attribute, this should be observable in fixation durations (Goldstein & Brockmole, 2017; Orquin & Mueller Loose, 2013). As the attention-focusing hypothesis (Read et al., 2005) and the hypothesis of stronger deliberation (Dshemuchadse et al., 2013) imply potentially different predictions (attentional hypothesis: longer fixation durations on reward attributes because rewards are more highly weighted; deliberation hypothesis: longer fixation durations on time attributes because of the need to adapt to dates), we formulated an undirected hypothesis: We hypothesized that attentional focus would shift toward either reward attributes or time attributes in the date condition (as compared to the delay condition), as represented by longer mean cumulative fixation durations either on reward or time attributes (Hypothesis 2c). Longer fixation durations on reward (vs. time) attributes in the date compared to the delay condition would be in favor of the attention-focusing hypothesis, while longer fixation

[1] That study was published after submission of our preregistration.

Table 1
Subjective Experiences of Delay Versus Date Conditions

	Delay		Date					
Variable	*M*	*SD*	*M*	*SD*	*t*	*df*	*p*	g_{av}
Mental demand	32.33	20.58	36.23	20.01	−1.75	53	.09	0.19
Frustration	16.14	15.53	17.57	18.37	−0.62	53	.54	0.08
Fatigue	27.26	23.61	27.39	22.62	−0.09	53	.93	0.01
Worry	18.23	21.16	19.43	20.07	−0.57	53	.57	0.06

Note. Ratings (ranging from 0 to 100) are based on continuous scale items presented after the completion of the conditions. The mental demand and frustration items stem from the NASA-TLX (German version; Hart & Staveland, 1988), the fatigue and worry items are based on Hockey (1997). NASA-TLX = National Aeronautics and Space Administration task load index; g_{av} = Hedge's *g*, using the average standard deviation of measurements as standardizer (Lakens, 2013).

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durations on time (vs. reward) attributes would be in favor of the hypothesis of stronger deliberation.

Finally, we hypothesized that eye movement data (saccades and/or fixation durations) would be associated with interindividual differences in the magnitude of the date/delay effect (Hypothesis 3).

Method

Sample

To determine the required sample size, we conducted an a priori power analysis using G*Power 3.1.9.7 (Faul et al., 2009). Specifically, to replicate the date/delay effect (within-subject *t* test), given an effect size of $d_z = 0.45$ (cf., Hedge's *g* according to Rung & Madden, 2018), an alpha level of .05 (two-tailed), and a power of 90%, a sample size of 54 participants was required. Thus, we aimed for 54 participants after application of any exclusion criteria. Data were collected until the intended final sample size was reached.

The study was advertised through personal contacts as well as university mailing lists and online forums. To be eligible to participate in the study, participants had to meet the following inclusion criteria: age between 18 and 40 years, right-handedness, nonsmoker, normal or corrected-to-normal visual acuity (glasses or contact lenses), no current physical or mental illness, and no consumption of medication (exceptions: contraceptives, thyroid medication). Moreover, only participants with complete data (i.e., choice data for all decisions, usable eye-tracking data for at least 20 choices per condition [see the Eye-Tracking Data section],[2] complete questionnaire data) were included in the data analysis. Furthermore, participants whose mean RTs in the intertemporal choice tasks (summarized over all trials) deviated at least 3 *SD*s from the sample mean, as well as participants for whom an estimation of discount rates was not possible, were excluded.

In total, $N = 68$ participants took part. Of these, $N = 5$ were excluded because eye-tracking calibration was unsuccessful, $N = 8$ were excluded because they did not provide usable eye-tracking data in at least 20 trials per condition and $N = 1$ was excluded because their mean RT deviated more than 3 *SD*s from the sample mean. No participant had to be excluded due to unsuccessful estimation of discount rates. Thus, as initially planned, data of $N = 54$ participants were used for analysis.

After completing the intertemporal choice task, and with prior knowledge, participants entered a lottery in which three participants were randomly selected and paid according to the amount and delay of one choice they made in the task. The choice was selected randomly. Additionally, psychology students from the University of Bonn were rewarded with hourly credit for their studies.

Participants in the final sample (31.48% male, 68.52% female) were on average 22.50 ($SD = 3.63$) years old. Given that participants were mainly university students, educational level was generally high (except for one participant without indication of International Standard Classification of Education [ISCED], all participants had at least completed upper secondary education).

Eye-Tracking Experiment

The study was conducted in agreement with departmental ethical regulations and was compliant with the Declaration of Helsinki. After providing written informed consent and generating a pseudonymous code to ensure matching of experiment and questionnaire data, participants first completed two conditions of the Monetary Choice Questionnaire (MCQ; Kirby et al., 1999) during which eye movements were recorded.

MCQ

The MCQ (Kirby et al., 1999) comprises 27 items in which participants choose between a smaller-immediate and a larger-later reward. The task is commonly used to assess temporal discounting and generally shows high test–retest reliability (Kirby, 2009). Participants completed a German version (i.e., € instead of $) of the MCQ in two conditions: one with a delay unit framing (e.g., 22 euros in 0 days vs. 25 euros in 136 days) and one with a date framing (e.g., 22 euros on April 7, 2022 [=today] vs. 25 euros on August 21, 2022). The order of conditions was counterbalanced; the order of trials was randomized within conditions. Positions of smaller-immediate and larger-later rewards (left vs. right side of the screen) were counterbalanced between trials.

Participants were instructed to press the "F" key to choose the option presented on the left side of the screen and the "J" key to choose the option presented on the right side of the screen on a QWERTZ keyboard. Moreover, they were informed about the lottery, told to answer each trial as if it was the one later selected in the lottery and reminded of the current date. Each trial started with

[2] Deviating from our preregistration, we lowered the criterion for eye-tracking data from "all choices" to 20 choices per condition because otherwise, only 26 data sets could have been analyzed.

a fixation cross, which participants needed to fixate for 1,000 ms to proceed to the choice screen. The choice screen was presented until a decision was made. Afterward, a black screen was presented for 500 ms (see Figure 2 for an illustration of a trial).

Subjective Experiences of MCQ Conditions

After each condition of the MCQ, participants were asked to answer four questions about the perceived degree of cognitive demand required and the frustration level felt during the task (from National Aeronautics and Space Administration task load index [NASA-TLX], German version; Hart & Staveland, 1988) as well as about fatigue and worry felt during the task (based on Hockey, 1997). Participants responded on a continuous scale ranging from very low to very high (with 20 visual separators) by clicking on a point on the scale (Supplement A in the online supplemental materials). The scale was coded from 0 to 100, based on the horizontal position of the mouse click.

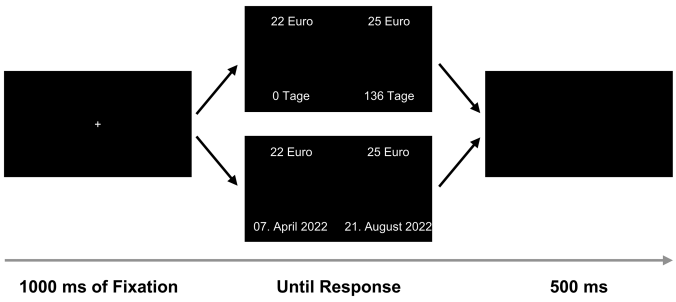
Eye Movement Recording

During completion of the MCQ, horizontal and vertical eye position of the right eye were recorded using an EyeLink 1000 system (SR Research Ltd., Kanata, Ontario, Canada) at 1,000 Hz sampling rate (no head tracking). The EyeLink 1000 uses the video based dark pupil–corneal reflection technique and has an end-to-end sample delay below 1.8 ms on average (SR Research Ltd, 2010). Version 4.40 of the EyeLink host software was used for recording. Participants were seated 70 cm away from a 24-in. BenQ screen (display height: 29.9 cm, width: 53.1 cm; resolution: 1,920 × 1,080 px; refresh rate of 60 Hz during the experiment) in a darkened room, with their head stabilized by a chin and forehead rest. The experiment was programmed and displayed using Experiment Builder (SR Research Ltd., Version 2.3.38). After presentation of the intertemporal choice task instructions, a 9-point horizontal–vertical calibration (grid of 3 × 3 round white targets with a black dot in the middle, presented in random order) with subsequent validation was done using the manufacturer provided routines and default settings. To ensure sufficient spatial accuracy, we aimed to reach a validation classified as "good" (i.e., worst point error below 1.5° and average error below 1° of visual angle) and excluded participants from the study if their validation was not at least classified as "fair" (i.e., worst point error below 2.0° and average error below 1.5° of visual angle; see the Sample section). After successful validation, participants completed the MCQ. Spatial locations of reward and time attributes on the screen were separated in order to ensure clear separation of eye movements.

Stimuli sizes and distances as well as gaze information in this study are stated in degrees of visual angle, calculated based on the position of stimuli on the screen in pixel/mm (relative to the center), screen dimensions in mm and distance from screen in mm. Based on these metrics, the fixation cross, placed in the center (0°, 0°) of the screen, had a width and height of approximately 1.45°. The width of reward attributes was 3.97°, the width of time attributes varied between 3.58° (for the shortest character string, i.e., "0 Tage") and 10.26° (for the longest character string, i.e., "September 11, 2022"). The height of all attributes was 1.37°. The visual angle from screen center to the center of each of the four choice attributes (e.g., "22 euros," "April 07, 2022") was 14.45°.

To determine empirical accuracy and precision of the eye tracker in our experiment, we analyzed the sample data of the first and the last trial of the experiment, focusing only on the last fixation within the fixation cross period. Specifically, for each participant and data sample within the last fixation in the fixation cross period of the two trials, we calculated the mean distance from the center of the fixation cross in visual degrees. We then computed the mean (for accuracy) and standard deviation (for precision) of all data samples within a fixation for both the X and Y coordinates and combined them using the Pythagorean theorem. To obtain measures of accuracy and precision summarized over all participants, we computed means of the combined measures. This analysis yielded the following results: For the first trial, accuracy ranged from 0.09° to 1.62° and was 0.62° on average, while precision ranged from 0.04° to 0.51° and was 0.18° on average. For the last trial, spatial accuracy ranged from 0.07° to 1.69° and was 0.67° on average, while spatial precision ranged from 0.01° to 0.76° and was 0.19° on average. Note, however, that we cannot rule out the possibility that accuracy might be somewhat overestimated in these measures because participants had to fix the fixation cross to proceed and might have adapted the position of their last fixation of the fixation cross period to a certain extent.

Figure 2
Illustration of Trials in the MCQ



Note. In each trial, participants first had to look at a fixation cross for 1,000 ms before the choice screen was displayed. The choice screen (above: example of a delay trial; below: example of a date trial) was presented until the decision was made. Finally, a blank screen was presented for 500 ms. Trials were presented in German (translation: Tage = days). The font size was adjusted for better readability. MCQ = Monetary Choice Questionnaire.

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Questionnaires

Following the experiment, participants completed an online questionnaire on the platform SosciSurvey (https://www.soscisurvey.de/), consisting of demographic questions, the Impulsive Behavior Scale (UPPS-P; Lynam et al., 2006) and the Zimbardo Time Perspective Inventory (ZTPI; Zimbardo & Boyd, 1999).

Demographic Questions

Demographic questions asked participants about their gender, handedness (as control of inclusion criteria), age, and educational level (according to the ISCED; United Nations Educational Scientific and Cultural Organization Institute for Statistics, 2012).

Impulsive Behavior Scale (UPPS-P)

The UPPS-P (Lynam et al., 2006) comprises 59 items and assesses five impulsivity subscales: negative urgency (tendency to act rashly when aroused by negative emotion), lack of premeditation (tendency to act without thinking), lack of perseverance (tendency to easily give up on tasks that are boring or hard), sensation seeking (tendency to seek new and exciting experiences), and positive urgency (tendency to act rashly when aroused by positive emotion). We used the German version of the questionnaire (Schmidt et al., 2008; positive urgency items were translated by us). Participants responded to items on a 5-point Likert scale (0 = *completely disagree*, 1 = *rather disagree*, 2 = *neutral*, 3 = *rather agree*, 4 = *completely agree*). Sum scores were computed for each subscale.

ZTPI

The ZTPI (Zimbardo & Boyd, 1999) comprises 56 items and assesses individual differences in five different time perspectives: future, past positive, past negative, present hedonism, and present fatalism. We used the German version of ZTPI (Reuschenbach et al., 2013). Participants responded to items on a 5-point Likert scale (0 = *very untrue*, 1 = *untrue*, 2 = *neutral*, 3 = *true*, 4 = *very true*). Sum scores were computed for each subscale.

Data Preprocessing

Choice Data

To ensure valid choice data, trials with extreme RT values (i.e., RT $<$ 300 ms or RT $>$ 20,000 ms) were excluded from further analysis.

Eye-Tracking Data

Eye-tracking events were preprocessed according to the default settings in the EyeLink host software. Data reports were generated using Data Viewer (SR Research Ltd., Version 4.2.1). Further preprocessing was done in R (Version 4.2.2) using RStudio (Version 2022.07.2) as follows.

To compute the number of trials per participant for which valid data were available, we checked the following criteria: First, trials had to be answered within a reasonable time (RT as defined above). Second, participants were required to have fixated all of the four attributes displayed, that is, both reward and time attributes of each option. To ensure this, we defined AOIs as rectangles around answer attributes (12.83° visual angle in total in the horizontal frame, 6.51° visual angle in total in the vertical frame), resulting in an AOI each for the smaller-immediate reward attribute, larger-later reward attribute, smaller-immediate time attribute and larger-later time attribute. We checked whether all AOIs had been fixated at least once in a trial (eye movements were classified as saccades and fixations based on the default settings of the EyeLink host software). If participants did not meet these criteria for at least 20 trials per condition, they were excluded from data analysis. In total, 8 participants were excluded based on this criterion (usable trials: M = 33.33%, SD = 33.96%). The remaining 54 participants had usable eye-tracking data in 97.26% (SD = 4.22%) of trials on average, with no significant difference between delay (M = 97.19%, SD = 4.93%) and date condition (M = 97.33%, SD = 5.36%), $t(53) = -0.17$, $p = .86$, $g_{av} = 0.02$. Within the decision periods of the usable trials, on average, 1.37% (SD = 3.28%) of data per participant was lost due to blinks. Proportional data loss due to blinks was significantly higher in the date (date: M = 1.60% SD = 1.90%) than in the delay condition (delay: M = 1.18%, SD = 1.34%), $t(53) = 2.85$, $p = .006$, $g_{av} = 0.26$, potentially due to the higher RTs in the date condition (see the Deliberation section). As planned in our preregistration, blinks were excluded from fixation data.

To obtain measures of the visual search strategies used, we computed means of the frequency of horizontal, attribute-wise saccades (i.e., transitions between the two reward or the two time attributes) and vertical, option-wise saccades (i.e., transitions between reward and time attribute of one of the two options) between AOIs per trial for each condition in each participant. Note that these measures were computed based on the fixation data (i.e., first and last fixations of an AOI focus), since we were not interested in characterizing the details of saccades between AOIs, for example, whether there were blinks during a saccade or several saccades were made for a transition, but only in start and end AOIs of a transition. Thus, it could be the case, for example, that a participant made a blink or several saccades in an AOI transition (though this should only rarely be the case), which would affect a measure of saccadic frequency between AOIs but not the fixation data within an AOI. Diagonal saccades (i.e., transitions between the reward attribute of one and time attribute of the other option) were excluded from analyses concerning visual search strategies, as they may be part of both comparative and integrative search (Figure 1).

Moreover, to obtain summary measures of fixation duration, we computed mean cumulative fixation durations on AOIs per trial in each condition and each participant (i.e., for each participant, fixation durations within an AOI were summed over all valid trials and divided by the number of valid trials). These measures were either computed over each of the two reward or time AOIs, respectively, or for each of the four AOIs separately.

Finally, we used the summary measures to calculate indices of eye-tracking behavior. First, for both conditions, we computed the Payne index (Payne, 1976),[3] which represents the proportion of

[3] The Payne index (Payne, 1976) slightly deviates from the index we planned to compute in our preregistration in that it is computed as the ratio between the difference of vertical and horizontal eye movements and the sum of vertical and horizontal eye movements instead of the ratio of horizontal eye movements alone and the sum of horizontal and vertical eye movements. However, given that these indices are linearly transferrable, they ultimately yield the same results. Following a reviewer comment, we decided to present results based on the Payne index here (and also for the index of relative reward vs. time attribute) to provide better comparability with previous studies.

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vertical saccades relative to horizontal saccades in a range of −1 to 1, where more negative values indicate a higher relative proportion of horizontal saccades and more positive values indicate a higher relative proportion of vertical saccades. Second, again for both conditions, we computed the proportions of mean cumulative fixation durations on reward attributes relative to mean cumulative fixation duration on time attributes in an analogous way to the Payne index (as was done similarly in a previous study, see Formula 4 in Amasino et al., 2019). Thus, the range of this measure was also −1 to 1, with more negative values indicating a higher relative proportion of time focus and more positive values indicating a higher relative proportion of reward focus. To obtain single indices of differences in strategies and attentional allocations on reward versus time attributes between conditions, we computed two difference measures of eye movement behavior, that is, we subtracted the Payne index in the conditions from each other and the relative reward focus in the conditions from each other (both date minus delay).

Transparency and Openness

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. The study's design, hypotheses, and analysis plan were preregistered at https://osf.io/a3u54. Study materials, raw and processed data, analysis scripts, and supplementary materials are accessible at https://osf.io/xrkuf/.

Statistical Analyses

Statistical analyses were conducted in R (Version 4.2.2) using RStudio (Version 2022.12.0). For Bayesian inference, we used RStan (Version 2.26.1).

Estimation of Discount Rates

Bayesian hierarchical modeling was used to estimate separate discount rates for each condition (e.g., Vincent, 2016). Specifically, we estimated the natural logarithm of discount rate k, $\ln(k)$, assuming (a) an exponential, (b) a hyperbolic, and (c) a quasi-hyperbolic discount function. Each participant's (individual-level) parameters, that is, $\ln(k)$ and the logarithm of the softmax parameter, $\ln(\beta)$, were assumed to be drawn from common group-level distributions. For example, for participant i, the parameters were defined as $\ln(k_i) \sim \text{normal}(\mu_k, \sigma_k)$ and $\ln(\beta)_i \sim \text{normal}(\mu_\beta, \sigma_\beta)$. The model allowed for separate values of $\ln(k)$ for the two conditions. The priors for the group-level parameters were estimated using a previous study by our group of the date-delay effect using the same task and a large sample ($N = 1{,}000$; Keidel et al., in press): normal(−6, 1) for μ_k, normal(1.5, 1) for σ_k, normal(0, 1) for μ_β and σ_β. Individual discount rates were computed based on the mean of the posterior distributions of individual-level discount rates, $\ln(k_i)$. We used leave-one-out cross-validation (LOO-CV; Vehtari et al., 2017) to identify the best-fitting model.[4] This analysis revealed that the hyperbolic function had the best fit. We note that we additionally estimated an attribute-based model, that is, the tradeoff model (M. Scholten & Read, 2010). Comparison of the widely applicable information criterion and LOO-CV revealed that it fitted our data less well than the hyperbolic model. For further analyses, we therefore used $\ln(k)$ based on the hyperbolic model. An index of the date/delay effect (date premium) was calculated by subtracting $\ln(k)$ of the delay condition from $\ln(k)$ of the date condition (i.e., lower values represent a stronger date/delay effect).

Inference Testing

First, to test whether the date/delay effect was replicated, we computed 95% highest density intervals (HDIs) of the estimated log-transformed discount rates and determined with which probability their paired differences (i.e., the date premiums) differed from 0 using the Bayesian Estimation Supersedes the *t*-test approach (Kruschke, 2013) for paired samples implemented in the Bayesian First Aid package in R (Bååth, 2014). We also carried out a frequentist within-subject *t* test of the two-point estimates of mean discount rates in the two conditions. Moreover, we ran four additional within-subject *t* tests on data from NASA-TLX and the items based on Hockey (1997) to test for differences in subjective experiences between conditions. For these and all further within-subject *t* tests, Hedge's g_{av} was calculated as effect size, using the average standard deviation of measurements as standardizer (Lakens, 2013).

Second, we conducted three within-subject *t* tests to determine whether RT, number of saccades and number of fixations differed between conditions. Due to multiple testing, *p* values were Bonferroni-Holm corrected. In nonpreregistered exploratory analyses, we used further within-subject *t* tests to examine whether the conditions differed in the number of saccades made between AOI and within AOI. Additionally, we ran $2 \times 2 \times 2$ (condition: date vs. delay; attribute type: reward vs. time; option: smaller-immediate vs. larger-later option) repeated-measures analyses of variance (ANOVAs) to explore differences in fixation number, saccade number and mean cumulative fixation duration between conditions with respect to each AOI (i.e., each combination of attribute type and option). For this and all further ANOVAs, partial eta-square (η_p^2) was calculated as effect size and significant effects were examined using Bonferroni-Holm corrected post hoc within-subject *t* tests. Afterward, we tested whether the Payne index and the frequency of saccades in horizontal and vertical directions separately differed between conditions using within-subject *t* tests.[5] As additional nonpreregistered exploratory analyses, we ran further within-subject *t* tests to explore the differences in transition proportions with respect to each of the four direction types (horizontal between reward attributes; horizontal between time attributes; vertical between smaller-immediate option attributes; vertical between larger-later option attributes). Then, we examined whether the date condition shifted the overt attentional focus between reward versus time attributes by conducting another

[4] Unlike specified in the preregistration, we did not compute Bayes factors for model comparison but used LOO-CV because LOO-CV appears to yield the best-approximating model as well as the most accurate parameter estimations (Lartillot, 2023).

[5] In our preregistration, we had initially planned to conduct a 2×2 repeated-measures ANOVA (condition: date vs. delay; direction: horizontal vs. vertical) to analyze the Condition × Direction interaction effect. However, following comments in the review process, we decided that a traditional ANOVA approach was not appropriate, given that saccade direction had not been experimentally manipulated. We note, however, that examining the difference measures such as the Payne index as dependent variable in a within-subject *t* test yielded similar results as the interaction in an ANOVA.

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2×2 repeated-measures ANOVA (condition: date vs. delay; attribute type: reward vs. time) with mean cumulative fixation durations as dependent variable.

Third, to determine whether the strategy and attentional changes were associated with the magnitude of the date/delay effect, we regressed the individual estimates of the date premium on the two difference measures. In a nonpreregistered analysis, we added difference in RT (date minus delay) as additional predictor. Then, in another nonpreregistered analysis, we ran a logistic mixed-effects model to explore whether choice behavior (0 = *smaller-immediate* vs. 1 = *larger-later reward*) was predicted by differences in absolute values of attributes in the two conditions, and whether this interacted with condition (i.e., differences in reward attributes [Δreward], differences in time attributes [Δtime] and condition as well as their interactions were included as fixed factors and participants as random factor). As there was a significant interaction with condition, we ran separate analyses for each condition to determine the source of this effect. Then, following a reviewer's comment, we set up two nonpreregistered mediation models (based on mixed-effects regressions) to examine whether the relationship between condition (0 = *delay*, 1 = *date*) and choice behavior (0 = *smaller-immediate reward*; 1 = *larger-later reward*) was mediated by the eye-tracking difference measures (Model 1 mediator: Payne index, i.e., relative proportion of vertical saccades; Model 2 mediator: relative reward focus). Finally, as indicated in our preregistration, we explored associations between temporal discounting, the date/delay effect and various study variables. Specifically, we computed Pearson correlations between the following variables for the two conditions and the difference measures of the two conditions: (a) discount rates, (b) mean RTs, (c) RT variability relative to the individual mean RT (intraindividual coefficient of variation, i.e., SD/M), (d) proportions of vertical (relative to horizontal) saccades (Payne index), and (e) proportions of mean cumulative fixation durations on reward (relative to time) attributes. Additionally, we computed Pearson correlations between discount rates in the two conditions (and the date premium) and the UPPS-P and ZTPI subscales.

Results

Date/Delay Effect

The 95% HDIs of the posteriors of the estimated log-transformed discount rates were [−6.19, −5.51] in the date and [−5.66, −4.82] in the delay condition. The mean paired difference (median) between the estimates was −0.63 with a 95% HDI of [−0.83, −0.45]. It had a probability of more than 99.9% to be below 0, thereby providing strong evidence for reduced temporal discounting in the date compared to the delay condition. Similarly, a frequentist within-subject t test comparing $\ln(k)$ between date ($M = -5.85$, $SD = 1.16$) and delay ($M = -5.21$, $SD = 1.48$) conditions showed that discount rates were significantly lower in the date compared to the delay condition, $t(53) = -6.99$, $p < .001$, $g_{av} = 0.48$, replicating the date/delay effect. Descriptive statistics indicated that nearly all participants showed the date/delay effect in the expected direction (Supplement B in the online supplemental materials).

Nonpreregistered, explorative within-subject t tests of subjective ratings of cognitive demand, frustration, fatigue, and worry did not reveal any significant differences between conditions (Table 1).

Attentional Measures

Deliberation

To examine whether participants showed higher deliberation in the date compared to the delay condition, we compared RTs as well as total numbers of fixations and saccades between conditions. Preregistered analyses revealed that RTs were higher in the date ($M = 4.36$ s, $SD = 1.62$ s) than in the delay condition ($M = 3.63$ s, $SD = 1.16$ s), $t(53) = 5.11$, $p_{adj} < .001$, $g_{av} = 0.52$. The same was true for the number of saccades (date: $M = 15.15$, $SD = 4.96$; delay: $M = 12.28$, $SD = 3.30$), $t(53) = 6.69$, $p_{adj} < .001$, $g_{av} = 0.69$, and number of fixations (date: $M = 16.03$, $SD = 4.95$; delay: $M = 13.15$, $SD = 3.30$), $t(53) = 6.70$, $p_{adj} < .001$, $g_{av} = 0.69$.

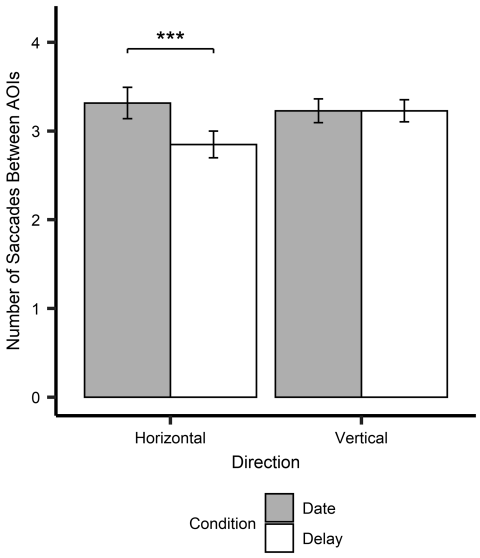
However, since these measures could reflect both longer deliberation as well as higher reading requirements in the date compared to the delay condition (i.e., in our experiment, dates comprised three components while delays only comprised two), we conducted further nonpreregistered exploratory analyses. Specifically, to examine whether participants had indeed deliberated more in the date than in the delay condition, we tested (a) whether the higher number of saccades in the date condition was due to relatively more saccades between AOIs (representing higher deliberation through more information search) or within AOI (representing either higher deliberation or higher reading requirements or both) and (b) whether the increased time spent in the date condition was due to relatively more time spent on all or on specific AOIs (such as time attributes). Results revealed that, while the number of saccades within AOIs differed significantly between conditions (date: $M = 6.44$, $SD = 3.20$; delay: $M = 4.05$, $SD = 2.02$), $t(53) = 9.27$, $p < .001$, $g_{av} = 0.91$, the overall number of saccades between AOIs did not (date: $M = 6.73$, $SD = 1.85$; delay: $M = 6.40$, $SD = 1.42$), $t(53) = 1.71$, $p = .09$, $g_{av} = 0.20$. Moreover, analyses of the differences in the number of saccades, the number of fixations and fixation time spent within AOIs revealed that the overall differences were primarily due to increased time spent on time attributes in the date condition (Supplements C1–C6 in the online supplemental materials). Overall, these results do not lend support to the deliberation hypothesis.

Search Strategies

Next, we investigated whether the frequency of saccades in different directions (horizontal vs. vertical) differed between conditions (date vs. delay; Figure 3). A within-subject t test revealed that the Payne Index, that is, the proportion of vertical compared to horizontal saccades, was lower in the date than in the delay condition, $t(53) = -4.20$, $p < .001$, $g_{av} = 0.33$. To examine this effect more closely, we compared the frequency of vertical and horizontal saccades made in the two conditions in separate Bonferroni–Holm corrected t tests. Results revealed that the number of horizontal saccades was higher in the date compared to the delay condition, $t(53) = 5.20$, $p_{adj} < .001$, $g_{av} = 0.39$, while the number of vertical saccades did not differ significantly between conditions, $t(53) = 0.00$, $p_{adj} > .99$, $g_{av} = 0.00$.

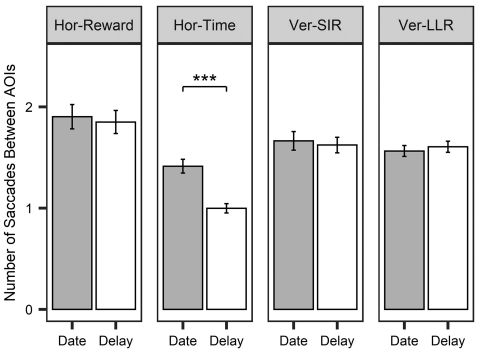
Additional Bonferroni–Holm corrected t tests differing between all possible horizontal and vertical saccade directions between AOIs (horizontal between reward attributes, horizontal between time attributes, vertical between smaller-immediate attributes, vertical between larger-later attributes; Figure 4), revealed that, when comparing the date and delay conditions, the number of saccades

Figure 3
Mean Number of Horizontal and Vertical Saccades Between AOIs per Trial in Date Versus Delay Conditions



Note. Error bars represent standard errors of the mean. Only significant differences between date versus delay conditions within the same direction type are indicated by asterisks. AOI = area of interest.
*** $p_{adj} < .001$.

Figure 4
Mean Number of Saccades Between AOIs per Trial, Separated by Direction Type and Condition



Note. Error bars represent standard errors of the mean. Only significant differences between date versus delay conditions within the same direction type are indicated by asterisks. AOI = area of interest; Hor-Reward = horizontal saccades between reward attributes; Hor-Time = horizontal saccades between time attributes; Ver-SIR = vertical saccades between attributes of smaller-immediate option; Ver-LLR = vertical saccades between attributes of larger-later option.
*** $p_{adj} < .001$.

between AOIs only differed for horizontal eye movements between time attributes, $t(53) = 7.55$, $p_{adj} < .001$, $g_{av} = 0.99$, but not for the other three directions (all $p_{adj} > .05$). Thus, the difference between conditions in horizontal saccades was solely due to a higher proportion of horizontal transitions between time attributes in the date compared to the delay condition, lending support to the choice strategy hypothesis.

Attentional Focus

We then tested for differences in mean cumulative fixation durations on different attribute types (reward vs. time) between conditions (delay vs. date; Figure 5). A 2×2 repeated-measures ANOVA yielded a significant Condition × Attribute Type interaction, $F(1, 53) = 125.62$, $p < .001$, $\eta_p^2 = .70$, a significant main effect of condition, $F(1, 53) = 22.54$, $p < .001$, $\eta_p^2 = .30$, and a significant main effect of attribute type, $F(1, 53) = 54.25$, $p < .001$, $\eta_p^2 = .51$. Bonferroni–Holm corrected post hoc t tests revealed that in the delay condition, reward attributes were fixated significantly longer than time attributes, $t(53) = 12.42$, $p_{adj} < .001$, $g_{av} = 1.37$, and that time attributes were fixated significantly longer in the date compared to the delay condition, $t(53) = 8.82$, $p_{adj} < .001$, $g_{av} = 1.16$ (all other $p_{adj} > .05$). Additional analyses, exploring effects of the manipulation on fixation durations on each of the four AOIs (Supplements C5 and C6 in the online supplemental materials), revealed that the higher mean cumulative fixation durations on time attributes in the date compared to the delay condition applied to both the smaller-immediate and larger-later options. Moreover, when comparing mean cumulative fixation durations on options, participants spent more time fixating both options in the date condition, aligning with results outlined in the Deliberation section, and the difference between conditions was slightly higher for the smaller-sooner than the larger-later option. These results are in agreement with the deliberation hypothesis or could be due to higher reading requirements in the date condition.

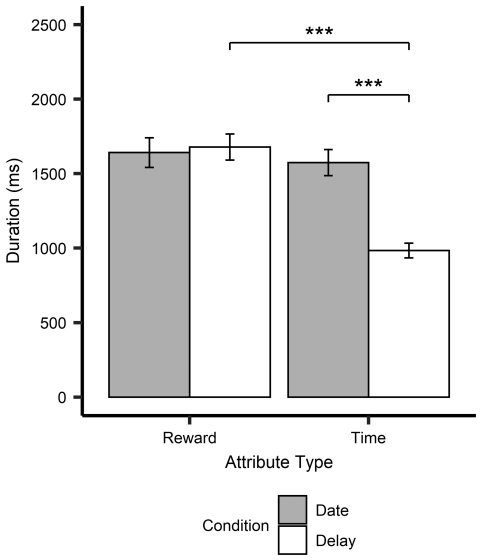
Prediction of the Date/Delay Effect

To test whether the magnitude of within-subject changes in oculomotor behavior between conditions contributes to between-subject differences in the magnitude of the date/delay effect, we regressed the date premium on the difference measures of the relative proportion of vertical saccades and the relative proportion of mean cumulative fixation durations on reward attributes. The linear regression did not yield any significant associations (Table 2). In a nonpreregistered explorative analysis, we also added a difference measure of RT as predictor, which did not significantly change the results (Table 2).

Since the predictor of the relative proportion of mean cumulative fixation durations on reward attributes did not achieve significance ($p = .06$), we ran a logistic mixed-effects model to explore whether choice behavior (0 = *choice for smaller-immediate reward*; 1 = *choice for larger-later reward*) was predicted by condition and differences in absolute reward (Δreward) and time (Δtime) values as well as their interactions. As displayed in Table 3 (for predicted values [marginal effects]; see Supplement D1 in the online supplemental

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Figure 5
Mean Cumulative Duration of Fixations on Reward Versus Time AOIs, Separated by Condition



Note. Error bars represent standard errors of the mean. AOI = area of interest.
*** $p_{adj} < .001$.

materials), we found that a higher difference in absolute reward values (Δreward) and a lower difference in absolute time values (Δtime) predicted a higher probability of choosing the larger-later reward, as may be expected. Importantly, the Condition × ΔReward interaction was significant. Separate analyses of the conditions (Supplements D2 and D3 in the online supplemental materials) revealed that Δreward was a stronger predictor in the date than in the delay condition. A significant Condition × ΔReward × ΔTime interaction showed that this effect is particularly strong when Δtime is higher. This means that the absolute difference in reward values is more predictive of choosing the larger-later reward in the date than in the delay condition, especially when the difference in time values is higher.

Moreover, we set up two mediation models to test whether the relationship between condition and choice behavior found in the logistic-mixed model regression would be mediated by the eye-tracking difference measures (Model 1 mediator: Payne index, i.e., relative proportion of vertical saccades; Model 2 mediator: relative reward focus). In the single regressions of the mediation, we expectedly found a significant association of condition and the respective eye-tracking measure ($a_{m1} = -.21$, $p < .001$; $a_{m2} = -.93$, $p < .001$) as well as significant associations between condition and choice behavior ($c_{m1} = .29$, $p < .001$; $c_{m2} = .30$, $p = .001$). However, as in our linear regressions examining the date/delay effect, the eye-tracking measures were not significantly related to the choice behavior ($b_{m1} = -.04$, $p = .40$; $b_{m2} = -.01$, $p = .87$). While traditional approaches recommend to stop mediation analyses here (Baron & Kenny, 1986), more recent research proposes to focus on the indirect mediation effect (Zhao et al., 2010), which is why we present the mediation results in Supplement E in the online supplemental materials. Of note, only the direct and total effects of the models were significant, while the indirect effects were not. Thus, the association between condition and choice was not significantly mediated by eye-tracking measures.

Finally, we conducted preregistered explorative correlational analyses to examine associations between temporal discounting, eye movement and questionnaire variables and the date/delay effect (Tables 4 and 5). We found that the date/delay effect was higher for participants who (a) had higher discount rates in the delay condition, $r(52) = -.65$, $p < .001$, but not the date condition, $r(52) = -.25$, $p = .07$, (b) had lower RTs in the date condition, $r(52) = .27$, $p = .046$, as well as those who had lower RTs in the date compared to the delay condition, $r(52) = .27$, $p = .049$, (c) showed a lower coefficient of variation in RTs in the delay, $r(52) = .30$, $p = .03$, or date condition, $r(52) = .32$, $p = .02$, (d) followed a more integrative search strategy,

Table 2
Multiple Linear Regression Results Predicting the Magnitude of the Date/Delay Effect by Difference Measures of Eye Movements

Variable	*B*	95% CI for *B* LL	95% CI for *B* UL	*SE B*	β	*p*	R^2
Total model (two predictors)							.075
Constant	−0.987	−1.443	−0.530	0.228	—	—	
D(% AOI ch_{ver})	0.434	−0.889	1.757	0.659	.09	.51	
D(% Fix_{rewdur})	−1.601	−3.296	0.095	0.845	−.26	.06	
Total model (three predictors)							.125
Constant	−1.097	−1.565	−0.630	0.233	—		
D(% AOI ch_{ver})	0.008	−1.386	1.401	0.694	.00	.99	
D(% Fix_{rewdur})	−1.447	−3.122	0.229	0.834	−.23	.09	
D(% RT)	0.157	−0.028	0.342	0.092	.24	.09	

Note. All *D*(*x*) represent difference measures and are computed as difference of the given variables (date–delay). CI = confidence interval; LL = lower limit; UL = upper limit; % AOI ch_{ver} = proportion of vertical saccades (relative to horizontal saccades) between areas of interest; % Fix_{rewdur} = proportion of mean cumulative fixation duration on reward attributes (relative to time attributes); RT = reaction time.

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Table 3
Logistic Mixed-Model Regression on Choice by Attribute Differences

Variable	*B*	*SE*	*p*
Constant	0.75	0.42	.08
Condition	0.93	0.14	<.001
ΔReward	2.42	0.24	<.001
ΔTime	−2.89	0.22	<.001
Condition × ΔReward	0.64	0.22	.005
Condition × ΔTime	0.33	0.20	.09
ΔReward × ΔTime	0.43	0.28	.12
Condition × ΔReward × ΔTime	0.47	0.23	.04

Note. Choices are coded 0 for *smaller-immediate* and 1 for *larger-later rewards*. Condition (effect coded: $-1 = delay$, $1 = date$), difference in reward, and difference in time are modeled as fixed effects. Random effects for participants are included for the constant.

that is, made relatively more vertical, option-wise compared to horizontal, attribute-wise saccades between AOIs in the delay, $r(52) = -.50$, $p < .001$, or date condition, $r(52) = -.50$, $p < .001$, and (e) looked shorter at reward relative to time attributes in the delay condition, $r(52) = .50$, $p < .001$.

Additionally, participants who used a more comparative strategy in the delay condition showed relatively longer mean cumulative fixation durations on rewards in the delay condition, $r(52) = -.58$, $p < .001$, while this correlation did not reach significance for the date condition, $r(52) = -.27$, $p = .051$. Moreover, use of a more integrative strategy in the date condition was significantly associated with the difference measure of attentional focus, $r(52) = .28$, $p = .04$, showing that a more integrative strategy was associated with a relatively stronger focus on rewards in the date compared to the delay condition. Regarding questionnaires, a significant relationship of the date/delay effect with the past negative scale of the ZTPI emerged, $r(52) = .29$, $p = .03$, indicating that higher values on the past negative scale were associated with a weaker date/delay effect.

Discussion

In this study, we used eye tracking to investigate the attentional mechanisms underlying the date/delay effect in intertemporal choices. The date/delay effect was successfully replicated, and detailed analyses of RT and eye movement data revealed crucial insights into the cognitive strategies used in the two conditions.

Replication of the Date/Delay Effect

The replication of the date/delay effect (confirmation of Hypothesis 1) is consistent with a number of previous studies (Dshemuchadse et al., 2013; Keidel et al., in press; LeBoeuf, 2006; Naudé et al., 2018; Read et al., 2005). The effect size in our study ($g_{av} = 0.48$) was comparable to the medium effect size reported in a meta-analysis of studies of the date/delay effect (Rung & Madden, 2018), and descriptive statistics indicated that the effect was almost universal in our sample. Interestingly, participants did not rate conditions significantly differently in terms of experienced mental demand, frustration, fatigue, or worry, suggesting that they did not subjectively experience the two conditions in a different way. It should be noted, however, that the comparison of mental demand yielded a *p* value of .09, warranting further

Table 4
Descriptive Statistics of and Correlations Between Temporal Discounting and Eye Movement Variables

Variable	*M*	*SD*	Sk	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Ln(k) delay	−5.21	1.48	−0.02	—													
2. Ln(k) date	−5.85	1.16	0.10	.90***	—												
3. D(ln(k))	−0.64	0.67	−0.37	−.65***	−.25	—											
4. M_{RT} delay (s)	3.63	1.16	0.16	−.27*	−.27*	.14	—										
5. M_{RT} date (s)	4.36	1.62	0.65	−.32*	−.25	.27*	.77***	—									
6. D(M_{RT})	0.73	1.04	0.78	−.20	−.10	.27*	.08	.70***	—								
7. CV_{RT} delay	0.46	0.17	0.65	−.44***	−.38**	.30*	.36**	.37**	.18	—							
8. CV_{RT} date	0.43	0.13	−0.05	−.51***	−.46***	.32*	.29*	.35**	.22	.52***	—						
9. D(CV)	0.02	0.15	−0.08	−.05	−.03	.06	.15	.11	.00	.66***	−.29*	—					
10. % AOI ch_{ver} delay	0.08	0.25	0.26	.57***	.44***	−.50***	−.20	−.33*	−.29*	−.43**	−.44***	−.10	—				
11. % AOI ch_{ver} date	0.00	0.22	0.07	.49***	.33*	−.50***	−.26	−.25	−.11	−.45***	−.49***	−.07	.84***	—			
12. D(AOI ch_{ver})	−0.08	0.14	−0.50	−.27	−.28*	.10	−.05	.20	.36**	.07	.01	.06	−.48***	.08	—		
13. % Fix_{newdur} delay	0.25	0.12	−0.05	−.41**	−.24	.50***	.32*	.34*	.17	.26	.45***	−.11	−.58***	−.55***	.18	—	
14. % Fix_{newdur} date	0.01	0.13	0.08	−.30*	−.25	.24	.29*	.24	.06	.11	.37**	−.20	−.31*	−.27	.14	.61***	—
15. D(% Fix_{newdur})	−0.24	0.11	−0.61	.09	−.03	−.26	−.01	−.08	−.11	−.15	−.06	−.12	.27	.28*	−.03	−.37**	.51***

Note. All D(x) represent difference measures and are computed as difference of the variables given in the two lines above (date minus delay). Sk = skewness; ln(k) = discount rate; RT = reaction time; CV = coefficient of variation (mean/standard deviation); % AOI ch_{ver} = proportion of vertical saccades (relative to horizontal saccades) between areas of interest; % Fix_{newdur} = proportion of mean cumulative fixation duration on reward attributes (relative to time attributes).
* $p < .05$. ** $p < .01$. *** $p < .001$ (unadjusted).

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Table 5
Descriptive Statistics of and Correlations Between Temporal Discounting and Questionnaire Variables

Variable	*M*	*SD*	Sk	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Ln(k_{delay})	−5.21	1.48	−0.02	—												
2. Ln(k_{date})	−5.85	1.16	0.10	.90***	—											
3. D(ln(k))	−0.64	0.67	−0.37	−.65***	−.25	—										
4. Positive urgency	26.04	8.40	0.61	−.04	−.07	−.02	(.91)									
5. Negative urgency	28.44	8.49	0.33	−.13	−.09	.13	.74***	(.88)								
6. Sensation seeking	39.96	9.10	−0.23	.01	−.08	−.16	.23	−.04	(.83)							
7. Lack of premeditation	27.26	5.63	0.00	.36**	.33*	−.22	.43**	.19	.36**	(.73)						
8. Lack of perseverance	20.96	6.01	0.14	−.17	−.07	.24	.26	.22	−.07	.37**	(.85)					
9. Past positive	33.96	6.82	−0.89	−.16	−.12	.16	−.07	.01	−.13	−.03	−.04	(.86)				
10. Past negative	26.00	7.95	0.31	−.24	−.13	.29*	.33*	.53***	−.08	−.07	.32*	−.28*	(.85)			
11. Present hedonism	48.61	7.20	0.13	.12	.04	−.20	.42**	.16	.45***	.56***	.19	.03	−.22	(.78)		
12. Present fatalism	21.02	5.35	1.04	.07	.14	.09	.30*	.27*	−.01	.25	.46***	.24	.21	.38**	(.73)	
13. Future	47.74	7.88	−0.37	.01	.03	.04	−.33*	−.09	−.08	−.44**	−.74***	.13	−.06	−.35**	−.44***	(.85)

Note. $D(\ln(k))$ represents the date/delay effect as difference measure of the two estimated discount rates (date–delay). Numbers in the parentheses represent Cronbach's alphas. Sk = skewness; $\ln(k)$ = discount rate.
* $p < .05$. ** $p < .01$. *** $p < .001$ (unadjusted).

investigation, especially with regards to the deliberation hypothesis (see the Attentional and Computational Mechanisms section).

Moreover, an explorative analysis showed that the date/delay effect was higher in participants with higher discount rates in the (baseline) delay condition. While we note that this finding should be interpreted with caution since the discount rate of the (baseline) delay condition also formed part of the date/delay effect itself (thereby potentially inflating the correlation by overlapping measurement errors), it may support the idea that date framing is particularly effective in impulsive decision makers, that is, people who tend to choose smaller-sooner option regardless of reward magnitude and delay of the larger-later option (Keidel et al., in press; Klapproth, 2012). In line with this, Klapproth (2012) previously found that substance users tend to have higher discount rates (Amlung et al., 2017; Bickel et al., 2012) but that these were attenuated when decision options were presented using date framing. Similarly, Keidel et al. (in press) found individuals with higher levels of positive schizotypy to show a stronger date/delay effect when controlling for other schizotypy subscales. Future studies might want to replicate our finding using two measurements of the (baseline) discount rate (ensuring their independence in the correlation) and extend the presented findings to other groups that have been shown to suffer from impulsive, maladaptive decision making, such as other clinical populations (Amlung et al., 2019).

Attentional and Computational Mechanisms

Different hypotheses regarding putative attentional mechanisms underlying the date/delay effect have been discussed in the literature. A primary aim of this study was to evaluate the hypothesized roles of stronger deliberation (Dshemuchadse et al., 2013), a shift toward more comparative search strategies (Kurokawa & Ohtake, 2013) and a stronger focus on reward compared to time attributes (Dshemuchadse et al., 2013; LeBoeuf, 2006; Read et al., 2005) in the date compared to the delay condition and to interpret these findings in light of alternative-based and attribute-based computational models of intertemporal choice.

Our findings at best only partially support the deliberation hypothesis. While higher RTs and more eye movements overall in the date compared to the delay condition (confirmation of Hypothesis 2a) could be an indicator of a more deliberative processing mode, our additional analyses suggest these findings may be driven by differences in reading requirements. Specifically, we found that the number of saccades significantly differed only when comparing the number of saccades within AOIs but not when comparing the overall number of saccades between AOIs. Additionally, differences in RTs as well as fixation and saccade numbers were due to relatively more time spent within specific AOIs, that is, within those of the time attributes. On the one hand, this could be due to higher deliberation when considering dates rather than delay units; on the other hand, it could be due to the relatively larger number of characters in the date condition (e.g., August 22, 2022, compared to 136 days). While our study cannot ultimately resolve this question, several explorative findings provide evidence against the deliberation hypothesis: First, mental demand did not differ significantly between conditions. While this test yielded a p value of .09, it should be noted that, by definition, deliberative compared to intuitive processing should be associated with higher mental demand and effort (Evans, 2008; Kahneman & Frederick, 2002). Second, participants with higher RTs in the date

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compared to the delay condition as well as those showing more variation in RTs in trials in either condition showed a weaker date/delay effect. The former result shows that interindividually, stronger deliberation, as reflected by higher RTs, is associated with a smaller rather than a larger date/delay effect. Similarly, on a trial-by-trial basis, more variability with regards to time spent in different trials is associated with a smaller date/delay effect, which could indicate that the date/delay effect is particularly driven by participants who adapt their RTs less to features (rewards, times) of intertemporal choices. Thus, consistent with the result reported by Dshemuchadse et al. (2013), we conclude that our findings do not support the deliberation hypothesis.

The finding that the proportion of horizontal saccades (relative to vertical saccades) between choice attributes was higher in the date than in the delay condition (confirmation of Hypothesis 2b) confirms previous results (Kurokawa & Ohtake, 2013). This suggests that, on average, participants indeed use a more comparative (vs. integrative) strategy in the date compared to the delay condition, which is more in line with attribute-based rather than alternative-based computational models. However, our results revealed that this effect was solely due to a higher proportion of saccades between time attributes, (partly) replicating the finding by S. N. Sharma and Khan (2022). Additionally, unlike postulated, the within-participant change in the proportional use of a comparative (vs. integrative) strategy was not significantly associated with the magnitude of the date/delay effect, as represented both in the linear regression predicting the date/delay effect itself and in a mediation model in which the proportional use of comparative strategies did not predict choice behavior. Thus, despite the overall switch toward a more comparative strategy in the date condition, there is no evidence that a change in strategy use is the central mechanism driving interindividual differences in the date/delay effect.

Interestingly, however, the explorative correlational analyses nevertheless suggest that choice strategies play a major role in the date/delay effect—not in terms of within-subject changes but in terms of stable between-subject strategy preferences. Specifically, participants who generally made relatively more vertical compared to horizontal saccades, that is, used a more integrative strategy in both conditions, showed a stronger date/delay effect. Given that previous studies showed that a more comparative strategy leads to lower discount rates (Amasino et al., 2019; Reeck et al., 2017; in line with our results presented in Table 4), it is not directly evident why a more integrative strategy (in both conditions) might be associated with lower discount rates in the date compared to the delay condition. However, considering the relative disadvantage of the integrative strategy might explain this phenomenon: As outlined above, the use of an integrative strategy likely increases the cognitive demand of making decisions in the date compared to the delay condition because it is harder to compute discounted values of the decision options (Dshemuchadse et al., 2013; Read et al., 2005), or, in other words, to follow an alternative-based model. Assuming that participants' cognitive resources are limited, it could be speculated that a cognitive capacity constraint leads to a failure of (correctly) calculating discounted values—for example, due to a switch to a heuristic involving less consideration of time attributes in the decision process (i.e., less time sensitivity; M. Scholten & Read, 2010), ultimately yielding more decisions for larger-later rewards in the date compared to the delay condition (Amasino et al., 2019; Reeck et al., 2017).

Indeed, this idea is consistent with the correlation between the difference measure of mean cumulative fixation duration on rewards versus time (date minus delay) and a higher proportion of vertical versus horizontal saccades in the date condition; that is, the more a participant uses an integrative strategy in the date condition, the higher is the relative mean cumulative fixation duration on reward compared to time attributes in the date compared to the delay condition. The correlative and explorative nature of this association notwithstanding, this result ultimately supports the attention-focusing hypothesis (Read et al., 2005) rather than a hypothesis of within-participant strategy change (choice strategy hypothesis) because there is no indication of a functional adaptation of choice strategy but of a failure of the integrative strategy, potentially resulting in a higher consideration of reward differences. On a computational level, this could be reflected in lowered time sensitivity in the trade-off model (M. Scholten & Read, 2010), that is, in higher interattribute weighting of rewards compared to times (even if this is not necessarily reflected in an increased proportion of comparative saccades).

However, the potentially higher consideration of rewards in the date compared to the delay condition is not evident in the average values of overt attention because in the date condition, participants fixated time (as compared to reward) attributes longer than in the delay condition (confirmation of Hypothesis 2c). As discussed earlier, it is not unlikely that this is merely due to reading requirements. Therefore, it is all the more important to consider within-subject changes. Again, however, our results did not yield any significant associations between within-subject change of attentional focus and the magnitude of the date/delay effect, neither in the linear regression nor in mediation models predicting choice behavior. Since the association between attentional focus and the date/delay effect yielded a p value of .06, we speculate that our analysis suffers from power limitations[6] because differences in absolute reward values predicted choice behavior more strongly in the date than in the delay condition—a finding consistent with the results from Dshemuchadse et al. (2013) and the attention-focusing hypothesis in general. The finding that this effect is particularly strong with higher differences in time attributes could reflect that high time differences were largely ignored (or underestimated) in the date condition (but not in the delay condition) when reward differences were high. Another important finding is that the relative attentional focus on rewards was only related to the date/delay effect in the delay but not in the date condition, indicating that participants who focused more on time attributes (and less on reward attributes) in the delay condition showed a stronger date/delay effect, while this effect was not significant for the date condition—the latter could be explained through participants who tended to choose the smaller-immediate reward in the delay condition paying relatively more attention on rewards in the date condition.

In sum, our study shows that, while we did not find convincing evidence for the deliberation hypothesis, there is support for both the choice strategy and the attention-focusing strategy, although possibly not as initially proposed. One the one hand, while there is no evidence for a within-subject strategy change contributing to the date/delay effect (as suggested by the choice strategy hypothesis;

[6] Specifically, a sensitivity analysis using G*Power 3.1.9.7 (Faul et al., 2009) revealed that our study, which had a sample size of $N = 54$ and assumed a two-tailed alpha probability of .05, was only adequately powered (i.e., had 80% power) to detect correlations of $r = .37$.

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Read et al., 2005), the date manipulation was more effective for participants using a more integrative strategy, potentially because they focused more on rewards. On the other hand, the association between within-participant change of attentional focus with the magnitude of the date/delay effect did not reach significance—potentially due to lack of power. However, in line with attribute-based models of intertemporal choice (Amasino et al., 2019; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; M. Scholten & Read, 2010), participants appeared to place a higher weight on reward than time values in the date compared to the delay condition. While the results generally support the attention-focusing hypothesis (Read et al., 2005), the name of the hypothesis might be somewhat misleading since it does not seem to be necessary to direct overt visual attention more strongly toward rewards in the date compared to the delay condition. Rather, the weighting of the reward attributes relative to the time attributes appears to be increased (LeBoeuf, 2006), resulting in a reward-weighting hypothesis.

Ultimately, our study shows that future research should look deeper into the individual strategies and computations that participants use to perform intertemporal choices. The date/delay effect illustrates that intertemporal choice behavior is malleable (Lempert & Phelps, 2016), and it would be interesting to determine to what extent strategies used in intertemporal choices are malleable as well. While the current study was not designed to compare computational models directly, the eye movement data suggest that attribute-based models may reflect intertemporal choices as well as alternative-based models, especially in the date condition (e.g., the Payne indices reported in Table 4 are near 0). Specifically, it appears that (some) participants are nudged toward a more attribute-based strategy in the date condition, but only regarding time attributes. Notably, one may speculate that this reaction is associated with the proposed underestimation of time intervals in the date condition (Jiang & Dai, 2021; Zauberman et al., 2009). That is, if participants tend to compare time attributes more in the date condition (i.e., use a more comparative strategy), they may adapt to the date condition better (i.e., show similar discount rates as in the delay condition). On the other hand, if participants integrate reward and time attributes (i.e., use and maintain a more integrative strategy), they may not be able to compensate for an underestimation of time, so that the larger-later reward becomes more attractive through a better reward-delay tradeoff, explaining the date/delay effect. Future studies should explicitly compare different alternative-based and attribute-based models and combine them with approaches to measuring subjective time estimation (Zauberman et al., 2009). For instance, our finding that the number of horizontal saccades increased only between time and not between reward attributes could indicate that hybrid models may better fit the choice data.

Personality Differences

Explorative analyses of the personality measures revealed that the date/delay effect was significantly associated only with the past negative scale of the ZTPI, indicating that participants with higher past negative scores showed a lower date/delay effect. People with a past negative time perspective have a negative view of, and ruminate over, the past (Zimbardo & Boyd, 1999). Since rumination has been shown to be associated with poor working memory updating and high task switching difficulties and therefore is associated with cognitive rigidity (Meiran et al., 2011; Whitmer & Banich, 2007; see Morris & Mansell, 2018, for a review), one may speculate that a stronger tendency to ruminate prevents people from adapting to different framing versions in intertemporal choice tasks, resulting in maintained cognitive strategies (and attribute weightings) and thereby preventing the date/delay effect. However, given that the size of this effect is rather small, any interpretation is rather speculative and warrants replication.

Self-reported impulsivity in the UPPS-P, however, was not significantly associated with the magnitude of the date–delay effect. Interestingly, higher scores on the lack of premeditation subscale, which may be considered a core dimension of impulsivity (Keidel et al., 2022; L. Sharma et al., 2014), was significantly associated with stronger discounting in both the date and delay conditions. Given that effect sizes in individual differences research in temporal discounting tend to be small (Keidel, Rramani, et al., 2021), the limited statistical power of this experimental study may be the reason why we could not detect an association between impulsivity and the date/delay effect.

Limitations

The current study was subject to several limitations. One important point is that, as outlined throughout the manuscript, in our study, eye movement measures allowed inferences regarding cognitive processing only to a limited degree, leaving findings open to interpretation and allowing no definite answers regarding the hypotheses related to the date/delay effect. Two ambiguous findings may serve as examples of this point. First, given that eye tracking only reflects overt attention, changes in cognitive mechanisms do not necessarily need to be accompanied by differences in eye movement patterns. This is perhaps best illustrated by our finding of an apparently higher weight put on the reward comparison of a decision, which was not (directly) evident in the eye-tracking data, in line with the hypothesis by LeBoeuf (2006) and our reward-weighting hypothesis. Second, and relatedly, reading demands may play an important role. For instance, we found a higher number of eye movements in the date compared to the delay condition. Initially, this could be attributed to either more deliberative processing or higher reading demands. While our correlative results render more deliberative processing rather unlikely, future studies could try to target this issue by displaying dates and delay units in a more similar format (e.g., "02/10/22" vs. "1m/1w/5d", i.e., 1 month, 1 week, 5 days, or—supposing that all dates are in the same year—"02/10" vs. "42 d"). In general, these examples show that, while our results provide interesting insights and tentative evidence, more research, for example, involving neuroimaging, is needed to find more definite answers regarding the cognitive mechanisms of the date/delay effect.

A different although related point is that some of the conclusions are based on nonpreregistered, exploratory analyses. While we closely followed our preregistered analysis plan and were able to confirm most of our hypotheses, further explorations of the within-subject effects averaged over the whole sample (Hypothesis 2) were necessary to evaluate attentional mechanisms of the date/delay effect more deeply, partly resulting in power issues. Specifically, our study initially was not designed and powered to detect between-subject correlations low in effect size (see our a priori power analysis in the Sample section, as compared to our sensitivity analysis in Footnote 6). Thus, high-powered replication studies are needed to confirm our findings. Along similar lines,

given the correlational eye-tracking approach used in our study, future studies should also consider experimental designs (Fisher, 2021; Reeck et al., 2017) to draw more robust causal inferences.

Finally, while the current study provides evidence of differences in attentional strategies that depend on the format with which temporal information is displayed, it cannot provide an overall explanation of the date/delay effect. However, establishing a comprehensive explanation for the date/delay effect was beyond the scope of this study. Future studies are needed to link the different hypotheses and find an integrative explanation, potentially combining eye tracking and computational with experimental and imaging approaches.

Conclusion

In the current study, we used eye tracking to examine the cognitive mechanisms underlying the date/delay effect, a robust framing effect in intertemporal choice. As one of the first studies that combined the date and delay conditions of an intertemporal choice task with attentional eye-tracking measures, it provides evidence for attentional mechanisms playing an important role in the date/delay effect. Specifically, apart from replicating the date/delay effect, we found that participants on average use a more comparative strategy in the date condition than in the (baseline) delay condition. While we did not find any evidence of a substantial within-subject strategy change, the date manipulation was more effective in participants who used an integrative strategy. Additionally, participants fixated dates longer in the date condition than delay units in the delay condition, potentially due to reading requirements. However, contrary to this general result, it appears that participants weight rewards more highly when making choices in the date than in the delay condition, supporting a reward-weighting hypothesis, in line with attribute-based computational models.

Constraints on Generality Statement

Our study replicated the date/delay effect in a healthy young adult sample and examined underlying attentional mechanisms using eye tracking. Since the date/delay effect had been replicated several times, both by different research groups (e.g., Dshemuchadse et al., 2013; LeBoeuf, 2006; Naudé et al., 2018; Read et al., 2005) and by ourselves (e.g., Keidel et al., in press), we expect the date/delay effect to further generalize to other samples as well. It may be potentially even stronger in clinical populations (see the Replication of the Date/Delay Effect section). However, as our study was one of the first to combine the date and delay conditions of an intertemporal choice task with attentional eye-tracking measures, we decided to examine a homogenous group that is well-suited for eye-tracking experiments (healthy young adults, mostly university students), excluding potential confounding factors that might influence either eye-tracking data assessment or intertemporal choice behavior (age between 18 and 40, nonsmokers, etc.; see the Sample section for complete exclusion criteria). Thus, while we expect that findings about attentional mechanisms will also hold for other samples (because the date/delay effect itself seems to be robust), we cannot rule out the possibility that they only apply to (healthy) young adults. Future studies will need to extend our findings in more diverse samples, especially regarding gender and education. Moreover, the MCQ was used as temporal discounting task in a delay and a date version. Based on studies from our own laboratory (Keidel et al., in press), we do not expect the date/delay effect to depend on the magnitude of monetary rewards. However, the time attributes of the intertemporal choice task might play a role for the date/delay effect, both in terms of lengths of delays in general (as the date/delay effect might not emerge with shorter delays, as discussed by LeBoeuf, 2006, and Lempert et al., 2016) and presentation of the time attributes in the date condition (reading requirements; see the Limitations section). Thus, replication studies should consider systematically varying different delays and using another date format (as proposed in the Limitations section) to generalize and extend our results. We have no reason to believe that the results depend on other characteristics of the participants, materials, or context.

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Appendix C | Study III

Keidel, K., Schröder, R., Trautner, P., Radbruch, A., Murawski, C., & Ettinger, U. (2024). The date/delay effect in intertemporal choice: A combined fMRI and eye-tracking study. *Human Brain Mapping*, *45*(3), Article e26585. https://doi.org/10.1002/hbm.26585

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RESEARCH ARTICLE

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The date/delay effect in intertemporal choice: A combined fMRI and eye-tracking study

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Abstract

Temporal discounting, the tendency to devalue future rewards as a function of delay until receipt, is influenced by time framing. Specifically, discount rates are shallower when the time at which the reward is received is presented as a date (date condition; e.g., June 8, 2023) rather than in delay units (delay condition; e.g., 30 days), which is commonly referred to as the date/delay effect. However, the cognitive and neural mechanisms of this effect are not well understood. Here, we examined the date/delay effect by analysing combined fMRI and eye-tracking data of $N = 31$ participants completing a temporal discounting task in both a delay and a date condition. The results confirmed the date/delay effect and revealed that the date condition led to higher fixation durations on time attributes and to higher activity in precuneus/PCC and angular gyrus, that is, areas previously associated with episodic thinking. Additionally, participants made more comparative eye movements in the date compared to the delay condition. A lower date/delay effect was associated with higher prefrontal activity in the date > delay contrast, suggesting that higher control or arithmetic operations may reduce the date/delay effect. Our findings are in line with hypotheses positing that the date condition is associated with differential time estimation and the use of more comparative as opposed to integrative choice strategies. Specifically, higher activity in memory-related brain areas suggests that the date condition leads to higher perceived proximity of delayed rewards, while higher frontal activity (middle/superior frontal gyrus, posterior medial frontal cortex, cingulate) in participants with a lower date/delay effect suggests that the effect is particularly pronounced in participants avoiding complex arithmetic operations in the date condition.

KEYWORDS
date/delay effect, episodic thinking, eye-tracking, fMRI, precuneus, temporal discounting

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Practitioner Points

- In intertemporal choices, temporal discounting is reduced when the timing of rewards is presented in terms of dates rather than delay units (date/delay effect).
- The date condition is associated with longer fixation durations on time compared to reward attributes, more comparative eye movements between time attributes and higher neural activity in areas associated with episodic future thinking (precuneus, posterior cingulate cortex, angular gyrus), in line with hypotheses positing differences in time estimation.
- People with a lower date/delay effect had relatively higher frontal activity (e.g., middle/superior frontal gyrus) in the date condition, suggesting that doing mental math in that condition may undermine its effectiveness.

1 | INTRODUCTION

Choosing between smaller rewards available sooner and larger rewards available later is known as intertemporal choice. When making such choices, people typically prefer smaller but earlier rewards to larger but later rewards, devaluing future rewards as a function of time. This phenomenon is referred to as temporal discounting (Frederick et al., 2002). Higher temporal discounting has been associated with negative life outcomes (e.g., higher credit debts, more risky behaviour) in the general population (Keidel et al., 2021) and has been documented for a broad range of mental disorders (Amlung et al., 2019). Various experimental manipulations have been shown to attenuate temporal discounting (Rung & Madden, 2018; H. Scholten et al., 2019), including the date/delay effect (LeBoeuf, 2006; Read et al., 2005): People discount future rewards less when time until receipt of rewards is framed in terms of dates (date condition; e.g., 8th June 2023) instead of delay units (delay condition; e.g., 30 days). While this effect has been replicated several times (Dshemuchadse et al., 2013; Jiang & Dai, 2021; Keidel, Murawski, & Ettinger, 2023; Keidel, Murawski, Pantelis, & Ettinger, 2023; Naudé et al., 2018), its cognitive and neural underpinnings are still ambiguous. We therefore combined, for the first time, functional magnetic resonance imaging (fMRI) with eye-tracking to investigate the neural and cognitive mechanisms of the date/delay effect.

1.1 | Neural mechanisms of intertemporal choice

Neural activity patterns during intertemporal choices have been studied extensively (Frost & McNaughton, 2017; Kable & Glimcher, 2007; Peters & Büchel, 2011). Frost and McNaughton (2017) deduced a cognitive model of intertemporal decision-making comprising five brain systems, viz. (i) an object representation system responsible for transmitting sensory information (occipital lobe), (ii) a memory-driven system to derive gain-related information (memory-related regions, e.g., medial prefrontal cortex [mPFC], precuneus, medial temporal lobe, lateral temporal cortex and lateral parietal cortex), (iii) a subjective value (SV) computation system (e.g., mPFC, ventral striatum [vS]; also see Bartra et al., 2013), (iv) a comparator system to compare choice alternatives (regions involved in evaluating choice difficulty, e.g., striatal and prefrontal areas, amygdala, and their connectivity) and (v) a motor system to produce and suppress responses (motor areas). In our study, we did not target one specific part of the process (e.g., valuation) but differences between date and delay conditions in intertemporal choice processes as a whole. We were particularly interested in whether activity patterns in the date and delay conditions might differ in the memory-driven, SV computation or comparator systems.

1.2 | Potential mechanisms of the date/delay effect

Different cognitive mechanisms of the date/delay effect have been proposed (Dshemuchadse et al., 2013; LeBoeuf, 2006; Read et al., 2005), including the differential time estimation hypothesis (Read et al., 2005; Zauberman et al., 2009), the attention-focusing or reward-weighting hypothesis (Keidel, Murawski, & Ettinger, 2023; LeBoeuf, 2006; Read et al., 2005) and the choice strategy hypothesis (Read et al., 2005).

The differential time estimation hypothesis states that time intervals presented in terms of dates are subjectively estimated to be shorter than intervals presented as delay units (Read et al., 2005; Zauberman et al., 2009). Thus, underestimating the waiting time (Ebert & Prelec, 2007; Jiang & Dai, 2021; Zauberman et al., 2009) for the delayed reward in the date compared to the delay condition may lead to less temporal discounting. One reason for this phenomenon could be that time estimation is influenced by the abstractness of time information (Lempert & Phelps, 2016). According to Construal Level Theory (Trope & Liberman, 2003), abstract, high-level construals have a high psychological distance, while more concrete, lower-level construals have a low psychological distance. As dates might be more concrete because of their specificity and have potentially higher personal relevance (e.g., triggering more episodic processing) than delay units, the psychological distance might be lower in the date frame, and thus, a date might appear closer to the current day than a specific delay unit. In the context of the systems proposed by Frost and McNaughton (2017), time estimation could be influenced by episodic memory and thinking about the future (Cooper et al., 2013; Peters & Büchel, 2010). Accordingly, differences between conditions should

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cause divergent activity in the memory-related or SV systems in response to time information.

Second, the attention-focusing (Read et al., 2005) or reward-weighting hypothesis (Keidel, Murawski, & Ettinger, 2023; LeBoeuf, 2006) postulates that when time is given in delay units, attention is drawn to the waiting time, whereas dates draw attention to the time at which a reward is received and to the reward at that time. As such, dates are assumed to lead to a relatively higher weighting of reward than time attributes. This could also be associated with overt shifts of attention toward rewards (Read et al., 2005). However, two recent studies contradict this notion. They found that the date condition led to higher fixation durations on time rather than reward attributes, while there was no change in the number of reward attribute comparisons (Keidel, Murawski, & Ettinger, 2023; Sharma & Khan, 2022). Nevertheless, one of the studies found that reward differences were more important for the ultimate decision, suggesting potential differences in internal weighting processes (Keidel, Murawski, & Ettinger, 2023). At the neural level, a stronger focus on rewards should be associated with divergent signalling in valuation areas such as mPFC or vS in response to reward information. In case of overt attentional shifts, this should also be accompanied by higher fixation durations on reward vs. time attributes and potentially by more saccades between reward attributes (see next paragraph).

Third, in combination with the reward-focusing hypothesis, the choice strategy hypothesis is based on the assumption that dates impede the calculation of interest rates (Read et al., 2005). This hypothesis is related to the distinction between traditional alternative-based (Frederick et al., 2002) and more recently introduced attribute-based models (Amasino et al., 2019; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; Scholten & Read, 2010) of intertemporal choice. Specifically, in traditional intertemporal choice tasks with delay units, reward values and delay units are integers that can be combined to estimate SVs of choice options (integrative strategy), which can then be compared in a common neural currency (Levy & Glimcher, 2012; see Hayden & Niv, 2021, for a recent challenge). This procedure follows alternative-based models, given that SVs of options are computed and compared to derive a decision (Frederick et al., 2002). Interestingly, with regard to the date condition, estimating SVs of choice options is not directly possible. Instead, people need to either transform dates to delay units to be able to continue using the integrative strategy or they need to adapt their strategy. It has been suggested that they might change from integrating reward and time information to comparing attributes separately (comparative strategy) (Amasino et al., 2019; Fisher, 2021; Reeck et al., 2017) and deciding based on the attribute type that is considered more important, which is thought to be the reward (Read et al., 2005). This reflects an implementation of the attribute-based model, that is, differences in attributes are computed and the decision is based on the more favourable difference (Amasino et al., 2019; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Read et al., 2013; M. Scholten & Read, 2010). Indeed, a higher number of saccades between time attributes have been found in the date condition (Keidel, Murawski, & Ettinger, 2023). Such a change towards a comparative strategy could speak for a change in attentional search and a stronger reward focus (see above). It should be observable in eye-tracking behaviour (i.e., an increase in the number of saccades comparing attributes of the same type between options relative to the number of saccades between reward and time of one option). Importantly, the idea of different strategy uses in combination with the potential reward focus may reflect more generally that the date condition prompts participants to calculate less in the date compared to the delay condition and take a more intuitive approach to intertemporal decision-making (e.g., focusing more on episodic processes). A less arithmetic approach may then cause differences between conditions in the activity in prefrontal parts of the comparator system.

Finally, factors that can explain interindividual differences in the magnitude of the date/delay effect are largely unclear. Previous studies suggest that in impulsive individuals, for example, people with substance use disorder (Klapproth, 2012) and those showing steeper discounting rates in the traditional delay condition (Keidel, Murawski, Pantelis, & Ettinger, 2023), discounting is reduced more by the date manipulation (compared to the delay condition). Therefore, differences in impulsivity traits, commonly assessed by questionnaires such as the UPPS-P Impulsive Behaviour Scale (Lynam et al., 2006; Whiteside & Lynam, 2001), would be expected to be associated with the date/delay effect.

Here, we used fMRI to compare neural activity between date and delay conditions to draw conclusions about the cognitive and neural mechanisms of the date/delay effect and the mechanisms involved in time processing in intertemporal decision-making. We hypothesised that temporal discounting would be lower in the date compared to the delay condition, thereby replicating the date/delay effect. Furthermore, since our study was the first to use fMRI to investigate the date/delay effect and, as discussed above, a wide range of cognitive and neural mechanisms may potentially be involved, we planned to jointly examine the neural and oculomotor mechanisms of the date/delay effect applying an explorative analysis approach. Generally, for the eye-tracking data, we expected to find the same effects as in a previous experiment (Keidel, Murawski, & Ettinger, 2023). Finally, we explored whether the date/delay effect or its neural correlates would be associated with questionnaire-assessed interindividual differences in levels of impulsivity.

2 | MATERIALS AND METHODS

The study was preregistered at https://osf.io/d9u74. Study materials, behavioural data, analysis scripts and supplementary material are accessible at https://osf.io/td5gf/.

2.1 | Sample

We based our intended final sample size on an a priori power analysis in G*Power 3.1 (Faul et al., 2009). Specifically, we determined the sample size needed to reveal the date/delay effect (paired *t*-test) with

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80% power, expecting an effect size of $d = 0.45$ (see Hedge's g in Rung & Madden, 2018) and assuming an alpha-level of .05 (one-tailed). This analysis yielded a target sample size of $N = 32$.

Participants were drawn from the student population. They had to be 18–35 years old, male or female, right-handed, healthy and of good command of German language. Additionally, for valid eye-tracking measurements, they needed to have normal or corrected-to-normal eyesight (contact lenses). Exclusion criteria comprised a current diagnosis of a psychiatric disorder, a current diagnosis or history of neurological disorders, a current diagnosis or history of psychotic disorders, learning disabilities, history of loss of consciousness for more than 5 min, history of alcohol or drug abuse within the last 12 months, serious physical illness or consummation of any prescription or over-the-counter medication 3 days previous to the examination (apart from contraceptives, thyroid or vitamin medications). Participants were also excluded if they had any condition making them unsuitable for fMRI (i.e., claustrophobia, metalliferous implant, large tattoos on the upper half of the body, history of welding work, injury or disease of the inner ear with loss of hearing, pregnancy, currently breastfeeding a baby, history of any heart or head surgery). Additionally, we administered an intertemporal choice task in a laboratory screening before the fMRI session to estimate individual discount rates (see Section 2.5.1), ensuring that the 95% credible interval of the discount rate (per annum) was not entirely below 0, did not include 0 or was not entirely above 2. Meeting any of these criteria would have led to the participant's exclusion, which never occurred. Inclusion and exclusion criteria were assessed in an online pre-screening and a laboratory screening (see Section 2.2).

As planned, the sample consisted of $N = 32$ participants (16 male, 16 female). One male participant had to be excluded because of excessive head movement, so the final sample comprised $N = 31$ participants (15 male, 16 female) aged 19–29 years ($M = 23.26$, $SD = 3.19$). All participants were students and had completed at least upper secondary education.

2.2 | Study procedures

All study procedures were approved by the ethics committee of the Department of Psychology at the University of Bonn (#21-06-30). Participants were recruited through personal contacts, flyers on the campus of the University of Bonn, mailing lists and online platforms. To ensure that all participation criteria were met, potential participants had to take part in an online pre-screening and a laboratory screening before being invited to the fMRI session.

First, during the online pre-screening (approximately 5 min), participants gave informed consent to take part in the online screening and were asked about the inclusion and exclusion criteria listed above. If they were deemed eligible for the study, they were invited to a laboratory screening.

Second, in the laboratory screening, participants provided informed consent for all further study procedures and were asked about the same information they had provided in the online screening. This included questions about the inclusion/exclusion criteria mentioned above as well as the MINI International Neuropsychiatric Interview (Sheehan et al., 1998; German translation by Ackenheil et al., 1999) to test for mental disorders and measurements of weight and height. Additionally, the UPPS-P Impulsive Behavior Scale (Lynam et al., 2006; see Section 2.3) was assessed at this stage. Afterwards, participants completed all trials (27) of the delay condition and three trials of the date condition of the intertemporal choice task (see Section 2.3). Apart from demonstration purposes, delay condition data were also used to test for suitability to estimate the discount rate and to estimate the test–retest correlation across laboratory and fMRI sessions. The total duration of the laboratory screening was approximately 45 min. If participants passed the laboratory screening, a date was set for the fMRI session. The time period between laboratory screening and fMRI session varied between 0 and 19 days ($M = 8$ days).

Third, in the fMRI session at the MRI Core Facility of the Medical Faculty at the University Hospital of Bonn, female participants provided a urine sample which was tested for pregnancy (OneStep®, 10 miu/ml; none of the participants had to be excluded). Participants were once again informed about the fMRI procedures and criteria. Afterwards, they completed two different tasks in the fMRI scanner (the intertemporal choice task for this study as well as an eye movement task for a study published elsewhere [Schröder et al., 2023]). Afterwards, a structural T1 scan was obtained. The total duration of the fMRI session was approximately 90 min.

Participants were compensated with €30. Alternatively, psychology students from the University of Bonn could choose to be compensated with course credit. Additionally, all participants who had completed the fMRI session entered a lottery in which three winners were drawn. For these winners, one of their decisions in the intertemporal choice task during fMRI was randomly selected and paid out according to the choice made in the decision.

2.3 | Materials

2.3.1 | Intertemporal choice task

The Monetary Choice Questionnaire (MCQ; Kirby et al., 1999) was used as intertemporal choice task. It comprises 27 items, asking participants to decide between a smaller-immediate reward (SIR) and a larger-later reward (LLR). In the current study, the MCQ was assessed in a German version. In the original MCQ, time attributes are given in intervals of days stating the waiting time (e.g., 24 Euro | 0 days vs. 35 Euro | 29 days; delay condition). We added a second set of 27 items with the time attributes in the format of dates (e.g., 24 Euro | November 24, 2021 [=today] vs. 35 Euro | December 23, 2021; date condition). Thus, each of the 27 original delay items has a corresponding date item. While the MCQ was also conducted in the laboratory (see Section 2.2), the following information only applies to the fMRI session.

The task was programmed using Experiment Builder software (SR Research Ltd., version 2.3.38) and displayed on a 32-inch LCD

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monitor (NordicNeuroLab, 1920 × 1080px, height: 392.85 mm; width: 698.4 mm; refresh rate: 120 Hz). The monitor stood at the head end of the MR scanner, at a distance of approximately 190 cm from the participant's eyes. The task was presented to the participants using a first-surface reflection mirror.

The MCQ was presented in blocks, each consisting of 27 trials of the respective condition (delay and date). The task consisted of a sequence of four blocks (2 per condition) in alternating order. The starting condition was counterbalanced between participants (i.e., A-B-A-B or B-A-B-A). Between blocks, participants had a break of 15 s before the next block began. The trial order within each block was randomised. SIR and LIR were presented simultaneously and side by side on the screen. Positions of SIR and LLR (left/right) were counterbalanced. Specifically, in half of the trials, the SIR was presented on the left side (LLR on the right side) of the screen and vice versa. The positions for the first delay block were randomly determined beforehand and were used for the corresponding items in the respective date block. These positions were also used for blocks 3 and 4 with reversed sides.

Before the start of the task, participants were instructed to press the buttons on the response grips (NNL, NordicNeuroLab) in their left and right hands with their index finger to choose the left or right option, respectively. Additionally, participants were reminded of the lottery and the current date. Each trial started with a fixation cross. The duration of the fixation period was 6000 ms in the first trial of a block or else depended on the decision time and jitter from the previous trial. Afterwards, the decision screen was presented. The decision screen showed the four choice attributes (two monetary amounts, two time attributes). Participants had to choose one of the options within 6000 ms; otherwise, the task proceeded to the next trial (without any error message). After the decision screen, a fixation cross was shown again (duration: 6000 ms—response time of the trial + intertrial interval [drawn uniformly from an interval between 4000 and 8000 ms]). Mean trial duration was approximately 12,000 ms. An example trial is illustrated in Figure 1.

2.3.2 | UPPS-P Impulsive Behavior Scale

The UPPS-P (Lynam et al., 2006) is a 59-item questionnaire assessing five facets of trait impulsivity. It comprises the subscales positive urgency (tendency to react rashly after experiencing positive affect; 14 items), negative urgency (tendency to react rashly after experiencing negative affect; 12 items), sensation seeking (tendency to seek new and exciting experiences; 12 items), lack of premeditation (tendency to act without thinking; 11 items) and lack of perseverance (tendency to give up early on boring or hard tasks; 10 items). The UPPS-P was completed in the laboratory. It was assessed in a German version (translation of the UPPS-subscales from Schmidt et al., 2008, translation of the Positive Urgency subscale by the research group of the authors from the University of Bonn). Items were answered on a five-point Likert scale (1 = strongly disagree, 2 = rather disagree, 3 = neutral, 4 = rather agree, 5 = strongly agree).

2.4 | Data acquisition and preprocessing

2.4.1 | Choice behaviour and questionnaire

Choice behaviour was assessed using the MCQ. Trials with no answers within 6000 ms were excluded from behavioural analyses. The data revealed no unrealistic RTs (i.e., all RTs > 300 ms).

For the UPPS-P subscales, sum scores were computed.

2.4.2 | Eye-tracking

Eye movements were recorded using an MR-compatible video-based combined pupil and corneal reflection long-range eye-tracker EyeLink 1000 system (SR Research Ltd., Kanata, ON, Canada) at 1000 Hz sampling rate (no head tracking). The EyeLink 1000 has an end-to-end sample delay below 1.8 ms on average (SR Research Ltd., 2010). It measured horizontal and vertical gaze position data of the right eye in pixels on the screen, with (0,0) corresponding to the top-left corner of the screen (note that pixels were transformed to degrees of visual angle from screen centre to indicate stimulus sizes and measurement uncertainty). The eye-tracker was placed at the head end of the scanner bore, recording pupil and corneal reflection signals through the first-surface reflection mirror through which the participant also saw the task. The participant's head was restrained by the head coil and cushions to minimise movement. Light was switched off during the task to ensure consistency of background lighting across participants. The eye-tracker was calibrated and validated using a nine-point horizontal-vertical 3 × 3 grid (round white targets with a black dot in the middle, displayed in random order; coordinates: [960,540], [960,92], [960,988], [115,540], [1805,540], [115,92], [1805,92], [115,988], [1805,988]; visual angles were 9.19°, 4.90° and 10.38° of calibration stimuli positioned horizontally, vertically and diagonally from the screen centre, respectively). Calibration and validation followed the built-in routines and settings provided by SR Research Ltd. We aimed to reach a validation classified as at least "fair" (i.e., worst point error should be below 2.0° and average error below 1.5°) and otherwise performed a new calibration. In the task, stimuli positions and sizes in degrees of visual angle were as follows: The fixation cross was positioned in the centre of the screen (0°, 0°), with a width of 1.11° and a height of 0.83°. The centres of reward and time attributes were always presented at a distance of 6.93° visual angle from the screen centre. The width of monetary amounts was 1.98°, and the width of times ranged from 1.75° (e.g., "0 Tage") to 5.05° (e.g., "1 September 2022"). The height of all task stimuli was 0.52°. To determine whether a participant had looked at a specific attribute, we defined a priori areas of interest (AOIs) around the attribute centres (AOI width: 9.76°, AOI height: 2.46°).

Eye-tracking events were preprocessed using the default settings of the EyeLink host software (version 4.56), unless specified otherwise. Data Viewer software (SR Research Ltd., version 4.2.1) was used to visually inspect data and generate data reports. All other preprocessing was done in R (version 4.2.2) using RStudio (version 2022.07.2).

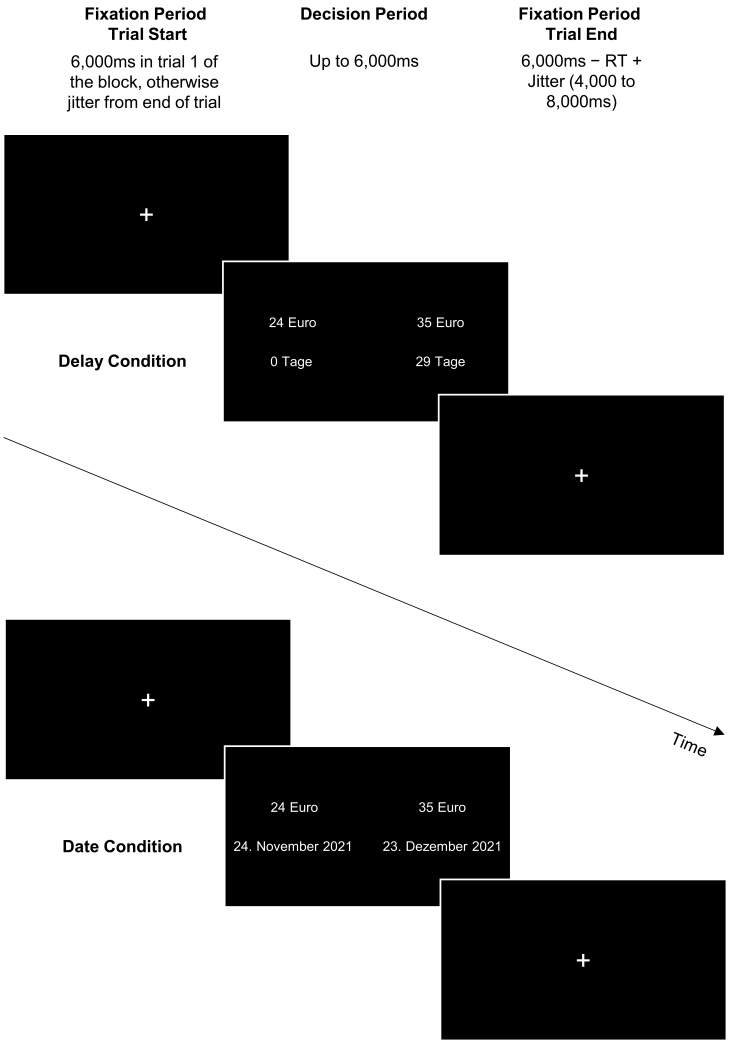


FIGURE 1 Illustration of the Intertemporal Choice Task. Each trial started with a fixation period. The duration was fixed at 6000 ms for the first trial and corresponded to the trial end fixation for the other trials. Afterwards, the decision screen (above: example of a delay trial; below: example of a date trial) was presented for 6000 ms during which a choice had to be made. Finally, a fixation cross was presented again. The duration of the latter stage was the sum of the time that would have been left during the decision screen (i.e., 6000 ms − reaction time [RT]) plus a jitter of 4000 ms to 8000 ms (drawn uniformly). All trials were presented in German (translation: Tage = days, Dezember = December). The font size was adjusted for better readability.

Since data inspection revealed major drift errors, we decided to recalibrate the data based on the fixation period before each trial. Specifically, for each trial, correction constants for *x*- and *y*-coordinates were computed based on the deviations of gaze from the fixation cross in the last 4 s of the fixation period. These correction constants were then added to the original data of the decision period to correct for drift errors. Furthermore, to ensure that we only analysed eye-tracking measures of trials with valid data, we excluded not only all trials in which participants did not answer in time (i.e., RTs as above) but also those in which data suggested that not all four AOIs were looked at. If this was the case for more than 20 trials in one of the conditions, we excluded the corresponding participant from eye-tracking analyses, as this suggested either poor eye-tracking data quality or a search strategy that excluded looking at specific AOIs. In total, $N = 13$ participants had to be excluded because they did not fulfil the criteria (trials with valid data: $M = 25.78\%$, $SD = 14.96\%$). Most of them ($N = 9$) had to be excluded because they did not look at the time attribute of the SIR in a sufficient number of trials (as this information was the same in all trials). Thus, data of $N = 18$ participants remained for the analyses (trials with valid data: $M = 73.41\%$, $SD = 16.39\%$). We note, however, that significantly fewer trials had to be excluded in the date (trials with valid data: $M = 79.01\%$, $SD = 18.42\%$) compared to

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the delay condition (trials with valid data: $M = 67.80\%$, $SD = 17.82\%$), $t(17) = -3.07$, $p = .007$, $g_{av} = 0.61$, which is probably due to the RT difference between conditions (see Section 3.1). Due to blinks, 1.08% (SD = 1.65%) of data in the decision period (per participant) were lost on average. Within-participant comparisons showed that mean data loss due to blinks did not significantly differ between conditions (delay: $M = 1.47\%$, $SD = 2.74\%$; date: $M = 0.82\%$, $SD = 1.22\%$), $t(17) = 1.16$, $p = .261$, $g_{av} = 0.32$.

Empirical accuracy and precision of eye-tracking measurements were analysed using the sample data of the first and last trial of the experiment. Specifically, we focused on the part of the fixation period earlier than 4 s before the decision period and selected the last fixation that ended before this time to ensure that data were independent of our recalibration procedure. Within each participant, we calculated the *x*- and *y*-deviation in visual angle between the centre of the fixation cross and each sample of the fixation of the corresponding trial. Then, we computed the mean (for accuracy) and standard deviation (for precision) of the *x*- and *y*-deviations for each sample within the fixation. We combined the measures for *x*- and *y*-deviations using the Pythagorean theorem. Finally, we computed means of the combined measures to get indices for accuracy and precision. Results were as follows: For the first trial, mean accuracy was 3.68° (range: 0.54°–15.39°) and mean precision was 0.16° (range: 0.04°–0.36°). For the last trial, mean accuracy was 3.17° (range: 0.14°–5.71°) and mean precision was 0.25° (range: 0.07°–0.61°). While precision was relatively high, accuracy was relatively low. We suspect that this could be due to two reasons. First, the complicated setting (MR scanner), which also made the manual recalibration necessary, could have impeded data quality and the recalibration corrected for this only to a limited extent. Second, we speculate that participants might not have looked at the fixation cross throughout the whole fixation period, as it was relatively long. Thus, potential accuracy limitations should be considered when interpreting the eye-tracking data.

2.4.3 | fMRI

Imaging data were collected with a 3 T MRI scanner (Siemens Magnetom Trio) using a 32-channel head coil. During completion of the MCQ, a functional T2*-weighted echo planar image (EPI) sequence was used to measure BOLD fMRI data (TR = 2500 ms, TE = 30 ms, flip angle = 90°, field of view = 192 mm, matrix size = 96 × 96, number of slices = 37, voxel size = 2 × 2 × 3 mm, interslice gap = 0.3 mm). Three-dimensional T1-weighted high-resolution structural scans were obtained using Magnetization Prepared Rapid Acquisition with Gradient Echoes (MPRAGE) (TR = 1660 ms, TE = 2.54 ms, flip angle = 9°, field of view = 256 mm, matrix size = 320 × 320, number of slices = 208, voxel size = 0.8 × 0.8 × 0.8 mm).

BOLD data preprocessing was done in SPM12 using Matlab 2022b. Functional images were slice-time corrected and then realigned to the first image of the time series using a least-squares approach and a six-parameter rigid body transformation. We segmented the individual structural T1-weighted images into grey and white matter and cerebral spinal fluid and used the segmented image for co-registration of anatomical and functional images. The co-registered functional images were then normalised into standard Montreal Neurological Institute (MNI) space and smoothed using an 8 mm full width at half maximum (FWHM) Gaussian kernel.

2.5 | Statistical analyses

All behavioural analyses were conducted in R (version 4.2.2) using RStudio (version 2022.07.2) and Rstan (version 2.26.1). BOLD analyses were done in SPM12 using Matlab 2022b.

2.5.1 | Estimation of discount rates

Log-transformed discount rates were estimated using hierarchical Bayesian modelling in Rstan. Specifically, for choice data from the laboratory, we fitted a computational model assuming a hyperbolic function to get initial estimates of the individual discount function. For choice data from the fMRI task, we fitted a computational model to estimate discount rates, assuming each a hyperbolic, an exponential and a quasi-hyperbolic function. Using leave-one-out cross-validation to compare model fits (LOO-CV; Vehtari et al., 2017),[1] the hyperbolic function appeared to fit the data best. While differences between predictive accuracies of the different models were small, we nevertheless decided to use discount rates estimated based on the hyperbolic function, as this is also in line with previous studies (Kable & Glimcher, 2007; Keidel, Murawski, & Ettinger, 2023; Peters & Büchel, 2010). We estimated separate discount rates for the delay and date conditions. To get an estimate of the date/delay effect (date premium), we subtracted the estimated log-transformed discount rates from each other (date minus delay). That is, more negative values reflect a higher date/delay effect.

2.5.2 | Behavioural analyses

First, we computed the test–retest reliability of temporal discounting by computing the Pearson correlation between log-transformed discount rates in the delay condition in the laboratory and fMRI. Then, to analyse whether the date/delay effect was replicated, we inspected the 95% highest density intervals (HDIs) of the estimated log-transformed discount rates from the fMRI task and used the Bayesian Estimation Supersedes the *t*-test (BEST) approach (Bååth, 2014; Kruschke, 2013) to estimate the probability with which the paired difference of the point estimates of discount rates, that is, the date premium, differed from zero. Additionally, we compared the point estimates of the log-transformed discount rates in the delay and date conditions using a paired-sample *t*-test. We also used paired *t*-tests to

[1]We note that we deviated from the preregistration here, as we initially planned to use Bayes factors to compare model fits. However, recent evidence suggests that LOO-CV yields the best-approximating model and the most accurate parameter estimations (Lartillot, 2023).

examine whether reaction times (RTs) and log-transformed RTs differed between conditions.

Next, we carried out eye-tracking data analyses similar to those reported in Keidel, Murawski, and Ettinger (2023). We computed means for saccade frequencies within different AOIs, saccade frequencies between different AOIs (based on fixation data; a change of fixated AOI was considered a saccade) and cumulative fixation durations within different AOIs. Moreover, we created summary measures for saccade direction (vertical/horizontal) and fixation focus (reward/time) for each condition. Specifically, for saccade direction, we computed the Payne index (Payne, 1976), which represents the ratio of the difference of vertical and horizontal saccades relative to their sum. Values range from −1 to 1, with values higher than zero reflecting more vertical eye movements (i.e., a more integrative strategy) and values below zero reflecting more horizontal eye movements (i.e., a more comparative strategy). For fixation focus, we computed a similar index based on the fixation durations ranging between −1 and 1 (Amasino et al., 2019, formula 4), where values higher than zero reflected a relative reward focus and values below zero reflected a relative time focus. Given that we analysed eye-tracking data from 18 participants only (see Section 2.4.2) and wanted to reduce the influence of outliers, we excluded all individual data of variables used in the analyses that were above or below 2.5 standard deviations of the sample mean. We then used two paired *t*-tests to compare the number of saccades within AOIs and between AOIs (horizontal, vertical, diagonal) between the delay and date conditions. To investigate differences in the number of vertical vs. horizontal saccades between AOIs in the two conditions (delay vs. date), we conducted a paired *t*-test comparing the Payne indices. To examine this in more detail, we examined differences between conditions in the number of all possible types of horizontal and vertical saccades (horizontal between rewards vs. horizontal between times vs. vertical between SIR attributes vs. vertical between LLR attributes) using further paired *t*-tests. We then compared fixation durations on attribute types (reward vs. time) in the two conditions (delay vs. date) using a 2 × 2 repeated-measures ANOVA. Effects in this and the following ANOVA were further examined using Bonferroni-Holm corrected post hoc *t*-tests. To analyse whether the effects were the same for each option, we added an additional factor for the option (SIR vs. LLR) and conducted a 2 × 2 × 2 repeated-measures ANOVA. Then, to see whether the differences we found on the within-subject level were also predictive of the between-subject magnitude of the date/delay effect, we ran a linear regression analysis of the date/delay effect on difference measures (date minus delay) of saccade direction (i.e., Payne index) and of fixation focus measures. Similarly, we calculated Pearson correlations between temporal discounting and eye-tracking measures (as in Keidel, Murawski, & Ettinger, 2023). Finally, to see whether differences in attribute values interacted with condition to predict choice behaviour, we ran a linear mixed model with choice as dependent variable (0 = SIR;1 = LLR). Condition (effect coded: −1 = delay, 1 = date), difference in reward (Δreward) and difference in time (Δtime), and their interactions were modelled as fixed effects. We included participant random effects on the intercept.

2.5.3 | fMRI analyses

The preprocessed BOLD data were used to estimate a general linear model (GLM) at the first level. Conditions were modelled as separate regressors by convolving variable boxcar functions (trial onset until reaction) with the hemodynamic response function for each trial. We added the sum of the SVs of both options of a trial as parametric modulator (Reeck et al., 2021). Specifically, for each trial, the SV of each option was computed using the hyperbolic discount function as follows: $SV = A/(1 + kD)$, where SV represents the subjective value of the chosen option, A is the objective value of the reward, *k* is the discount rate for the respective condition and D is the delay (Mazur, 1987). Note that for the SIR, SV = A. The sum of SVs was demeaned and added to the respective condition. In SPM, the parametric regressor is automatically orthogonalised with respect to the unmodulated regressor (Mumford et al., 2015). Thus, in total, four regressors of interest were included in the GLM: delay trial, modulation of the delay trial by SV, date trial, modulation of the date trial by SV. The six motion parameters from realignment were added as regressors of no interest. Fixations and pauses between blocks (note that data acquisition continued through pauses) were not modelled and served as implicit baseline. Slow-signal drifts were removed using a 128-s high-pass filter.

We computed first-level contrasts by comparing the delay and date regressors to an implicit baseline (delay > baseline, date > baseline) and against each other (delay > date, date > delay). The first-level contrasts were then analysed on the second level (whole-brain) using random-effect one-sample *t*-tests. We applied a familywise error rate (FWE) corrected voxel-related threshold of $p < .05$ and a minimum cluster size of 10 voxels for the contrasts against baseline and a voxel-related threshold of $p < .001$ and an FWE-corrected cluster threshold, following the SPM procedure, for the comparison of conditions and all following analyses.

Next, we analysed the parametric modulation effects of SV. Following a whole-brain analysis of SV differences between conditions, we used a region of interest (ROI) approach. Specifically, given that the SV signal is usually found in bilateral vS and bilateral ventromedial prefrontal cortex (vmPFC) (Bartra et al., 2013; Frost & McNaughton, 2017; Kable & Glimcher, 2007; Moreira et al., 2016), we defined ROIs according to the meta-analysis by Bartra et al. (2013) using masks from their fig. 9 (https://www.sas.upenn.edu/~mcguirej/meta-analysis.html). We compared parametric modulation effects of the sum of SVs in vS and vmPFC against baseline and between conditions. In additional analyses, we replaced the sum of SVs with the SV of the chosen option, the difference of SVs (LLR − SIR) and the ratio of SVs (LLR/SIR) as parametric modulators. To examine SV effects more precisely, we additionally computed two models in which differences (or sums) of objective rewards and objective timings of the options were included as parametric modulators. As objective reward and timing differences are correlated in the MCQ, we used the automated orthogonalisation in SPM and set up two separate models in which either reward or timing was entered first and the other entered second to obtain variances specific to the variable entered second (Mumford et al., 2015).

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We then analysed individual differences in the date/delay effect by adding discount rates in the two conditions and the date/delay effect as second-level covariates to the corresponding contrast images of the original model. Specifically, we examined in which brain regions the discount rates in the two conditions were associated with the delay > baseline and date > baseline contrasts and in which brain regions the magnitude of the date/delay effect was associated with the date > delay contrast. Similarly, to explore potential associations with personality, we also used the UPPS-P subscale scores as covariates in the date > delay contrast.

Finally, we used Pearson's correlations to explore whether contrast estimates of significant clusters in the date > delay contrast as well as the date/delay effect covariate effects in this contrast were associated with the eye-tracking difference measures.

3 | RESULTS

3.1 | Behavioural analyses

The test–retest reliability of the log-transformed discount rate estimates in the standard delay condition between the laboratory and fMRI sessions was $r(29) = .70$. When excluding one outlier, this correlation increased to $r(28) = .81$.

The 95% HDIs of the posterior distributions of the log-transformed discount rates were (−6.19; −5.28) in the date and (−5.89; −4.75) in the delay condition. The mean paired difference of their point estimates was −0.43 with a 95% HDI of (−0.66; −0.20) and had a probability of more than 99.9% of being less than zero, replicating the date/delay effect. Similarly, a paired *t*-test showed reduced temporal discounting in the date ($M = -5.72$, SD = 1.17) compared to the delay condition ($M = -5.27$, SD = 1.55), $t(30) = -3.96$, $p < .001$, $g_{av} = 0.33$. Descriptive values for each condition revealed that the majority of participants showed the date/delay effect in the expected direction but that this effect varied in magnitude between participants (Supplement A).

Moreover, we found that participants had higher RTs in the date ($M = 2.59$ s, SD = 0.66 s) compared to the delay condition ($M = 2.26$ s, SD = 0.55 s), $t(30) = 7.22$, $p < .001$, $g_{av} = 0.54$. Given that RTs within participants were characteristically skewed to the right (Whelan, 2008), with an average within-participant skewness of 0.94 (SE = 0.08), we tested whether this effect was robust by log-transforming the RTs and comparing their means. Results of the previous analysis were confirmed, $t(30) = 7.31$, $p < .001$, $g_{av} = 0.53$.

With regard to eye-tracking, we found that participants made more saccades within AOIs in the date ($M = 3.48$, SD = 1.38) than in the delay condition ($M = 2.45$, SD = 1.01), $t(17) = 6.87$, $p < .001$, $g_{av} = 0.84$, but the number of saccades between AOIs did not differ significantly (delay: $M = 4.66$, SD = 1.10; date: $M = 4.81$, SD = 1.00), $t(16) = -0.74$, $p = .470$, $g_{av} = 0.21$.

Focusing on differences between conditions in the frequency of vertical vs. horizontal saccades between AOIs (Figure 2a), a paired *t*-test revealed that the Payne index, that is, the proportion of vertical relative to horizontal saccades, was lower in the date than in the delay condition, $t(17) = -3.09$, $p = .007$, $g_{av} = 0.41$. Separate Bonferroni-Holm corrected *t*-tests showed that participants made significantly more horizontal saccades in the date than in the delay condition, $t(17) = 5.13$, $p_{adj} < .001$, $g_{av} = 0.61$, while the frequency of vertical saccades did not significantly differ between conditions, $t(17) = 0.98$, $p_{adj} = .341$, $g_{av} = 0.15$. Additional Bonferroni-Holm corrected *t*-tests comparing differences between conditions for all possible types of saccade direction (Figure 2b) showed that the difference in horizontal saccades could be traced back to the higher number of saccades between time attributes in the date compared to the delay condition, $t(17) = 7.73$, $p_{adj} < .001$, $g_{av} = 1.20$ (all other $p_{adj} > .05$).

To analyse fixation durations within AOIs, we conducted a 2 × 2 repeated-measures ANOVA, using condition (delay vs. date) and attribute type (reward vs. time) as factors (Figure 2c). We found a significant interaction effect, $F(1,16) = 65.02$, $p < .001$, $\eta_p^2 = 0.80$, and main effects of condition, $F(1,16) = 20.69$, $p < .001$, $\eta_p^2 = 0.56$, and attribute type, $F(1,16) = 25.11$, $p < .001$, $\eta_p^2 = 0.61$. Post hoc *t*-tests revealed that participants fixated time attributes significantly longer in the date than in the delay condition, $t(16) = 8.75$, $p_{adj} < .001$, $g_{av} = 1.59$, and reward attributes significantly shorter in the date than the delay condition, $t(16) = -2.58$, $p_{adj} = .020$, $g_{av} = 0.36$. To distinguish between all four AOIs, we conducted a 2 × 2 × 2 repeated-measures ANOVA that additionally included option (SIR vs. LLR) as a factor (Figure 2d). Most importantly, we found a significant two-way interaction between condition and attribute type, $F(1,15) = 103.74$, $p < .001$, $\eta_p^2 = 0.87$ (complete ANOVA results in Supplement B1). Post hoc *t*-tests indicated that this effect emerged for both SIR, $t(15) = 10.50$, $p_{adj} < .001$, $g_{av} = 2.56$, and LLR, $t(15) = 6.89$, $p_{adj} < .001$, $g_{av} = 1.03$ (other post hoc *t*-test comparing fixation durations for attribute types in the two conditions: $p_{adj} > .05$). Thus, we found that participants fixated time attributes of both SIR and LLR longer in the date than in the delay condition, while there was no significant difference for the reward attributes. Similar results emerged when analysing the number of saccades and fixations within AOIs (Supplement B2 and B3).

On a between-subject level, a linear regression showed that the date/delay effect was not significantly predicted by difference measures of the proportion of vertical (vs. horizontal) saccades, $\beta = 0.02$, $t(14) = 0.06$, $p = .950$, and the fixation duration on rewards (vs. times), $\beta = 0.21$, $t(14) = 0.81$, $p = .431$ (model $R^2 = .05$, $p = .725$). Pearson correlations of temporal discounting and eye-tracking measures (which reflect in part the same calculations as in tab. 4 of Keidel, Murawski, & Ettinger, 2023) can be found in Supplement C1 and C2 and Pearson's correlations of temporal discounting and UPPS-P variables (not yielding any significant effects) in Supplement D. Generally, all but one of the significant associations in Supplement C1 are in the same direction as in Keidel, Murawski, and Ettinger (2023).

Finally, to analyse whether differences in reward or time values (or both) interacted with condition to predict choice behaviour, we ran a mixed-effect model predicting choice behaviour (0 = SIR; 1 = LLR) by condition (effect coded: −1 for delay, 1 for date), absolute differences in reward (Δreward) and time (Δtime) and their

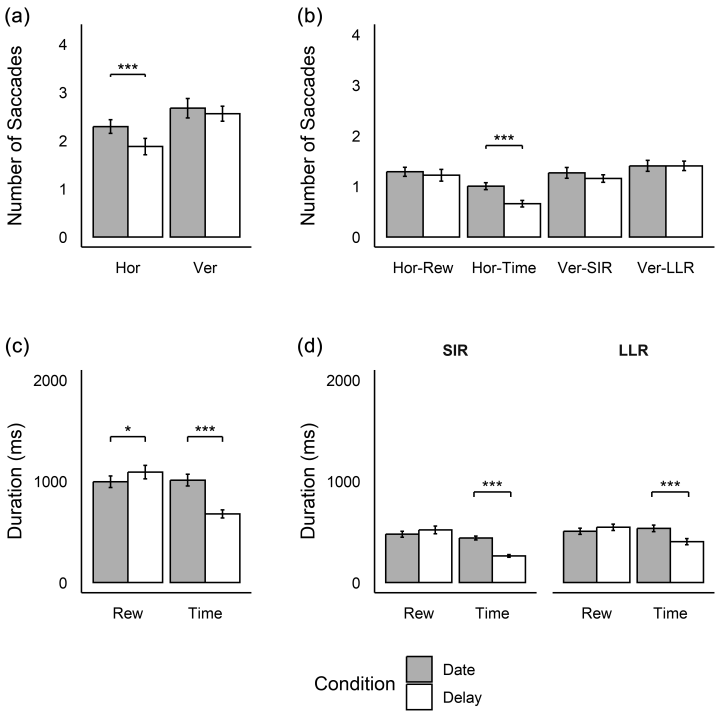


FIGURE 2 Number of Saccades Between Areas of Interest (AOIs) and Duration of Fixations Within AOIs. (a) represents all horizontal (Hor) and vertical (Ver) saccades between AOIs, and (b) represents saccades separated by attribute-wise (Rew = reward), horizontal saccades and option-wise (SIR, smaller-immediate reward; LLR, larger-later reward), vertical saccades. (c) represents the fixation duration on reward and time AOIs, summarised over options, and (d) represents fixation durations on reward and time AOIs, separated by options. Error bars represent standard errors of the mean. Asterisks are only depicted for post hoc *t*-tests within the same category (i.e., bars next to each other). $^{*}p_{adj} < .05$, $^{***}p_{adj} < .001$ (Bonferroni-Holm corrected for multiple comparisons).

interactions. While we found that, expectedly, the date condition, $\beta = 0.44$, $p < .001$, a higher Δreward, $\beta = 1.86$, $p < .001$, and a lower Δtime, $\beta = -2.94$, $p < .001$, significantly predicted a higher probability of choosing the LLR, we did not find any significant interactions (Supplement E).

3.2 | fMRI analyses

3.2.1 | BOLD activation in delay and date conditions

When compared separately to baseline, the delay and date conditions activated largely similar regions (Figure 3, Supplement F1 and F2). Specifically, compared to baseline, both conditions led to higher activations in occipital cortex (including V1, V3), anterior/mid-cingulate cortex (ACC, MCC), insula and inferior frontal gyrus. The delay condition also activated small clusters in caudate and putamen.

Comparing the two conditions, we did not find any significant differences for the contrast delay > date. However, in the contrast date > delay, we found higher activation in visual areas, left posterior cingulate cortex (PCC), right precuneus, left middle/superior frontal gyrus (MFG/SFG) and bilateral angular gyrus (Figure 4, Table 1).

3.2.2 | Analysis of the subjective value signal

First, a whole-brain analysis of the SV signal did not yield any significant activation differences between conditions. Next, in the ROI analyses focusing on vS and vmPFC, we found that a higher sum of SVs of SIR and LLR was associated with stronger activation in vS in the delay condition, $t(30) = 2.60$, $p = .014$, $d = 0.47$, but not in the date condition, $t(30) = -0.42$, $p = .674$, $d = 0.08$. Comparing the two conditions, the association in the delay condition was significantly higher than in the date condition, $t(30) = 2.18$, $p = .037$, $g_{av} = 0.57$. We did not find any significant effects for the vmPFC (all $p > .05$). While similar results emerged when using the SV of the chosen option as regressor, the correlations were not significant when using the difference or the ratio of SVs of SIR and LLR (Supplement G1). Consistently, however, whenever significant effects emerged, SV only correlated with neural activity in the delay but not the date condition, suggesting a more robust SV signal in the delay condition. Models in which both objective rewards and timings were included as parametric modulators showed that both higher reward differences and higher time differences were associated with higher vS activity in the delay (reward differences: $t(30) = 2.97$, $p = .006$, $d = 0.53$; time differences: $t(30) = 2.27$, $p = .030$, $d = 0.41$) but not in the date condition (reward differences: $t(30) = 0.70$, $p = .487$, $d = 0.13$; time differences: $t(30)$

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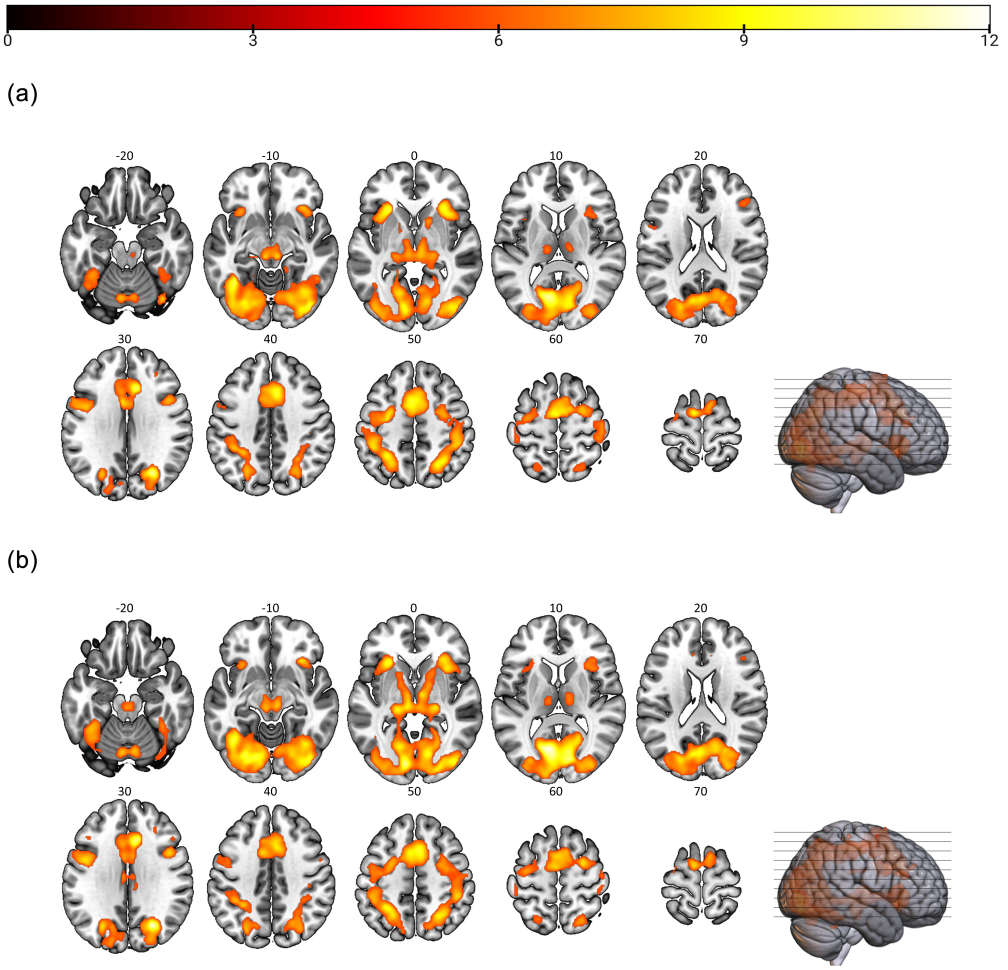


FIGURE 3 Blood-oxygen level-dependent (BOLD) signal during intertemporal choices. Depicted are significant areas from one-sample *t* contrasts (a) delay > baseline and (b) date > baseline with an FWE-corrected voxel-related threshold ($p < .05$) and a minimum cluster size of 10 voxels. Intensities of colours reflect the heights of *t*-values, as shown in the colour bar. Number labels refer to Montreal Neurological Institute (MNI) *z*-coordinates.

$= 0.80$, $p = .431$, $d = 0.14$), although the differences between the two conditions were not significant ($p > .05$). No significant effects emerged for the vmPFC (all $p > .05$). Similar results emerged when using reward and timing sums, except that (i) the difference in the association of reward sums and vS activity was significantly higher in the delay than in the date condition, and (ii) the objective time effect in the delay condition was not significant (Supplement G2). In sum, we found an SV signal as well as objective reward and (potentially) time signals in the vS in the delay but not in the date condition.

3.2.3 | Covariates of activation differences in date and delay conditions

We explored whether individual discount rates covaried with activation in the contrasts delay > baseline and date > baseline. Using the individual discount rates in each condition as covariate, we did not find any significant correlations. However, using the date/delay effect as covariate in the date > delay contrast, we found that a lower date/delay effect correlated with higher activity differences in bilateral

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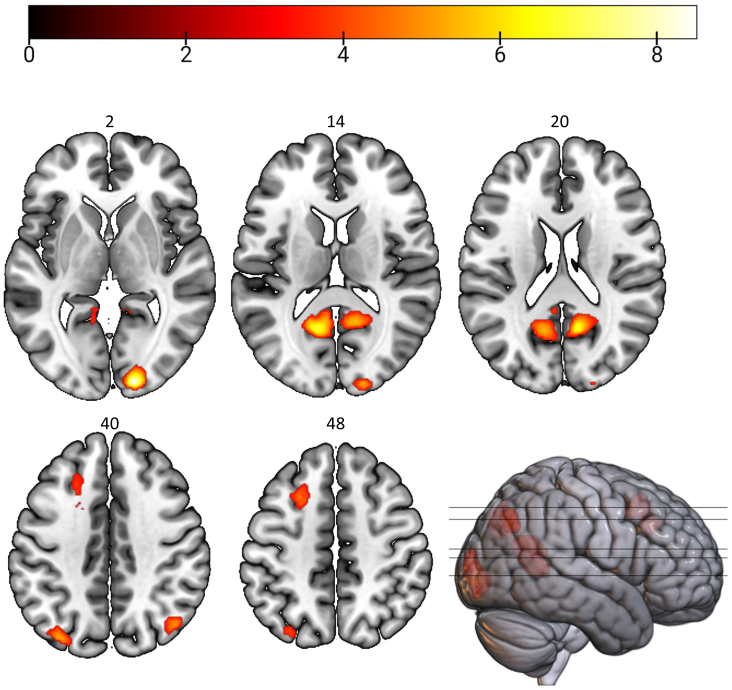


FIGURE 4 Blood-oxygen level-dependent (BOLD) signal in Date > Delay. Depicted are significant areas from a one-sample *t* contrast date > delay with a voxel-related threshold of $p < .001$ and an FWE-corrected cluster threshold. Intensity of colours reflects the heights of *t*-values, as shown in the colour bar. For the delay > date contrast, no significant clusters emerged. Number labels refer to Montreal Neurological Institute (MNI) *z*-coordinates.

occipital areas and cerebellum, right SFG, bilateral MFG, bilateral posterior medial frontal cortex (pMFC) and left ACC and MCC (Figure 5, Supplement H).[2] That is, people who had a less pronounced behavioural date/delay effect or the opposite effect (i.e., higher discounting in the date compared to the delay condition), showed activity that differed more strongly between conditions in brain regions associated with visual information processing, attention and eye movements as well as cognitive control.

Using the UPPS-P scores as covariates, we did not find any significant clusters in the date > delay contrast. Thus, we did not find any significant correlations between the neural date/delay effect and the five trait impulsivity constructs assessed with the UPPS-P.

3.3 | Explorative correlations of Eye-tracking and fMRI analyses

In the eye-tracking sample, we examined the between-subject relationships of significant clusters in the contrast date > delay and the covariate effects of the date/delay effect on this contrast with difference measures of the proportion of vertical (vs. horizontal) saccades and the fixation duration on rewards (vs. times) (Supplement I1 and I2). First, for the date > delay contrast, we found a significant negative correlation between the occipital cortex cluster and the duration of fixations on rewards (vs. times), $r(16) = -.50$, $p = .034$. That is, higher fixation durations on time attributes were associated with stronger activation in occipital cortex in the date compared to the delay condition, likely representing the higher number of symbols in dates compared to delay units. Second, for the effects of the date/delay effect as covariate in the date > delay contrast, we did not find any significant correlations.

[2]Note that, using the delay > date contrast, the interpretation would be vice versa, that is, a higher date/delay effect was associated with higher activity differences in these regions.

4 | DISCUSSION

We aimed to elucidate the mechanisms of the date/delay effect in intertemporal choice using eye-tracking and fMRI. Results showed that the date condition led to lower discount rates, replicating the date/delay effect (Dshemuchadse et al., 2013; Jiang & Dai, 2021; Keidel, Murawski, & Ettinger, 2023; Keidel, Murawski, Pantelis, & Ettinger, 2023; LeBoeuf, 2006; Naudé et al., 2018; Read et al., 2005). We also found higher RTs in the date compared to the delay condition. Furthermore, eye-tracking revealed a higher proportion of saccades between time attributes and higher fixation durations on time attributes in the date compared to the delay condition, also replicating

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TABLE 1 Blood-oxygen level-dependent (BOLD) signal in Date > Delay.

Anatomical label (functional label)	Cluster size	*t*-value	MNI coordinates		
			x	*y*	*z*
L Calcarine Gyrus	624	6.93	−12	−58	14
L PCC		4.77	−6	−48	16
R Precuneus	522	7.01	10	−60	20
R Precuneus		5.69	14	−54	12
R Lingual Gyrus		4.17	8	−46	6
R Calcarine Gyrus (V1)	505	8.49	16	−96	2
R Lingual Gyrus (V3)		8.48	18	−94	−2
L Middle Occipital Gyrus	365	5.32	−34	−78	40
L Middle Occipital Gyrus (IPL)		5.17	−40	−78	32
L Middle Occipital Gyrus (IPL)		5.12	−42	−76	34
L Angular Gyrus (IPL)		5.00	−46	−74	32
L Middle Frontal Gyrus	350	4.96	−24	16	48
L Middle Frontal Gyrus		4.84	−28	18	52
L Middle Frontal Gyrus		4.67	−24	18	54
N/A[a]		4.52	−22	22	36
N/A[a]		4.51	−22	26	34
N/A[a]		4.39	−22	10	46
L Superior Frontal Gyrus		4.23	−22	22	46
L Middle Frontal Gyrus		3.70	−18	26	42
R Angular Gyrus (IPL)	164	4.99	44	−70	40

Note: The Anatomy Toolbox (Eickhoff et al., 2005) was used to infer anatomical labels. In case of an unknown area (N/A), we additionally specified the region in the footnote using the Neuromorphometrics atlas in SPM. Cluster size is given in number of voxels. MNI = Montreal Neurological Institute.
[a]L Cerebral White Matter.

previous results (Keidel, Murawski, & Ettinger, 2023). Importantly, we observed greater activation in visual areas, angular gyrus, precuneus, and MFG/SFG in the date than in the delay condition. Furthermore, we detected a higher SV signal in the vS in the delay compared to the date condition. Lastly, we found significant correlations between lower behavioural date/delay effects (or opposite effects) and higher activity differences in bilateral occipital areas (including cerebellum), right SFG, bilateral MFG, pMFC, and ACC/MCC in the date > delay contrast.

4.1 | Mechanisms of the date/delay effect

With regard to the cognitive mechanisms of the date/delay effect, our results suggest that differences in time information processing play a role, as suggested by the differential time estimation hypothesis (Read et al., 2005). Specifically, replicating our previous study (Keidel, Murawski, & Ettinger, 2023), we found that people spent more time reading/processing and comparing dates than delay units, suggesting stronger consideration of time information (at least in overt attention). While the former finding alone could also be caused by different reading requirements in the two conditions, the current study emphasised the role of time processing by revealing higher activity in precuneus/PCC and angular gyrus (lateral parietal cortex) in the date than in the delay condition. These regions are associated with episodic thinking (Schacter et al., 2007) and as such are important for the memory-driven system specified by Frost and McNaughton (2017).

Interestingly, the regions identified in our study are similar to those found in a study examining the neural effects of episodic future thinking tags (tag effect) on intertemporal choices (Peters & Büchel, 2010; Sasse et al., 2015), which also have been shown to reduce temporal discounting (Rung & Madden, 2018; H. Scholten et al., 2019). Following Peters and Büchel, it would be possible that "similar mechanisms may underlie the decrease in discounting reported for date-based processing relative to that of delay-based processing (Read et al., 2005) and the tag effect" (Peters & Büchel, 2010, p. 144), that is, a stimulation of visual imagery through framing cues. Alternatively, activity in our study could also reflect higher specificity of the date cues and the resulting possibility for dates to act as a stimulus to trigger memories. In both cases, activity in episodic thinking regions could indicate higher personal relevance and lower psychological distance and, thus, would result in a subjectively closer temporal proximity of the LLR and as such represent a neural equivalent of the lower-level construal of dates compared to delay units suggested by Construal Level Theory (Trope & Liberman, 2003). Indeed, previous studies on Construal Level Theory

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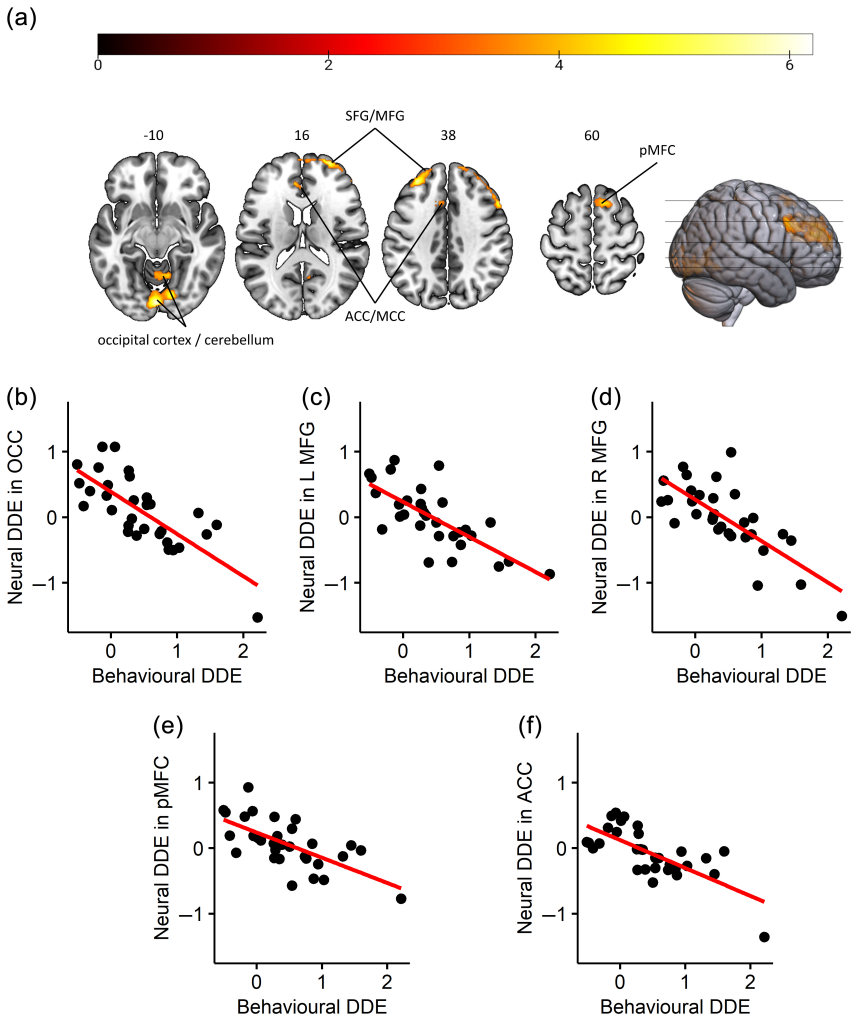


FIGURE 5 Associations Between the Behavioural Date/Delay Effect and the Neural Date/Delay Effect. The behavioural date/delay effect (DDE), that is, $\ln(k)_{Date} - \ln(k)_{Delay}$, was used as covariate for the date > delay contrast (neural DDE). (a) represents significant areas at a voxel-related threshold of $p < .001$ and an FWE-corrected cluster threshold. Intensity of colours reflects the heights of *t*-values, as shown in the colour bar. Upper labels refer to Montreal Neurological Institute (MNI) *z*-coordinates. As the behavioural DDE was initially negatively coded (date minus delay), that is, lower values represent a stronger behavioural DDE, activity in these areas differed more strongly in people showing a smaller (or opposite) behavioural DDE. (b)–(f) illustrate the direction of the DDE-dependent signal changes in significant clusters. For better interpretation, the *x*-axis was recoded so that higher values represent a higher behavioural DDE (i.e., $\ln(k)_{Delay} - \ln(k)_{Date}$). ACC, anterior cingulate cortex; L, left; MCC, medial cingulate cortex; MFG, middle frontal gyrus; OCC, occipital regions; pMFC, posterior medial frontal cortex; R, right; SFG, superior frontal gyrus.

emphasised the role of precuneus/PCC for lower-level construals (Stillman et al., 2017; Tamir & Mitchell, 2011), also within intertemporal choices (Lee et al., 2022). Thus, the date/delay effect can be explained by lower estimates of delay in the date compared to the delay condition—either through relatively more vivid anticipation of future rewards or through memory contents activated by higher specificity of dates. Future studies should therefore consider including subjective time estimate tasks in their designs, as time perception has been shown to influence intertemporal decision-making on behavioural (Zauberman et al., 2009) and neural levels (Cooper

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et al., 2013). Also, asking participants whether they experienced more vivid imagery or specificity in the date condition (Peters & Büchel, 2010) would be useful to pinpoint the cause of differential time estimation.

An additional explanation to a differential time estimation could be that, although reward attributes are not processed more intensively in the date compared to the delay condition, they may be weighted more heavily than time attributes in the ultimate decision process (Keidel, Murawski, & Ettinger, 2023; LeBoeuf, 2006), potentially mediated through more vivid anticipation of a delayed reward. However, in this study, we did not find a significant association of differences in fixation durations on rewards between the two conditions and the magnitude of the date/delay effect, nor an interaction between condition and Δreward in our linear mixed-model (unlike Keidel, Murawski, & Ettinger, 2023), nor any neural correlates suggesting a stronger reward/SV signal in the date condition. Conversely, we found a higher SV signal in the vS in the delay condition, which could reflect higher valuation of the SIR, the LLR or both. Thus, these findings make a higher valuation of rewards in the date condition appear very unlikely. However, as the previous study found Δreward to be more important in the date than in the delay condition in a larger sample (Keidel, Murawski, & Ettinger, 2023), it may be possible that a relatively higher reward weighting assigned to the LLR only occurs in a later, cognitively self-controlled choice stage of the decision-making process (Liu et al., 2012). As different stages of decision-making were not separated in our design, it would be useful in future to separate valuation and choice stages (Liu et al., 2012) to examine which differences occur in which parts of the decision process.

Lastly, according to the choice strategy hypothesis, participants either need to perform complex transformations (i.e., calculating delay units from dates) to use the same strategy in the date as in the delay condition or they need to adapt their strategy (Read et al., 2005). The higher activity in left MFG/SFG in the date > delay contrast might initially suggest more complex transformations in the date than the delay condition because these regions are involved in arithmetic operations (Arsalidou & Taylor, 2011; Fehr et al., 2007). However, the interindividual effects in more widespread prefrontal areas (including MFG/SFG) suggest that this effect is higher when the date/delay effect is lower. That is, higher activity in the SFG/MFG, pMFC and ACC/MCC in the date compared to the delay condition is associated with a smaller behavioural date/delay effect (or even an opposite effect). Given that these regions are involved in cognitive control (Niendam et al., 2012; Ridderinkhof et al., 2004; Wang et al., 2010; for neural intertemporal choice models involving self-control, see Figner et al., 2010; Liu et al., 2012) and—for SFG/MFG—in arithmetic operations (Arsalidou & Taylor, 2011; Fehr et al., 2007), this could suggest that people with a smaller behavioural date/delay effect rely on the same strategy in the two conditions but engage cognitive control or arithmetic processes more strongly, for example by transforming dates to delay units. On the other hand, people with a higher behavioural date/delay effect may calculate less and use a different, potentially more intuitive decision-making strategy to adapt to the date condition (e.g., they may rely more on episodic processes), supporting the choice strategy hypothesis. This strategy could be reflected by the higher total proportion of saccades between time attributes in the date than in the delay condition, replicating previous results (Keidel, Murawski, & Ettinger, 2023). We note, however, that these interpretations are rather speculative. Specifically, it should be noted that the direction in the association between activation of cognitive control regions and the size of the date/delay effect is not clear (i.e., it could also be interpreted that persons with a higher date/delay effect show higher activity in cognitive control regions for the delay > date contrast, reflecting more arithmetic operations in the delay than in the date condition). Moreover, our study did not find a significant association between the difference in strategy use and the date/delay effect. More generally, we note that our study was not sufficiently powered to draw robust conclusions about between-participant associations regarding the eye-tracking measures. Nevertheless, while the eye-tracking results replicate previous explorative findings (Keidel, Murawski, & Ettinger, 2023), our fMRI findings provide tentative evidence for the choice-strategy hypothesis on the neural level. Future studies could examine eye movements in larger samples using an intertemporal choice task with varying times of smaller-sooner rewards to manipulate the difficulty of estimating time differences and examine the effects on reward weighting (and to reduce potentially necessary exclusions, see Section 4.2).

Finally, we note that we did not find correlations of the date/delay effect with trait impulsivity according to the UPPS-P scales, neither on the behavioural nor on the neural level. Even if the power to detect such associations was limited, this suggests that differences in the date/delay effect (and in prefrontal activity) do not strongly reflect trait impulsivity differences but rather a specific task-dependent effect, for example, interindividual differences in the tendency to use comparative strategies and to calculate time differences. Nevertheless, interindividual differences such as intelligence or personality traits could be important, not least because they covary with temporal discounting itself (Keidel et al., 2021). Large-scale studies are needed to uncover such associations with the date/delay effect.

Overall, one may speculate that in general, people are influenced by their time perception but only people with a lower date/delay effect are able to compensate for the effect at least to some extent, for example by exerting cognitive control and converting dates into delay units (at least approximately). On the other hand, people with a higher date/delay effect are influenced more strongly by differential time estimation itself, leading to lower discount rates in the date compared to the delay condition. It remains open how individuals with a higher date/delay effect adapt their strategy to the new requirements of the date condition, that is, whether, for instance, they ultimately rely more on rewards or use a different heuristic to avoid complex transformations.

4.2 | Limitations

Our study has several limitations. First, our eye-tracking sample (after exclusions) was rather small, the accuracy estimate of eye-tracking

data was not high, and effects concerning time attributes were potentially confounded by different reading requirements in the two conditions (i.e., dates are longer than delay units). While the replication of several effects of our previous study with a similar experimental task speaks for the validity of the data (Keidel, Murawski, & Ettinger, 2023), eye-tracking results should only be seen as tentative evidence. Future studies should therefore aim to replicate and extend our results in larger samples. Additionally, given that we excluded several participants because they did not look at the time attribute of the SIR in a sufficient number of trials, future studies should consider varying the time attribute of the smaller-sooner option as well (e.g., manipulate the number of days between 0 and a couple of days in the future). Importantly, while it was not possible to statistically control for reading confounds in our study due to the perfect correlation of condition with the number of symbols within time AOIs, future eye-tracking studies could use different presentations of time attributes. For instance, using a different date format (e.g., "23/12/21") may increase comparability with the delay condition ("29 days") in terms of the number of symbols displayed. Additionally, studies could use a different delay format (e.g., 0 m/4w/1d, i.e., 0 months, 4 weeks, 1 day, vs. 23/12/21; or, supposing that all dates are in the same year, "29 d" vs. "23/12") to parallelise the number of characters used in the two conditions. While we aimed to use a typical presentation form of dates in our study, such experimental manipulations could substantiate our findings while controlling for reading confounds.

Second, the use of the MCQ made it impossible to calculate SVs in the same way as in previous studies (Kable & Glimcher, 2007; Peters & Büchel, 2010), where a fixed reward was set and the SV was computed only for the presented delayed reward. Our intention was to examine the date/delay effect in a design comparable to previous studies, that is, with varying monetary amounts and delays (e.g., Dshemuchadse et al., 2013; Klapproth, 2012; Naudé et al., 2018), to ensure successful replication and higher generalisability. However, this may have weakened potential SV signals in our data. As previous findings suggest that the date/delay effect is robust even with simpler designs (LeBoeuf, 2006; Read et al., 2005), future studies could use a different task to gain higher comparability with other studies regarding SV signals and to be able to independently dissociate parametric effects of reward and time in the date/delay effect. We note, however, that in case of comparative strategies as implied by attribute-based models (Amasino et al., 2019; Dai & Busemeyer, 2014; Marzilli Ericson et al., 2015; Zhang et al., 2022), this approach might not be valid for the date condition.

Third, our fMRI analysis approach was largely explorative, though preregistered. Thus, replication of our BOLD findings is needed.

5 | CONCLUSION

Our study is the first to examine the date/delay effect using fMRI. Combining this approach with eye-tracking, we found evidence for the differential time estimation hypothesis and the choice strategy hypothesis (Read et al., 2005; Zauberman et al., 2009). First, the date condition did not only lead to longer fixation durations on time versus reward attributes compared to the delay condition but we also found higher activity in precuneus/PCC and angular gyrus, that is, areas associated with episodic thinking, prospection and lower-level construals (Lee et al., 2022; Schacter et al., 2007; Stillman et al., 2017; Tamir & Mitchell, 2011). Second, we found more comparative eye movements between time attributes in the date compared to the delay condition and higher prefrontal activity in the date > delay contrast in people with a lower date/delay effect, suggesting that people with a higher date/delay effect exert less cognitive control and calculate relatively less than others in the date condition (Arsalidou & Taylor, 2011; Niendam et al., 2012). In sum, our study suggests that the date/delay effect is contributed to by differential time estimation and some heuristic facilitating intertemporal choices. Future studies should examine more closely whether this heuristic is reflected, for instance, in higher weighting of reward differences or in some other cognitive process.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The behavioural data that support the findings of this study are openly available in OSF at https://osf.io/td5gf/. The MRI data are available on request from the corresponding author. The MRI data are not publicly available due to ethical restrictions.

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Appendix D | Study IV

Keidel, K., Murawski, C., Pantelis, C., & Ettinger, U. (in press). The relationship between schizotypal personality traits and temporal discounting: The role of the date/delay effect. *Schizophrenia Bulletin*. https://doi.org/10.1093/schbul/sbad110

Preregistration: https://osf.io/7jxf9
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The Relationship Between Schizotypal Personality Traits and Temporal Discounting: The Role of the Date/Delay Effect

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Abstract

Background and Hypothesis: Many patients with psychiatric disorders show increased temporal discounting, i.e., they discount future rewards more steeply than healthy controls. However, findings for schizophrenia and schizotypy, a personality constellation considered to be on the schizophrenia spectrum, are less clear. Moreover, the role of future time representation in temporal discounting in the schizophrenia spectrum has not been examined. We hypothesised positive associations between schizotypal personality traits and temporal discounting and reduced temporal discounting when the timepoint of future rewards is represented in dates rather than delay units (the date/delay effect). Further, we explored associations between schizotypy and the magnitude of the date/delay effect.

Study Design: We conducted a large-scale, general-population online study (N=1,000) assessing temporal discounting with the Monetary Choice Questionnaire (MCQ) and schizotypal traits with the Short Oxford-Liverpool Inventory of Feelings and Experiences (sO-LIFE). Time representation in the MCQ (dates vs. delays) was manipulated within-subject.

Study Results: Associations between temporal discounting and sO-LIFE subscales were not significant after Bonferroni correction (all $r \leq .06$). The date/delay effect was successfully replicated ($p < .001$, $g_{av} = .22$). Interestingly, higher values in the sO-LIFE Unusual Experiences subscale predicted the magnitude of the date/delay effect when controlling for influences of other sO-LIFE subscales, age, education and drug use.

Conclusions: Temporal discounting was not associated with schizotypy, but individuals with higher levels of positive schizotypy were more sensitive to manipulations of the representation of future timepoints. Future studies should focus on these processes as potential mechanisms in the development and treatment of cognitive-perceptual deficits in the schizophrenia spectrum.

Keywords: future time perception, intertemporal choices, MCQ, schizotypy, sO-LIFE

1 Introduction

Schizotypy refers to a personality constellation resembling schizophrenia symptoms on a subclinical level and reflecting vulnerability for schizophrenia.[1] Schizotypy comprises positive, negative and disorganised dimensions,[2] although some conceptualisations include impulsive nonconformity as a fourth dimension.[3] The fully dimensional approach, conceptualizing schizotypy as personality dimensions within the general population,[4] has gained support by studies revealing a continuum between schizotypal traits and psychotic disorders like schizophrenia.[5–10] Therefore, studies examining schizotypy in the general population do not only allow conclusions to be drawn about this multifaceted construct itself but also about the aetiology and mechanisms underlying schizophrenia[5,9,11] whilst excluding confounds such as medication.[9] For instance, higher levels of schizotypy are, like schizophrenia, associated with deficits in cognitive functions such as attention, working memory and language,[7,11,12] albeit with less pronounced effect sizes.[9] Parallels between schizotypy and schizophrenia can also be found in maladaptive behaviours such as increased nicotine[13–16] and cannabis consumption,[14,17,18] or decreased physical activity,[19,20] pointing to more impulsive decision making and deficits in pursuing long-term goals in individuals on the schizophrenia spectrum.

Impulsive decision making can be assessed with intertemporal choice tasks, in which participants choose between smaller rewards available sooner and larger rewards available later. This phenomenon of subjectively devaluing future rewards is known as delay discounting or temporal discounting (TD).[21] Steeper TD is related to individual differences in impulsivity[22–24] and to a broad range of mental disorders,[25] including schizophrenia.[26–33] Steeper TD has also been found in high schizotypy.[34–36] However, for both schizophrenia and schizotypy, findings are not entirely consistent.[31,36–40] Given that only few studies have examined associations between schizotypy and TD, with most applying an extreme group approach,[34,35] further research is warranted to explore the entire continuum.

Beyond establishing the association between schizophrenia spectrum phenotypes and TD, its potential origins remain unclear. Hypotheses [33,34] include roles of cognitive deficits, genetics, smoking (given that smoking is both highly prevalent in schizophrenia[13,15] and related to TD[41]) and disease symptoms and medication. Importantly, studies in schizophrenia patients revealed that cognitive deficits at least partly play a role,[26–30,32,33] as patients represent future rewards differently than controls. In intertemporal choice tasks, divergent representations of future rewards may have three causes: aberrant valuation of *rewards*[42–44], aberrant valuation of (future) *time*[44–47] and aberrant cognitive mechanisms or strategies in the *integration* of reward and time information.[48,49]

All of these can potentially be observed in schizophrenia. First, schizophrenia patients show deviations in reward processing and valuation.[50–52] Particularly, they show reduced motivational drive and anticipatory pleasure than healthy controls[51,53–55] and use less – or biased – information on reward, probability and effort to make decisions.[31,55–58] As a result, they are less sensitive to changes in these environmental variables, ultimately leading to

potentially maladaptive and impulsive behaviours.[57] Second, schizophrenia patients show altered time processing and perception,[59–61] resulting in decreased precision (i.e., higher variability) and, in some tasks, aberrant accuracy of time estimates. A recent meta-analysis[60] showed that schizophrenia patients perceive durations, depending on the task, as either longer or shorter than objective time, reflecting altered internal clock mechanisms[62] and/or cognitive deficiencies relating to working memory.[63] Third, in agreement with working memory deficits in schizophrenia, schizophrenia patients show impairments in integrating affective and cognitive decision features, such as reward and time information of two options.[50,64]

Importantly, altered time estimation in schizophrenia not only concerns present time[60] but also future time[30,65], i.e., estimating time periods that individuals have not yet experienced.[46] Since the latter is essential in intertemporal choices,[46,66,67] it may be that schizophrenia spectrum individuals subjectively overestimate reward delays in intertemporal choice tasks.[66,68,69] In combination with above-mentioned differences in reward processing, which, incidentally, also lead to less anticipatory pleasure for more distal rather than proximal rewards,[34,70,71] overestimation of delay would ultimately lead to increased impatience and more impulsive behaviours.

The same argumentation may apply to schizotypy, where deviations in reward[35,54,72] and time processing[73,74] have also been found. However, it should be mentioned that for schizotypy, studies of the complete continuum are scarce and results are less consistent than for schizophrenia, particularly with regards to time perception where findings mostly refer to retrospective time bisection tasks[73–75] that generally revealed evidence of a decelerated internal clock.[60]

Thus, increased TD in the schizophrenia spectrum might be caused by alterations in reward or time processing or their integration. While previous studies have emphasized the role of reward processing,[27,34] here we wished to determine whether TD differences are partly due to altered time processing. Given that intertemporal choice tasks involve both reward- and time-related information, measuring the influence of either in isolation is difficult. However, differences in choice due to time perception may be examined using a framing that specifically manipulates sensitivity to time: Usually, time in intertemporal choice tasks is presented in delay units (i.e., days) from the present. However, when time is framed in dates, TD is reduced compared to the standard delay condition, an effect known as the date/delay effect.[76–79] While the exact cognitive mechanisms underlying the effect are not entirely clear, time sensitivity likely plays a major role. Specifically, time periods represented by dates are perceived as shorter than those represented by time units.[80] Thus, this manipulation of time attributes can be drawn upon to offer novel insights into the mechanisms that may underlie altered intertemporal choice in schizotypy.

In this preregistered study, we assessed schizotypal personality traits in a large, general-population sample (N=1,000) to investigate two primary research goals: First, given inconsistent associations between TD and schizotypy,[34–36,40] we aimed to examine, for the

first time, the association of TD with the four dimensions of schizotypy assessed by the Short Oxford-Liverpool Inventory of Feelings and Experiences (sO-LIFE).[81] Second, we attempted to replicate the date/delay effect and relate it to schizotypy in order to draw conclusions about the mechanisms of decision making impairments in the schizophrenia spectrum. We hypothesized that (i) TD is positively associated with schizotypy[81] in the original delay condition and that (ii) the date/delay effect[76,77] is replicated, and we planned to investigate whether the magnitude of the date/delay effect is associated with schizotypy.

2 Methods

2.1 Participants

Based on an *a priori* power analysis with G*Power,[82] we aimed for 1,000 participants (≥18 years), providing 88.68% power to reveal a correlation of r=0.1 between schizotypy and TD (two-tailed alpha level of 0.05; see preregistration: https://osf.io/7jxf9/?view_only=6f0fef4170a14cba9767211d69902c54). To exclude careless responders, we used ten items adapted from Jackson's Infrequency Scale[83] (e.g., "Have you ever kept a pet monkey for years?") embedded within the sO-LIFE. All participants who gave at least one "infrequent" answer were excluded before data analysis. Additionally, we followed recommendations[84] to exclude participants with low consistency in their response patterns in the Monetary Choice Questionnaire (MCQ).[85] Specifically, we excluded participants with consistency of <0.80 within any of the different magnitudes (small, medium, large) of either MCQ version (delay/date).

The study was advertised via social media and student mailing lists and data were collected online via Unipark (Tivian XI GmbH, Cologne, Germany). As incentives, participants were given the opportunity to take part in a lottery to win one of five Amazon vouchers (€25 each) and psychology students could additionally receive course credit (which was erroneously not mentioned in our preregistration). Study procedures were approved by the ethics committee of the Department of Psychology of the University of Bonn. In total, 1,338 participants completed the study, 338 of whom had to be excluded due to infrequency or consistency criteria, leaving a final sample of N=1,000. All participants provided written consent. Participants (25.6% male, 73.9% female, 0.5% diverse) were on average 29.93 years old (SD = 11.88; range 18–81) and had relatively high educational levels (Supplement A: 9.7% low, 50.5% medium, 38.8% high education; no response: 1.0%).

2.2 Measures

2.2.1 Monetary Choice Questionnaire (MCQ)

To assess TD, we used the MCQ[85] in a German version. The MCQ comprises 27 decisions between smaller-immediate (SIR) and larger-later rewards (LLR). Items can be divided into three different levels of reward magnitudes, with nine items at each magnitude level: small (LLR range: 25€–35€), medium (LLR range: 50€–60€) and large (LLR range: 75€–85€). The MCQ has been validated in clinical and non-clinical populations[24,85] and shows high test-retest reliability.[86] As we wanted to examine the date/delay effect,[76,77] two different MCQ versions were used: the time interval until receipt of the LLR was presented either as number of days (e.g., in 117 days) or as dates (e.g., on 30th November 2023). Participants completed both versions. Choices were hypothetical; however, participants were instructed to answer as if they would actually receive the rewards. The presentation order of items was as in Kirby et al.,[85] but the presentation order of the two versions was randomized. Choice consistency and hyperbolic discount rates were estimated based on previous procedures[85] and syntax.[84] After checking for sufficiently consistent choices, discount rates for each of the three magnitude levels in each version were combined into a single index (k) for each version by calculating their geometric mean. Subsequently, discount rates were log-transformed due to skewness (delay: skew=5.62, *SE*=0.08; date: skew=6.93, *SE*=0.08).

2.2.2 Short Oxford-Liverpool Inventory of Feelings and Experiences [sO-LIFE]

The sO-LIFE[81] comprises 43 items covering four schizotypy dimensions: (i) unusual experiences (UE), reflecting positive schizotypy (e.g., odd perceptual experiences, magical thinking); (ii) cognitive disorganization (CD), reflecting disorganized schizotypy (e.g., difficulties in attention and decision-making, social anxiety); (iii) introvertive anhedonia (IA), reflecting negative schizotypy (e.g., lack of pleasure, avoidance of intimacy); and (iv) impulsive nonconformity (IN), reflecting impulsive and eccentric behaviours (e.g., lack of self-control, anti-sociality). sO-LIFE subscales show high test-retest-reliabilities (.69–.87 for a 1-month interval) and acceptable-to-high internal consistencies (.62–.80).[87] Here, a German version was administered.[88] Participants provided dichotomous responses ("no" or "yes") and a sum score was computed for each subscale.

2.2.3 Alcohol, Smoking and Substance Involvement Screening Test (ASSIST)

The Alcohol, Smoking and Substance Involvement Screening Test (ASSIST, version 3.1)[89,90] is a measure developed by the World Health Organization (WHO) to screen for problematic substance use, resulting in risk scores for a range of psychoactive substances (such as tobacco products, alcohol, cannabis, etc.). For each substance, up to eight questions are asked, referring to amount, craving and negative consequences of drug use and failed abstinence attempts. Given that our study was conducted online, we used the ASSIST as self-report measure. Alcohol items were omitted since we also used the Alcohol

Use Disorders Identification Test (AUDIT).[91] Scoring was done according to the manual,[89] with a potential sum score range from 0 to 33 (due to a programming error, question number 3 of the ASSIST was not displayed for any drug, which is why the sum score does not go up to 39 and is not comparable to other studies; given that we only use a small part of the ASSIST as control variable, the missing item is unlikely to influence the results). If a participant indicated that they never had consumed any of the substances (item 1) nor any of them in the last three months (item 2), all subsequent questions were skipped, resulting in a score of 0. In our statistical analysis, we solely used the tobacco data, due to the large number of non-consumers of the other drugs.

2.2.4 Alcohol Use Disorders Identification Test (AUDIT)

The AUDIT[91] is a measure developed by the WHO to identify problematic alcohol use and to screen for excessive drinking. It contains 10 items on hazardous alcohol use, dependence symptoms and harmful alcohol use. Questions from the German version[92] were answered on three- or five-point Likert scales assessing the existence and frequency of harmful alcohol behaviours. Scoring was done according to the manual,[91] with a potential sum score range from 0 to 40. Questions 2 to 10 were skipped if a participant indicated they never had drinks containing alcohol (item 1), resulting in a score of 0.

2.3 Statistical Analysis

Data analysis was conducted in R (version 4.2.2) using RStudio (version 2022.12.0). All statistical tests were done using a two-tailed alpha level of .05, unless specified otherwise.

To investigate associations between schizotypy and TD, in a preregistered analysis we calculated Pearson correlations between sum scores of the four subscales and ln(k) in the standard delay version (Bonferroni-corrected alpha level of .05/4=.0125). Furthermore, following a reviewer comment, we calculated non-preregistered t-tests to compare schizotypy low- and high-scorers (with grouping based on the lower and upper 10% of the respective subscale score[35]). In additional non-preregistered exploratory analyses, we examined Pearson correlations between ln(k) in the date version and subscale scores, and used multiple linear regressions to explore associations while controlling for influences of (i) the other subscales and (ii) age, dummy-coded education (low/medium/high), alcohol and tobacco consumption as well as the other subscales (hierarchical linear regression).

To determine whether the date/delay effect was replicated, we conducted a preregistered paired sample t-test with MCQ version (date vs. delay) as independent variable and ln(k) as dependent variable. Hedges g_{av} was computed as measure of effect size[93]. For explorative purposes, we conducted a non-preregistered 2×3 (version×magnitude) within-subject ANOVA to analyse whether the date/delay effect interacted with reward magnitude (small, medium, large). Also, we tested the effect of MCQ presentation order (delay first vs. date first) on TD and the date/delay effect in a non-preregistered 2×2 (version×order) mixed ANOVA.

We then examined whether the magnitude of the date/delay effect was associated with schizotypy. First, in a preregistered explorative analysis we considered correlations between ln(k) in the two versions and schizotypy scores and compared them using Williams t-test[94] (Bonferroni-corrected alpha level of .05/4=.0125). Next, using the previously created groups, we calculated non-preregistered t-tests comparing schizotypy low- and high-scorers on the date/delay effect. Finally, in a non-preregistered exploratory analysis, we used multiple linear regressions to examine whether the difference in ln(k) between the two versions (delay minus date) was predicted by any of the four sO-LIFE subscale scores, controlling for influences of age, dummy-coded education, alcohol and tobacco consumption as well as the other subscales (hierarchical linear regression).

Study materials, data and analysis scripts as well as supplemental material can be accessed at https://osf.io/xdn7c/?view_only=d880dc99077e47ac82b3af7eeb54757b.

3 Results

Descriptive statistics, Cronbach's alphas and Pearson correlations are shown in Table 1. The association between schizotypy and TD in the delay condition was significant for UE, $r(998)=.06$, $p=.04$, but only at the non-adjusted alpha level. When adjusting for multiple comparisons, none of the associations between schizotypal traits and TD were significant, neither in the delay nor in the date condition (all $p>.0125$). Similarly, comparing TD in schizotypy high- and low-scorers using a non-preregistered extreme group approach did not reveal any significant differences (Supplement B1–B2). Non-preregistered multiple linear regressions in which sO-LIFE subscale scores were added as predictors for discount rates as well as hierarchical linear regressions in which age, dummy-coded education, alcohol and tobacco consumption were entered in the first and subscale scores in the second step only yielded significant effects of age, education and nicotine. Associations between subscale scores and discount rates were non-significant (Supplement B3–B6).

Comparisons of discount rates in the two versions showed that participants discounted future rewards significantly more steeply in the delay than in the date condition, $t(999)=16.25$, $p<.001$, $g_{av}=0.22$, replicating the date/delay effect (Supplement B7). An exploratory, non-preregistered within-subject ANOVA examining the interaction between the date/delay effect and the magnitude effect (Supplement B8) revealed main effects of time framing, $F(1,999)=263.89$, $p<.001$, $\eta_p^2=0.21$, and magnitude, $F(1.81,1811.58)=1030.00$, $p<.001$, $\eta_p^2=0.51$, but no interaction, $F(1.99,1985.02)=0.77$, $p=.46$, $\eta_p^2<.01$. Furthermore, a non-preregistered mixed ANOVA examining the effect of MCQ presentation order (Supplement B9) revealed that, while the date/delay effect was still highly significant, $F(1,998)=264.89$, $p<.001$, $\eta_p^2=.21$, TD was generally lower in participants who first completed the date and then the delay version (than vice versa), $F(1,998)=12.91$, $p<.001$, $\eta_p^2=.01$. Additionally, a significant version×order interaction

indicated that the date/delay effect was higher in participants who first completed the date version, $F(1,998)=33.61$, $p<.001$, $\eta_p^2=.03$.

Next, we explored whether the date/delay effect was related to schizotypy. Preregistered Williams tests did not yield significant differences between the correlations across the date and delay conditions for any of the subscales (UE: $t(997)=1.70$, $p=.09$; CD: $t(997)=-1.24$, $p=.22$; IA: $t(997)=-1.60$, $p=.11$; IN: $t(997)=-1.51$, $p=.13$). Similarly, in a non-preregistered extreme group approach comparing the date/delay effect between schizotypy high- and low-scorers, we did not find any significant differences (Supplement B10). However, a non-preregistered multiple linear regression in which all four subscale scores were used to predict the difference between ln(k) values of the two versions revealed that UE was significantly associated with the magnitude of the date/delay effect while the other subscales were not (Supplement B11). Specifically, higher UE scores were associated with a greater date/delay effect. This effect persisted when controlling for age, education, alcohol and tobacco consumption in hierarchical linear regression (Table 2).

Variable	*M*	*SD*	Sk	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) ln(*k*) Delay	−5.73	1.70	−0.05	(.93)								
(2) ln(*k*) Date	−6.10	1.65	0.19	.91***	(.93)							
(3) Date/Delay Effect	0.37	0.71	0.81	.27***	−.15***	(.25)						
(4) Unusual Experiences	3.77	2.57	0.50	.06*	.04	.06	(.71)					
(5) Cognitive Disorganization	4.89	2.96	0.22	.02	.03	−.04	.40***	(.77)				
(6) Introvertive Anhedonia	2.07	1.80	1.02	.02	.04	−.05	.09**	.32***	(.56)			
(7) Impulsive Nonconformity	3.14	1.94	0.57	.04	.06	−.04	.40***	.39***	.10**	(.52)		
(8) Alcohol (AUDIT)	5.14	4.87	1.41	< .01	.03	−.05	.02	.11***	−.07*	.25***	(.77)	
(9) Tobacco (ASSIST)	2.84	4.86	1.81	.11***	.10**	.04	.22***	.16***	.02	.30***	.23***	(.58)

Table 1 | Descriptive Statistics, Cronbach's Alphas and Pearson Correlations. *Note*. Values in the correlation diagonal represent Cronbach's Alphas, except for the date/delay effect (computed as ln(*k*) Delay minus ln(*k*) Date), for which the reliability was estimated using formula 4 from Trafimow[95]. Correlations: $df = 998$. $N = 1{,}000$. *M* = mean; *SD* = standard deviation; Sk = skewness; ln(*k*) = log-transformed discount rate based on the Monetary Choice Questionnaire[85]. * $p<.05$, ** $p<.01$, *** $p<.001$ (unadjusted)

Variable	*B*	95% CI for *B*		*SE B*	β	R^2	ΔR^2
		LL	*UL*				
Step 1						.010	.010
Constant	0.270***	0.135	0.404	0.069	–		
Age	0.004*	0.000	0.008	0.002	.07		
Education (low)	-0.067	-0.234	0.100	0.085	-.03		
Education (high)	-0.002	-0.103	0.099	0.052	.00		
Alcohol (AUDIT)	-0.009	-0.018	0.001	0.005	-.06		
Tobacco (ASSIST)	0.008	-0.001	0.018	0.005	.06		
Step 2						.019	.010*
Constant	0.323	0.145	0.501	0.091	–		
Age	0.004	-0.001	0.008	0.002	.06		
Education (low)	-0.052	-0.220	0.116	0.086	-.02		
Education (high)	0.007	-0.095	0.109	0.052	.00		
Alcohol (AUDIT)	-0.007	-0.017	0.003	0.005	-.05		
Tobacco (ASSIST)	0.008	-0.002	0.018	0.005	.06		
Unusual Experiences	0.024*	0.004	0.044	0.010	.09		
Cognitive Disorganisation	-0.007	-0.025	0.011	0.009	-.03		
Introvertive Anhedonia	-0.019	-0.045	0.007	0.013	-.05		
Impulsive Nonconformity	-0.021	-0.048	0.007	0.014	-.06		

Table 2 | Hierarchical Linear Regression Predicting the Magnitude of the Date/Delay Effect. *Note*. Education was entered as two dummy variables (reference category: medium). CI = confidence interval; *LL* = lower limit; *UL* = upper limit. *N*=990. * $p<.05$, *** $p<.001$

4 Discussion

The current study is the first to use the sO-LIFE to examine associations between TD and four dimensions of schizotypy. Furthermore, it is the first to replicate the date/delay effect in a large-scale study and to examine its relation to schizotypy. Results are as follows: First, none of the schizotypy traits were significantly related to TD, neither in the delay nor in the date condition. While a significant positive correlation between UE and discount rate occurred in the standard delay version, it did not persist after correcting for multiple comparisons. Second, as expected, the date/delay effect was replicated. The effect was independent of the magnitude effect. Third, when controlling for influences of the other sO-LIFE subscales (and age, education as well as alcohol and tobacco consumption), the UE subscale predicted the magnitude of the date/delay effect. That is, higher values in UE were associated with a higher reduction of TD in the date compared to the delay condition.

The null findings regarding relations between schizotypy and TD are consistent with the only other study examining these relations across the entire schizotypy continuum. Indeed, Weatherly[40] found only few subscales of the Schizotypal Personality Questionnaire (SPQ)[2] to be related to TD in undergraduates, with low effect sizes. Our study extends this finding to a larger sample using the sO-LIFE – a measure that is based on the fully dimensional approach rather than on clinically derived symptom descriptions.[1] So far, studies that have found considerable effect sizes of relations between schizotypal traits and TD are usually based on extreme group designs, often with a particular focus on negative schizotypy, be it in studies comparing schizotypy high- and low-scorers[34,35] or in those comparing schizophrenia patients and healthy controls.[27,29] In our study, however, we did not find TD differences in analyses comparing schizotypy high- and low-scorers. Given the inconsistent findings outlined above, our results could therefore either indicate that deviations in TD are non-existent (or very low in effect size) across the entire schizophrenia spectrum or that a certain limit of symptomatology has to be exceeded to show significant aberrations, which would better accord with quasi-dimensional than fully dimensional approaches of schizotypy.[1] The latter could additionally suggest that deviations in TD in schizophrenia are due to disease processes or medication effects, as previously suggested,[33,34] rather than to vulnerability in highly schizotypal individuals. Alternatively (or additionally), combinations of specific trait profiles, for example interactions between higher positive and negative schizotypy, could be necessary to reveal TD differences as both reward and time processing could be altered in such individuals. Given the overall inconsistent findings, however, more work is needed to clarify the magnitude of effect sizes of TD differences across the schizophrenia spectrum.

A more refined approach to this question is to examine the cognitive mechanisms suspected to lead to increased TD and to explore whether these are altered in schizophrenia spectrum individuals. Here, we focused on future time perception by using a date/delay manipulation.

Importantly, we replicated the date/delay effect and found it to be robust against the well-known magnitude effect in TD (i.e., larger rewards being discounted less steeply than smaller ones[96,97]) and against order of MCQ presentation (although it was greater when the date version was presented first). The date/delay effect has been found previously,[76,77,80,98–101] with a meta-analysis revealing a slightly larger effect size than our study.[78] However, this difference could be partly due to our effect size calculation in which we corrected for the correlation of measurements (i.e., our uncorrected effect size is d_z=0.51). Importantly, our study was one of the few using a within-subject design[99,100] and had by far the largest sample to date.

Importantly, the association of the date/delay effect with schizotypy had not previously been investigated. Here, we observed that higher positive schizotypy (UE) scores were associated with a stronger date/delay effect after controlling for the other subscales. This intriguing finding may indicate that not only reward but also time processing and/or their integration are aberrant in high schizotypy. Interestingly, previous studies have shown that negative symptoms and anhedonia are mainly responsible for deviations in reward valuation[50–52] and some studies found high levels in positive symptoms to be associated with aberrant time perception and internal clock mechanisms.[61,74] Thus, one may speculate that the distinction between positive and negative symptoms is important for differential influences on time and reward processing, respectively. Furthermore, the finding suggests that simple manipulations such as the date/delay framing could help particularly vulnerable populations to reduce impulsive decision making. This idea is in line with the finding that in schizotypy high-scorers, episodic future thinking (EFT)[102], i.e., presenting future rewards in combination with positive future (rather than recent) events, helped to reduce TD.[103] While that study lacked a control group (thus not revealing whether the manipulation might be particularly effective within schizotypy high-scorers), it is the only other study showing that manipulations of future time perspective can help to reduce TD in a sample with high schizotypy levels. It is of considerable interest to further investigate whether the date/delay and EFT manipulations have particularly beneficial impacts on people high in schizotypal traits and schizophrenia patients, especially considering that schizophrenia patients have been shown to have altered EFT.[104] This, of course, would not only provide insights into time processing mechanisms in schizotypy and schizophrenia but also a potential way to reduce impulsive decision making.[103]

There are some limitations to consider. First, the online setting prevented us from collecting comprehensive clinical data. Thus, diagnostics of mental disorders was not possible, although this may be desirable given the influences of different disorders on TD.[25] Similarly, our attempts to control for risky substance consumption must be interpreted with care because they were not validated independently. The possibility that our findings are driven by any one disorder is unlikely, however, given the large sample size. Second, we used a hypothetical intertemporal choice task because previous general population studies showed that they result in similar discount rates as incentive-compatible ones where participants are paid out one or more of their decisions.[105,106] However, a study comparing

schizophrenia patients and healthy controls only found a difference in TD when using an experiential rather than a hypothetical task, thus raising the question whether the association depends on realization of rewards.[31] Whilst other studies in part found significant effects with hypothetical tasks,[26,27,29,30,32] this is important to consider in future studies. Third, our analysis revealing the association between positive schizotypy and the date/delay effect was largely explorative, included a difference score with potentially limited reliability[95] (however, see [107]), and yielded only a small effect size, thus warranting replication. Fourth, while we accounted for educational status in our analyses, future studies might also consider assessing further control variables, such as working-memory capacity, IQ or socio-economic status as these are known to be associated with TD.[22] Fifth, a more representative sample regarding distributions of education and gender would be desirable, especially since the latter is associated with differences in O-LIFE subscale scores.[3]

Overall, our large-scale study revealed that schizotypal personality traits are not (or only very weakly) associated with TD. However, positive schizotypy was associated with the magnitude of the date/delay effect, suggesting deviations in future time perception in people with high levels of positive schizotypy and potential reductions of those through the simple date manipulation. Future studies are needed to determine whether this effect is robust in non-clinical and clinical samples to draw conclusions on cognitive mechanisms of altered decision-making in schizophrenia.

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Appendix E | Study V

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Association of temporal discounting with transdiagnostic symptom dimensions

Check for updates

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Temporal discounting (TD), the tendency to devalue future rewards as a function of delay until receipt, is aberrant in many mental disorders. Identifying symptom patterns and transdiagnostic dimensions associated with TD could elucidate mechanisms responsible for clinically impaired decision-making and facilitate identifying intervention targets. Here, we tested in a general population sample (N = 731) the extent to which TD was related to different symptom patterns and whether effects of time framing (dates/delay units) and monetary magnitude (large/small) had particularly strong effects in people scoring higher on specific symptom patterns. Analyses revealed that TD was related to symptom patterns loading on anxious-depression and inattention-impulsivity-overactivity dimensions. Moreover, TD was lower in the date than the delay version and with higher magnitudes, especially in people scoring higher on the inattention-impulsivity-overactivity dimension. Overall, this study provides evidence for TD as a transdiagnostic process across affective and impulsivity-related dimensions. Future studies should test framing interventions in clinical populations characterized by impulsivity.

Preregistration: This research was preregistered at https://osf.io/fg9sc.

When faced with a decision between a smaller-sooner reward and a larger-later reward (*intertemporal choice*), people devalue the future reward relative to the sooner reward as a function of delay until receipt, a phenomenon known as *temporal discounting* (TD)[1]. Steeper TD has been found in numerous mental disorders, including behavioral addictions[2–4], substance use disorders[2,5,6], major depression[7], attention-deficit/hyperactivity disorder (ADHD)[8] and bulimia nervosa[7], while shallower TD occurs in anorexia nervosa[7]. Therefore, TD has been proposed as a transdiagnostic marker of mental disorders[7,9–11].

Despite convincing evidence of aberrant TD in clinically diagnosed groups compared to healthy controls, few studies have examined transdiagnostic determinants, i.e., specific symptom clusters responsible for these relationships[7]. This is likely due to problems inherent in studying diagnostic categories. Specifically, in case-control studies, sample sizes are often limited, diagnostic groups are heterogenous, and controlling for treatment confounds is difficult[12,13].

Dimensional approaches like the Research Domain Criteria framework (RDoC), which aims to identify common behavioral and biological dimensions of mental disorders[14–16], or the Hierarchical Taxonomy of Psychopathology (HiTOP), which systematically describes and organizes psychopathological dimensions at different hierarchical levels[17,18], may help overcome these issues. These build upon the observation that many symptoms are not specific but characterize a range of mental disorders. For instance, impulsivity has been robustly related to various internalizing and externalizing psychopathologies[19]. Also, anxiety symptoms play a role not only in anxiety disorders but also in other (internalizing) disorders like depression or obsessive-compulsive disorder (OCD)[20–22]. Additionally, it has been observed that many symptom patterns are dimensional in extending from clinical groups into the non-clinical population[23,24]. Therefore, to account for both overlaps across clinical disorders and varying symptom expressions in the population, fully-dimensional transdiagnostic approaches identify transdiagnostic dimensions by recruiting large unselected samples experiencing psychopathology to a varying extent and reducing dimensionality using factor analysis of self-report questionnaire responses[12,25,26].

In the context of intertemporal choice, such an approach may help elucidate which transdiagnostic symptom patterns are associated with steeper or shallower TD efficiently and with limited psychopathology-related confounds. As a consequence, this may help explain inconsistent findings regarding associations of TD with disorders such as autism-

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spectrum disorders[27–30] or schizophrenia[31–36], which could be due to highly heterogenous symptom clusters[9] or medication confounds[13]. Furthermore, a dimensional approach may help find interventions targeting aberrant TD by evaluating the effectivity of interventions depending on specific symptom pattern severity[9]. Specifically, previous studies have shown that TD can be influenced by experimentally manipulating task framing, incidental affective states, or prospection-related processes[37]. Some of these manipulations, e.g., presenting time until receipt of rewards in dates instead of delay units (date/delay effect)[38–40], reduce TD not only in the general population but especially in individuals initially showing particularly steep TD, such as problematic alcohol users[41] or persons with high positive schizotypy scores[42]. Therefore, finding transdiagnostic symptom dimensions that are associated with TD and that are particularly responsive to such manipulations could be of high therapeutic value.

To our knowledge, only one study has examined TD using a transdiagnostic dimensional approach, finding elevated TD in substance use, ADHD, depression, and anxiety, supporting the transdiagnostic nature of TD[11]. Here, we used a similar approach but administered a largely different set of questionnaires to test whether various psychiatric symptom patterns can account for individual differences in TD in the population. Importantly, since within-subject manipulations of TD might be an effective intervention method[9], we manipulated time framing to investigate the date/delay effect and its association with psychiatric symptom patterns and transdiagnostic dimensions.

Our preregistered hypotheses were as follows:

1. We hypothesized that individual differences in psychiatric symptom patterns would be related to individual differences in TD. Specifically, we expected that higher scores in depression, anxiety, OCD, schizotypy, autism, and ADHD measures would be associated with steeper TD. Additionally, we expected that uncontrolled eating and emotional eating would be positively and eating-related cognitive restraint negatively associated with TD. For impulsivity, we expected positive associations of positive urgency, negative urgency, and lack of premeditation with TD.
2. We hypothesized that TD would be shallower when time was presented as dates (e.g., on November 30, 2022) compared to delay units (e.g., in 19 days), replicating the date/delay effect.

Furthermore, we conducted a preregistered explorative analysis to determine whether the date/delay effect was stronger in participants with higher levels in the symptom patterns examined.

Finally, in a non-preregistered explorative analysis following a reviewer's comment, we also considered associations between symptom patterns and (i) TD model fit and (ii) the extent of the magnitude effect, i.e., the reduction in TD with larger compared to smaller monetary rewards[43].

Method

The study was approved by the University of Melbourne Ethics Committee (ID: 21719). All participants provided written informed consent for study participation and re-use of anonymized data.

Design

The study was cross-sectional, conducted online on Qualtrics (https://www.qualtrics.com/) between 18/08/2022 and 15/12/2022.

Sample and exclusion criteria

Participants were recruited via Prolific (https://www.prolific.co/). Data were sampled from the U.S. general population, aged 18–65 years and fluent in English. Participants were excluded from data analysis if they failed at least one of five attention checks in the questionnaires (further details: Supplementary Methods; preregistration: https://osf.io/fg9sc). They were paid a base sum of USD10 plus bonus (averaging USD3.05) depending on performance in a complex decision-making task reported elsewhere. Participation took 85 minutes on average.

Intertemporal choice task

The Monetary Choice Questionnaire (MCQ)[44] comprises 27 decisions between hypothetical smaller-immediate and larger-later rewards, which can be divided into three magnitudes based on the amounts of the larger-later rewards: small ($25 to $35), medium ($50 to $60), and large ($75 to $85). Participants completed two versions of the MCQ: a delay version where times were presented in days (e.g., "Would you prefer $14 in 0 days, or $25 in 19 days?") and a date version where they were presented in dates (e.g., "Would you prefer $14 on November 11, 2022, or $25 on November 30, 2022?"). Decisions were presented one-by-one. Order of versions and items within versions were randomized.

Cognitive ability task

We used the 16-item sample test of the International Cognitive Ability Resource (ICAR)[45] to assess cognitive ability. It consists of four items each of the types verbal reasoning, letter and number series, matrix reasoning, and three-dimensional rotation.

Self-report psychometric questionnaires

Participants completed a range of questionnaires assessing depression/anxiety/stress, trait anxiety, obsessive-compulsive tendencies, schizotypy, different types of disordered eating behavior (uncontrolled eating, cognitive restraint, emotional eating), autistic tendencies, ADHD symptoms, and impulsivity (negative urgency, lack of premeditation, lack of perseverance, sensation seeking, positive urgency). The questionnaires used are listed in the Supplementary Methods. Five nonsensical items were embedded in the questionnaires as attention checks (Supplementary Methods).

Statistical analyses

G*Power 3.1[46] was used for power analysis, all other analyses were conducted in R (version 4.2.2) using RStudio (version 2023.06.1). For estimation of discount rates, we used RStan (version 2.26.1). Significance tests were conducted applying a two-tailed alpha-level of 0.05. In all analyses in which the discount rates of both the delay version and the date version were used to test the same research question (i.e., hypothesis 1) employing the same statistical approach, we computed p-values using Bonferroni-Holm correction (p_c) to account for testing across two dependent variables.

A priori power analysis. Given that associations between individual difference variables and TD are low[47], we a priori assumed a two-tailed alpha-level of 0.05, a power of 80%, and a correlation effect size of $r = 0.10$. This power analysis yielded a target sample size of 782, which we rounded to 800.

Estimation of discount rates. Log-transformed discount rates were estimated based on the 54 intertemporal choices using Bayesian hierarchical modelling (e.g.[48]). Specifically, we estimated group- and participant-level parameters based on hyperbolic, exponential, and quasi-exponential functions and compared model fits. We note that deviating from our preregistration and based on recent evidence[49], we did not compute Bayes factors but used leave-one-out cross-validation (LOO-CV)[50] based on participant-level estimates to test which function type provided the best fit. Results revealed that predictive accuracies of the hyperbolic (elpd [expected log pointwise predictive density] estimate = −8,996.0, $SE = 148.6$) and exponential (elpd estimate = −9,189.3, $SE = 150.4$) models were higher than of the quasi-hyperbolic model (elpd estimate = −16,774.3, $SE = 282.1$). Differences between the hyperbolic and exponential models were small (i.e., below two times the SE), with the hyperbolic discounting yielding slightly better accuracies. Therefore, and in line with previous studies[51,52], we estimated discount rates for the current study assuming a hyperbolic function.

We estimated a single hierarchical model accounting for differences in the two versions, estimating group- and participant-level parameters as well as their posterior distributions and point estimates for each version. The

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date/delay effect was computed as the difference of point estimates between versions (delay minus date). To test whether TD model fit differed between versions, we additionally estimated separate models for the two versions and compared model fits using LOO-CV. Results revealed that differences between the delay (elpd estimate = −4,330.0, *SE* = 80.1) and date (elpd estimate = −4,438.2, *SE* = 85.5) versions (elpd difference: −108.2, *SE* = 100.6) were small and non-significant (i.e., below two times the *SE*).

Then, to obtain log-transformed discount rates for the three different magnitudes of the MCQ, we estimated another Bayesian hierarchical model assuming a hyperbolic function, this time accounting for the differences in the three magnitudes. Thus, we estimated group- and participant-level parameters as well as their posterior distributions and point estimates for each MCQ magnitude (small, medium, large). The magnitude effect was computed as difference between point estimates of the small and large magnitudes.

Summary measures of ICAR, questionnaires and transdiagnostic dimensions. We computed sum scores for the ICAR (sum of correct answers) and the questionnaires (sum of item scores). For the disordered eating and the impulsivity questionnaires, sum scores were computed for the subscales instead of the complete scales. To obtain transdiagnostic dimensions, we conducted a non-preregistered exploratory factor analysis with maximum-likelihood estimation[53–55]. We entered participants' responses to the 176 questionnaire items into the factor analysis and, as item responses had different scale levels, computed a heterogenous correlation matrix (Fig. 1a). We determined the number of extracted factors using the Cattell-Nelson-Gorsuch (CNG) test[56,57] based on the screeplot (Fig. 1b), applied an oblique factor rotation (oblimin), and extracted factor scores for each participant (Pearson correlations between factor scores in Fig. 1c). Confidence intervals of item loadings were estimated using bootstrapping with 1,000 iterations. Based on inspection of item loadings (Fig. 1d) and similar to previous studies[53–55], we labelled the factors/dimensions "Anxious-Depression" (AD), "Inattention, Impulsivity and Overactivity" (IIO) and "Compulsive Behavior and Intrusive Thought" (CIT).

Psychiatric Symptom Patterns and TD. To examine associations between psychiatric symptom patterns and TD variables, we computed preregistered Pearson correlations. For these variables, outliers, i.e., values 3 *SD* above or below the mean were excluded from all analyses. To explore which predictor was strongest, we conducted preregistered linear regressions (ordinary least squares estimates) of discount rates on psychiatric symptom patterns. Due to the multicollinearity of depression/anxiety/stress and trait anxiety scores, we excluded trait anxiety scores from this analysis. Additionally, since Breusch-Pagan tests revealed at least some degree of heteroskedasticity in this and all following linear regression models, we calculated all models using heteroscedasticity-robust standard errors. Next, to examine associations between psychiatric symptom patterns and TD while controlling for covariates, we conducted non-preregistered linear regressions of discount rates in each version controlling for demographics and cognitive ability, i.e.: discount rates (delay/date) ~ age + gender1 + gender2 + cognitive ability + scale. All regressors were *z*-standardized. Afterwards, we computed the same models using the transdiagnostic dimensions as predictors. Dimensions were entered in separate and joint models (i.e., controlling for the other dimensions).

Psychiatric symptom patterns and the date/delay effect. As preregistered, to test for the date/delay effect, we inspected with which probability the paired differences of discount rate posteriors of the two versions differed from zero using the Bayesian Estimation Supersedes the *t*-test (BEST; 30,000 MCMC iterations)[58,59] and conducted a frequentist paired *t*-test. Then, to examine the association of psychiatric symptom patterns/dimensions with the date/delay effect, we conducted the same analyses as for the associations between psychiatric symptom patterns/dimensions and discount rates (Pearson correlations, linear regressions) but replaced discount rates with the date/delay effect.

Further explorative analyses: TD model fit and magnitude effect. In non-preregistered, explorative analyses, we analyzed whether the psychiatric symptom patterns/dimensions were associated with model fit. We used the individual point estimates of WAIC (widely applicable information criterion) as indicators of model fit and examined associations with psychiatric symptom patterns/dimensions using the same analyses as before (Pearson correlations, linear regressions).

Finally, we tested for the magnitude effect using a Bayesian approach (BEST; 30,000 MCMC iterations)[58,59] to compare the differences between small vs. medium and medium vs. large log-transformed discount rates as well as a frequentist repeated-measures ANOVA with post-hoc pairwise comparisons (*t*-tests). To analyze associations between psychiatric symptom patterns/dimensions and the magnitude effect in TD, we used the magnitude effect as a variable of interest in the same analyses as before (Pearson correlations, linear regressions).

Results

Participants

Of 800 participants, *N* = 68 participants were excluded due to failed attention checks and *N* = 1 dataset was lost in Qualtrics, yielding a final sample size of *N* = 731.

360 (49.2%) participants reported a female, 351 (48.0%) a male and 20 (2.7%) diverse gender. 367 participants had a female (50.21%), 361 a male (49.38%) biological sex, and data of 3 participants (0.41%) were missing. Mean age was 37.6 years (*SD* = 11.4). Educational attainment was slightly higher than in the U.S. population (Supplementary Table 1). Self-reported ethnicity was distributed as follows: 61 Asian (8.34%), 51 Black (6.98%), 40 Mixed (5.47%), 534 White (73.05%), 25 other (3.42%), and data of 20 participants (2.74%) were missing.

Psychiatric symptom patterns and TD

Descriptive data of all summary measures are presented in Table 1. Pearson correlations (Fig. 2, Supplementary Table 2) revealed statistically significant positive associations of TD in either version with depression/anxiety/stress, trait anxiety, OCD, schizotypy, ADHD, and different impulsivity constructs (*r*s between 0.08 and 0.17, all $p_c < 0.05$), while only eating-related cognitive constraint was negatively related to TD ($r = -0.11$ and $r = -0.08$, both $p_c < 0.05$). Other correlations were not statistically significant. When controlling for the influence of all scales, effects of OCD (β = 0.13, 95% CI [0.02, 0.24], $p_c = 0.046$), eating-related cognitive restraint (β = −0.10, 95% CI [−0.18, −0.03], $p_c = 0.02$), and lack of premeditation (β = 0.12, 95% CI [0.03, 0.20], $p_c = 0.01$) were statistically significant in the delay and the effect of lack of premeditation (β = 0.14, 95% CI [0.05, 0.22], $p_c = 0.006$) was statistically significant in the date version (Supplementary Table 3).

In linear regressions controlling for gender, age, and cognitive ability (Fig. 3a, Supplementary Table 4), we found in both versions that depression/anxiety/stress (delay: β = 0.11, 95% CI [0.03, 0.18], $p_c = 0.006$; date: β = 0.12, 95% CI [0.04, 0.20], $p_c = 0.004$), trait anxiety (delay: β = 0.11, 95% CI [0.04, 0.19], $p_c = 0.004$; date: β = 0.14, 95% CI [0.06, 0.22], $p_c = 0.002$), positive urgency (delay: β = 0.11, 95% CI [0.03, 0.19], $p_c = 0.02$; date: β = 0.09, 95% CI [0.01, 0.17], $p_c = 0.03$), negative urgency (delay: β = 0.10, 95% CI [0.03, 0.17], $p_c = 0.008$; date: β = 0.10, 95% CI [0.03, 0.18], $p_c = 0.008$), and lack of premeditation (delay: β = 0.15, 95% CI [0.08, 0.22], $p_c < 0.001$; date: β = 0.15, 95% CI [0.08, 0.22], $p_c < 0.001$) were positively associated with TD, while eating-related cognitive restraint was negatively associated with TD (delay: β = −0.10, 95% CI [−0.17, −0.03], $p_c = 0.01$; date: β = −0.08, 95% CI [−0.15, −0.01], $p_c = 0.04$). Positive effects for OCD (β = 0.09, 95% CI [0.01, 0.17], $p_c = 0.048$) were statistically significant in the delay version only.

Next, using the transdiagnostic dimensions extracted from factor analysis (Fig. 3b), we found that, controlling for gender, age, and cognitive ability, AD (delay: β = 0.09, 95% CI [0.02, 0.17], $p_c = 0.01$; date: β = 0.11, 95% CI [0.03, 0.19], $p_c = 0.01$) and IIO (delay: β = 0.10, 95% CI [0.02, 0.17],

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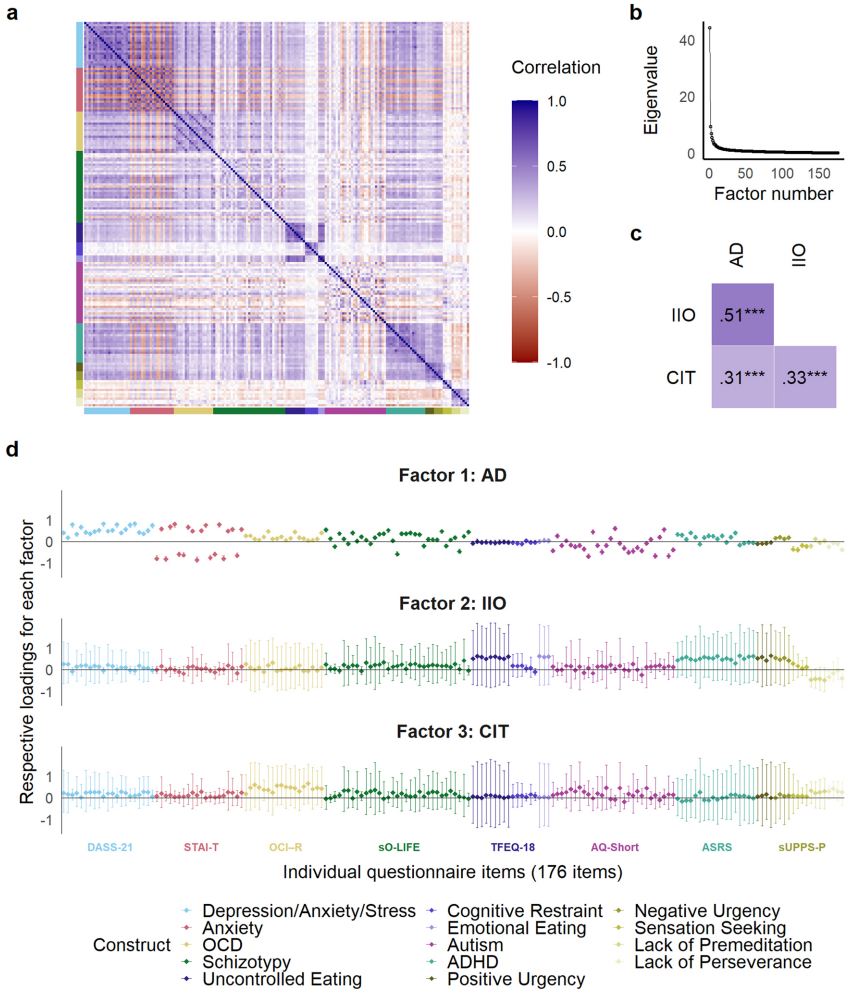


Fig. 1 | Results of exploratory factor analysis of clinical questionnaire items. **a** represents the heterogenous correlation matrix of the 176 items entered into the exploratory factor analysis; **b** represents the screeplot of the factor analysis; **c** represents Pearson correlations between participants' factor scores; **d** represents the item loadings for each respective factor. Error bars represent 95% confidence intervals. ***$p < 0.001$. AD Anxious-Depression, IIO Inattention, Impulsivity and Overactivity, CIT Compulsive Behavior and Intrusive Thought, DASS-21 Depression Anxiety Stress Scales 21, STAI-T State-Trait Anxiety Inventory (trait version), OCI-R Obsessive-Compulsive Inventory–Revised, sO-LIFE Short Oxford-Liverpool Inventory of Feelings and Experiences, TFEQ-R18 Three-Factor Eating Questionnaire-R18, AQ-Short Autism-Spectrum Quotient Short, ASRS Adult ADHD Self-Report Scale, sUPPS-P Short UPPS-P Impulsive Behavior Scale.

$p_c = 0.02$; date: $\beta = 0.08$, 95% CI [0.00, 0.16], $p_c = 0.04$) were positively related to TD, while CIT (delay: $\beta = 0.04$, 95% CI [−0.04, 0.12], $p_c = 0.60$; date: $\beta = 0.04$, 95% CI [−0.04, 0.13], $p_c = 0.60$) was not. When additionally controlling for all dimensions, no effect was statistically significant (Supplementary Table 5).

Psychiatric symptom patterns and the date/delay effect

The date/delay effect was replicated, as the paired difference (delay minus date) of discount rates had a probability of > 99.9% to be above zero (median paired difference = 0.39, 95% HDI [0.34, 0.45]), and the frequentist paired *t*-test was significant ($t(730) = 13.66$, $p < 0.001$, $g_{av} = 0.25$, 95% CI [0.22 to 0.29]).

A more pronounced date/delay effect was correlated with higher scores in uncontrolled eating, emotional eating, ADHD, positive urgency, negative urgency, and lack of premeditation (*r*s ranging between 0.07 and 0.12, all $p < 0.05$; Fig. 2, Supplementary Table 6). Using a single regression, uncontrolled eating ($\beta = 0.14$, 95% CI [0.01, 0.26], $p = 0.03$) and positive urgency ($\beta = 0.12$, 95% CI [0.00, 0.23], $p = 0.048$) persisted as statistically significant predictors (Supplementary Table 7). Associations between the date/delay effect and psychiatric symptom patterns were robust when controlling for

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Table 1 | Descriptive values of main variables after exclusions

Variable	N	Range	M	SD	Sk
ln(*k*) Delay	731	−9.44 to −0.35	−4.77	1.80	−0.35
ln(*k*) Date	731	−9.35 to −0.60	−5.20	1.63	−0.21
Date/Delay Effect	718	−1.85 to 2.96	0.43	0.74	0.30
ln(*k*) Small	731	−8.89 to −0.64	−4.31	1.57	−0.63
ln(*k*) Medium	731	−9.01 to −0.72	−3.93	1.60	−0.29
ln(*k*) Large	731	−9.36 to −0.70	−5.29	1.71	−0.14
Magnitude Effect	726	−1.20 to 3.13	0.99	0.69	−0.08
Model Fit (WAIC)	720	3.39 to 50.69	21.47	8.85	0.73
Cognitive Abilities	731	0 to 16	8.29	3.54	0.15
Depression/Anxiety/ Stress	729	21 to 79	38.38	13.79	0.60
Anxiety	731	20 to 80	44.92	14.26	0.15
OCD	726	18 to 67	31.94	11.56	0.91
Schizotypy	730	33 to 61	43.15	6.88	0.46
Uncontrolled Eating	731	9 to 36	17.59	6.21	0.75
Cognitive Restraint	731	6 to 24	12.57	4.05	0.33
Emotional Eating	731	3 to 12	5.88	2.75	0.61
Autism	730	35 to 101	66.43	11.91	−0.02
ADHD	729	18 to 85	43.31	13.69	0.26
Positive Urgency	723	4 to 14	6.32	2.47	0.93
Negative Urgency	731	4 to 16	8.08	3.17	0.37
Sensation Seeking	731	4 to 16	8.49	2.90	0.31
Lack of Premeditation	725	4 to 13	6.87	2.17	0.47
Lack of Perseverance	730	4 to 14	7.50	2.16	0.20

N represents the sample size after exclusions (values 3 *SD* above or below the mean). *ln(k)* log-transformed discount rate, *WAIC* widely applicable information criterion, *OCD* obsessive-compulsive disorder, *ADHD* attention-deficit/hyperactivity disorder, *Sk* skewness.

gender, age, and cognitive ability (Fig. 3c, Supplementary Table 8), i.e., we found associations for uncontrolled eating (β = 0.11, 95% CI [0.04, 0.19], $p = 0.003$), emotional eating (β = 0.09, 95% CI [0.01, 0.16], $p = 0.02$), ADHD (β = 0.08, 95% CI [0.00, 0.16], $p = 0.046$), positive urgency (β = 0.10, 95% CI [0.02, 0.18], $p = 0.01$), negative urgency (β = 0.08, 95% CI [0.00, 0.15], $p = 0.04$), and lack of premeditation (β = 0.08, 95% CI [0.01, 0.16], $p = 0.03$).

Finally, using the transdiagnostic dimensions extracted from factor analysis, we found that IIO was related to the date/delay effect (β = 0.11, 95% CI [0.03, 0.18], $p = 0.008$), while AD (β = 0.05, 95% CI [−0.03, 0.13], $p = 0.21$) and CIT (β = −0.01, 95% CI [−0.09, 0.06], $p = 0.75$) were not (Fig. 3d). This effect persisted when controlling for the other dimensions (Supplementary Table 9).

Psychiatric symptom patterns and TD model fit

A lower model fit (i.e., higher WAIC) was significantly correlated with lack of perseverance (r = 0.08, $p = 0.03$; all other $p < 0.05$; Supplementary Table 10). In a single regression controlling for the influence of other scales, no relationship was significant (Supplementary Table 11). However, the relationship of model fit and lack of perseverance was also significant when controlling for gender, age and cognitive abilities (β = 0.08, 95% CI [0.00, 0.15], $p = 0.04$). All other relationships between model fit and symptom patterns/dimensions were insignificant (Supplementary Fig. 1a–b; Supplementary Tables 12–13).

Psychiatric symptom patterns and the magnitude effect

Bayesian analysis of the magnitude effect revealed that the paired differences between log-transformed discount rates of small and medium (median paired difference = 0.62, 95% HDI [0.57, 0.66]) as well as medium and large (median paired difference = 0.37, 95% HDI [0.33, 0.41]) magnitudes had a probability of > 99.9% to be above zero. Moreover, the repeated-measures ANOVA was significant ($F(1.86,1354.58) = 870.90$, $p < 0.001$, $\eta_p^2 = 0.54$; all pairwise comparisons $p < 0.001$). Thus, the magnitude effect was replicated, i.e., TD declined with larger reward magnitudes.

A more pronounced magnitude effect was correlated with higher scores in schizotypy ($r = 0.08$, 95% CI [0.01, 0.15], $p = 0.03$) (Fig. 2, Supplementary Table 14). Using a single regression, no predictor was significant (Supplementary Table 15). In regressions controlling for gender, age, and cognitive ability, we found depression/anxiety/stress (β = 0.09, 95% CI [0.01, 0.16], $p = 0.03$), schizotypy (β = 0.11, 95% CI [0.03, 0.19], $p = 0.008$) and ADHD (β = 0.08, 95% CI [0.00, 0.15], $p = 0.048$) to be significantly associated with the magnitude effect (Supplementary Fig. 1c, Supplementary Table 16).

Analyzing associations between the magnitude effect and transdiagnostic dimensions, we found that IIO (β = 0.09, 95% CI [0.01, 0.17], $p = 0.03$) was significantly related to the magnitude effect, while AD (β = 0.07, 95% CI [−0.01, 0.14], $p = 0.07$) and CIT (β = 0.06, 95% CI [−0.02, 0.14], $p = 0.15$) were not (Supplementary Fig. 1d). The effect did not persist when controlling for the other dimensions (Supplementary Table 17).

Discussion

This study used a transdiagnostic approach to identify psychiatric symptom patterns associated with TD. Largely confirming our hypothesis, TD was higher in people scoring higher on depression/anxiety/stress, trait anxiety, OCD, schizotypy, ADHD, and different impulsivity constructs and lower in people with higher eating-related cognitive restraint. We did not find statistically significant associations for uncontrolled and emotional eating and autism. Analyses of transdiagnostic dimensions showed that higher TD was associated with dimensions representing AD and IIO. Moreover, we replicated the date/delay effect and found that people scoring higher in psychiatric symptom patterns loading on the IIO dimension (uncontrolled eating, emotional eating, ADHD, positive urgency, negative urgency, lack of premeditation) showed a stronger date/delay effect. Additionally, people scoring higher in lack of perseverance showed a worse TD model fit. Finally, the magnitude effect was replicated and people scoring higher in depression/anxiety/stress, schizotypy, and ADHD as well as IIO showed a stronger magnitude effect.

Our results are consistent with previous studies of aberrant TD in clinical populations with categorical diagnoses, replicating findings of both higher and shallower TD[7] on a dimensional level. We thereby show that previous findings are not due to medication or treatment confounds. More generally, we provide evidence for the validity of a dimensional approach to mental disorders.

Moreover, the findings largely align with the only other transdiagnostic dimensional study examining TD[11], confirming associations between TD and similar psychiatric symptom patterns (e.g., depression, anxiety) using different questionnaires. However, we significantly extend these findings by revealing associations with other psychiatric symptom patterns (e.g., schizotypy, impulsivity) and with transdiagnostic dimensions more closely resembling those found in previous transdiagnostic studies targeting different outcomes than TD[53–55,60,61]. Altogether, these results suggest that categorical findings are due to shared symptom dimensions, supporting the notion of TD as transdiagnostic marker. Specifically, the transdiagnostic nature of TD is reflected in anxiety/depression and inattention/impulsivity/overactivity but not in compulsion/intrusive symptoms. Future studies in clinical populations should explicitly test for associations between these symptom dimensions and TD[25].

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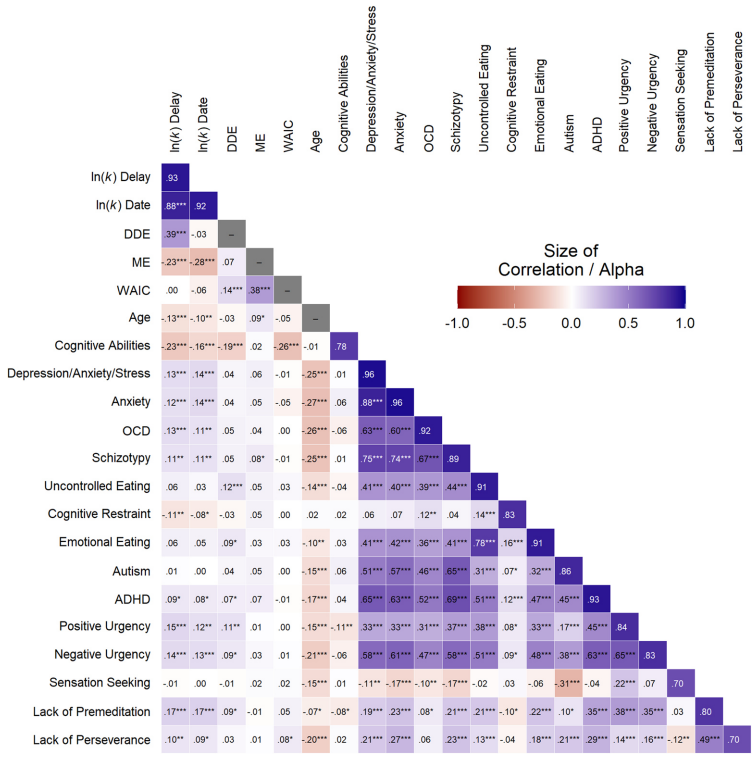


Fig. 2 | Pearson correlations between temporal discounting, demographic and questionnaire variables. ln(k) log-transformed discount rate, DDE date/delay effect, ME magnitude effect, WAIC widely applicable information criterion, OCD obsessive-compulsive disorder, ADHD attention-deficit/hyperactivity disorder. Values in the diagonal represent Cronbach's alpha. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ uncorrected.

Potential mechanisms underlying these associations include impaired valuation and cognitive control systems, impaired future-oriented cognitive processing, ruminative cognition, or intolerance of uncertainty[7,11,62]. While we cannot provide a comprehensive explanation, associations of the IIO dimension with both the date/delay and magnitude effects highlight the potential importance of specific mechanisms and reveal potential intervention targets.

The association between TD and the IIO dimension may not be unexpected, since TD is commonly assessed as a measure of behavioral impulsivity and also referred to as choice impulsivity[63]. However, recent studies emphasized that the term *impulsivity* represents a highly heterogenous umbrella term, subsuming various phenomena[64–66]. This necessitates a clear distinction between different impulsivity-related constructs[66]. In the context of our study, it is therefore crucial to determine which mechanisms underlie the relatively small association between TD and self-reported IIO scores. While the mechanisms mentioned above may potentially all be relevant, our primary experimental manipulation highlights the importance of future-oriented cognitive processing. Specifically, the date manipulation, which has been associated with narrower time estimation and more episodic thinking[42,67], was particularly effective in reducing TD in participants scoring high on the IIO dimension. Thus, it appears likely that higher TD in people who are more sensitive to the passage of time, e.g., impulsive individuals[68], can be alleviated by experimentally enhancing episodic thinking, e.g., by using episodic tags[52,69] or date cues[38–40]. Moreover, associations between the magnitude effect and IIO point towards another underlying mechanism. We speculate that this mechanism may be reflected in an aberrant self-control system because higher magnitude choices appear to rely on more self-control than lower magnitude choices[70]. Thus, an aberrant self-control system may be particularly detrimental in lower magnitude choices for people scoring higher on IIO, whereas higher magnitude choices may attenuate or alleviate these self-control impairments. Interestingly, this effect may also play a role in psychiatric dimensions underlying the AD factor (e.g., depression/anxiety/stress), although the association with AD itself did not reach significance. In sum, our findings suggest that both impairments in future-oriented cognitive processing and in self-control systems more generally may underlie the associations between TD and IIO. We would like to emphasize, however, that our interpretations are based on associations with two experimental effects only, one of which being the result of a non-preregistered explorative analysis, thus warranting replication. Furthermore, we only found evidence for mechanisms underlying the association between TD and IIO. That is, given that the date/delay effect and the magnitude effect did not significantly covary with AD, different mechanisms may (additionally) play a role. Future transdiagnostic studies could use additional experimental manipulations (e.g., of intolerance of uncertainty[71]) or examine neurobehavioral measures[62] to identify the mechanisms underlying altered intertemporal decision-making in clinical and subclinical populations more precisely. If the mechanisms relevant to IIO discussed here are confirmed in future studies,

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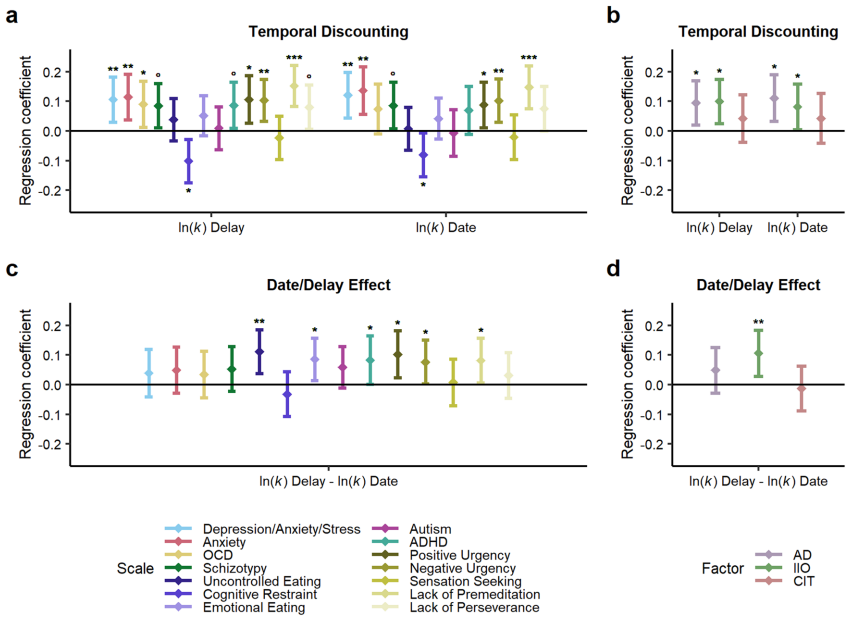


Fig. 3 | Associations between temporal discounting and psychiatric symptom patterns and the date/delay effect and psychiatric symptom patterns. Presented are separate regressions of discount rates in the two versions (**a**, **b**) or the date/delay effect (**c**, **d**) on different psychiatric symptom patterns (**a**, **c**) or transdiagnostic factors (**b**, **d**), controlling for gender, age and cognitive abilities. Error bars represent 95% confidence intervals. OCD obsessive-compulsive disorder, ADHD attention-deficit/hyperactivity, AD Anxious-Depression, IIO Inattention, Impulsivity and Overactivity, CIT Compulsive Behavior and Intrusive Thought $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, in **a** and **b** Bonferroni-Holm corrected for the two dependent variables tested; $^{\circ}p < 0.05$, uncorrected.

this may suggest that interventions framing outcomes as psychologically near (date/delay effect) and large rewards (magnitude effects; also see[70]), may particularly alleviate aberrant TD in people scoring higher on IIO.

Several limitations should be considered. First, we did not collect information related to clinical diagnoses[12]. That is, as in previous studies with transdiagnostic approaches[53–55,60,61], we recruited a large sample from the general population to examine psychopathology across a broad range of dimensional symptom patterns, but we did not screen participants for the presence or absence of psychiatric or neurological diagnoses, their developmental history or medication. Because of the lack of clinical information, inferences about clinical populations should be made with caution. Although previous studies found associations between temporal discounting and specific disorders[2–7], the transdiagnostic significance of dimensions such as AD and IIO in clinical populations has yet to be confirmed. Specifically, it would be highly beneficial to investigate whether the transdiagnostic dimensions found to play a role in our study are confirmed in large clinical populations with different diagnostic categories (see, e.g.[72], for an example of such a study in the context of goal-directed planning). Such studies may help to pinpoint the causes of clinically impaired decision-making and confirm the value of interventions such as the date/delay and magnitude effects whilst explicitly controlling for health-related third variables.

Second, given the correlation between AD and IIO, associations between TD and these dimensions are potentially confounded by the other dimension. Similar to comorbidities in categorical approaches, these dimensions are not entirely separable. Moreover, not directly health-related confounding third variables such as socio-economic status, other economic variables (such as risk perception) or, as outlined by Levitt and colleagues[11], substance use (e.g., smoking status) could be relevant.

Third, our focus was entirely on monetary TD. However, as discussed recently[7], other reward types may be more sensitive in specific populations. For example, associations between TD and emotional and uncontrolled eating may only be uncovered when using food instead of monetary rewards.

Overall, our study revealed positive associations of TD with psychiatric symptom patterns related to the dimensions AD and IIO and a negative association with eating-related cognitive constraints. These data support the view of TD as a transdiagnostic process across different mental disorders, although potential confounding variables should be considered. Importantly, the finding that people scoring high in IIO might be particularly influenced by the date manipulation and magnitude effects imply that clinical interventions targeting episodic processing and self-control systems could alleviate aberrant intertemporal decision-making in mental disorders characterized by inattention, impulsivity, and overactivity symptoms.

Data availability

Study materials as well as raw and processed datasets of the current study are available on the Open Science Framework (OSF) and accessible under the URL https://osf.io/ezaup/. The questionnaire data in this manuscript are also used for another transdiagnostic study relating complex decision-making based on the knapsack task to psychiatric symptom patterns. All main results reported here have not been submitted or published elsewhere.

Code availability

The underlying code for the current study is available on the Open Science Framework (OSF) and accessible under the URL https://osf.io/ezaup/.

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Author contributions
The study was conceptualized by K.K., X.L., S.S., C.M., and U.E. It was supervised by S.S., C.M., and U.E. Data acquisition was carried out by K.K. and X.L. Data analysis was done by K.K., C.M., and U.E. Figures were created by K.K. The original draft was written by K.K. The final manuscript was reviewed and edited by K.K., X.L., S.S., C.M., and U.E.

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Appendix F | Review I

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REVIEW
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Individual Differences in Intertemporal Choice

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Intertemporal choice involves deciding between smaller, sooner and larger, later rewards. People tend to prefer smaller rewards that are available earlier to larger rewards available later, a phenomenon referred to as temporal or delay discounting. Despite its ubiquity in human and non-human animals, temporal discounting is subject to considerable individual differences. Here, we provide a critical narrative review of this literature and make suggestions for future work. We conclude that temporal discounting is associated with key socio-economic and health-related variables. Regarding personality, large-scale studies have found steeper temporal discounting to be associated with higher levels of self-reported impulsivity and extraversion; however, effect sizes are small. Temporal discounting correlates negatively with future-oriented cognitive styles and inhibitory control, again with small effect sizes. There are consistent associations between steeper temporal discounting and lower intelligence, with effect sizes exceeding those of personality or cognitive variables, although socio-demographic moderator variables may play a role. Neuroimaging evidence of brain structural and functional correlates is not yet consistent, neither with regard to areas nor directions of effects. Finally, following early candidate gene studies, recent Genome Wide Association Study (GWAS) approaches have revealed the molecular genetic architecture of temporal discounting to be more complex than initially thought. Overall, the study of individual differences in temporal discounting is a maturing field that has produced some replicable findings. Effect sizes are small-to-medium, necessitating future hypothesis-driven work that prioritizes large samples with adequate power calculations. More research is also needed regarding the neural origins of individual differences in temporal discounting as well as the mediating neural mechanisms of associations of temporal discounting with personality and cognitive variables.

Keywords: decision making, personality, cognition, neuroimaging, molecular genetics

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INTRODUCTION

People frequently have to decide between rewards of different magnitudes that become available at different times in the future. Examples include whether to spend money on an event that is immediately rewarding, such as a night out, or to save it toward a future activity with potentially greater subjective value, such as an overseas holiday. The problem of choosing between smaller, sooner and larger, later rewards is referred to as *intertemporal choice* (Frederick et al., 2002).

People generally prefer smaller rewards that are available earlier over larger rewards available later, thereby devaluing future rewards. This phenomenon is known as *temporal* or *delay discounting* (Ainslie, 1975; Frederick et al., 2002). Devaluation of future rewards has far-reaching consequences for wealth and health not only of decision makers themselves, but also society at large (Mischel et al., 1989; Frederick et al., 2002; Golsteyn et al., 2014).

Temporal discounting is highly reproducible in humans and is ubiquitously observed in many other animal species (Berns et al., 2007; Kalenscher and Pennartz, 2008; Stevens, 2011; Frost and McNaughton, 2017). At the same time, temporal discounting has been found to display remarkable variability in magnitude both within and across individuals (Frederick, 2005; Peters and Büchel, 2011).

Regarding within-subject variability, the magnitude of temporal discounting, indexed by measures of the discount factor (**Figure 1**), can be reliably influenced by various experimental manipulations, including framing effects and cognitive strategies aimed at future thinking (Lempert and Phelps, 2016; Rung and Madden, 2018; Scholten et al., 2019). Moreover, developmental effects have been well-described, with the extent of temporal discounting decreasing from childhood into early adulthood (Achterberg et al., 2016).

Importantly, a growing body of evidence suggests that intertemporal choice is also subject to substantial *inter-individual variability* (Harrison et al., 2002; Shamosh and Gray, 2008; Mahalingam et al., 2014). These individual differences are for the most part not random or noise, but have instead been found to display both significant temporal stability and heritability. An important basis of this assumption is the test–retest reliability of intertemporal choice, which has been addressed in a number of studies. Specifically, test–retest correlations of measures of intertemporal choices are in the range of 0.5–0.8 and remain significant for test–retest intervals of up to 1 year (Beck and Triplett, 2009; Kirby, 2009; Jimura et al., 2011; Matusiewicz et al., 2013; Martínez-Loredo et al., 2017). Whilst such reliabilities are broadly comparable to those of other measures of cognitive function (Wöstmann et al., 2013; Buelow and Barnhart, 2018), it is clear that they are not perfect and, thereby, impose an upper limit on correlations that may be observed between intertemporal choice and other measures (Spearman, 1904). However, further evidence for the validity of an individual differences approach to intertemporal choice comes from the behavioral genetics literature. Specifically, twin studies have estimated genetic influences to account for approximately 50% of variance in temporal discounting (Anokhin et al., 2011, 2015; Isen et al., 2014); these data further underscore the stability and trait-like nature of the individual differences in intertemporal choice, justifying investigations of their covariation with other traits.

Individual differences in temporal discounting are also associated with numerous health-related outcomes. For example, higher rates of temporal discounting have been shown to be related to a reduced likelihood to check blood pressure, obtain cholesterol testing, attend dental visits, exercise, receive flu shots, engage in safe sexual behavior, and be medically adherent (Bickel, 2015). Higher rates of discounting have also been demonstrated in relation to psychiatric disorders including substance dependence disorders, attention-deficit/hyperactivity disorder, schizophrenia, major depressive disorder, problem gambling, and obesity (Amlung et al., 2019).

Regarding non-health-related behaviors and outcomes, people who discount to a greater degree spend less time searching for a good job (DellaVigna and Paserman, 2005), experience more shallow wage growth (Munasinghe and Sicherman, 2006), take up welfare programs later (Fang and Silverman, 2006), have lower credit scores (Meier and Sprenger, 2012), borrow more on credit cards (Meier and Sprenger, 2010), are more likely to default on their loans (Meier and Sprenger, 2012), are less likely to wear a seat belt (Bickel, 2015), and are more likely to text while driving (Hayashi et al., 2015).

Therefore, thorough characterization of the determinants of individual differences in temporal discounting is warranted. Such work is important not only to identify factors that covary with temporal discounting, but also to uncover the position of this phenomenon within the architecture of cognition and personality more widely and, importantly, to inform theories of the mechanisms that underlie this phenomenon (for the role of individual differences in theory development, see Cronbach, 1957; Underwood, 1975; Cohen, 1994).

The study of individual differences has a long tradition in psychology. Whilst traditionally focused on constructs such as personality and intelligence, there is also a substantial and growing body of evidence on individual differences in measures from cognitive psychology and cognitive neuroscience. Specifically, it has been argued that studies of (inter-)individual differences in those fields complement experimental studies that typically focus on intra-subject effects (Unsworth, 2019). Exemplified by the seminal work of Miyake et al. (2000), numerous studies have adopted individual differences approaches to examine, amongst others, the structure of executive functions (Friedman and Miyake, 2017), working memory (Engle, 2018), inhibitory control (Stahl et al., 2014), attention (Willems and Martens, 2016), and long-term memory (Unsworth, 2019), thereby integrating often separate approaches from differential and experimental psychology (Cohen, 1994).

Here, we review studies that have begun to shed light on individual differences in temporal discounting and the variables that are associated with it, with a view to elucidating the determinants of observed inter-individual variability and, ultimately, the mechanisms of intertemporal choice. We focus on key individual differences variables, including socio-economic factors, personality, cognition, brain structure and function, as well as molecular genetic variation (**Table 1**, **Figure 2**). We critically evaluate these studies and make methodological recommendations for individual differences research in intertemporal choice and decision neuroscience more broadly. Whilst we discuss findings from personality traits with evident clinical relevance such as impulsivity, we stop short of reviewing findings of altered intertemporal choice in mental disorders, as this literature has recently been thoroughly reviewed elsewhere (Amlung et al., 2019).

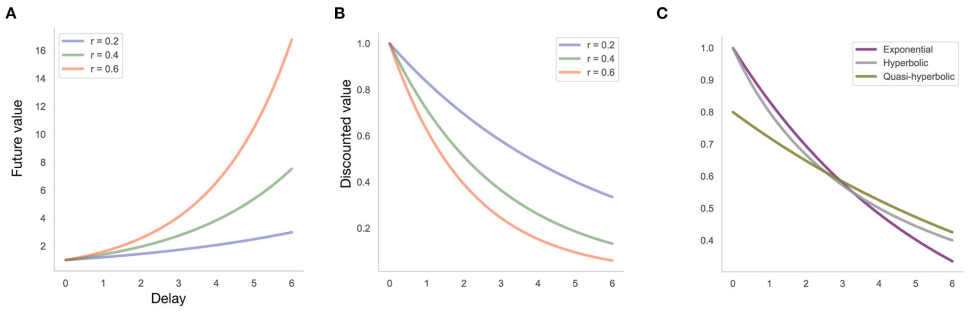


FIGURE 1 | Individual differences in discount functions. **(A)** Future value of $1 received today with exponential discount function at different discount rates r, that is, the value of an amount received after a given delay that is equivalent to $1 received today. This is the amount at which a decision-maker with a given discount function is indifferent between receiving this amount at a given delay, and $1 received today. **(B)** Discounted value of $1 received at a given delay, assuming an exponential discount function with discount rate r, that is, the value to the decision-maker today of $1 received at a given delay. **(C)** Discounted value of $1 received at a given delay, assuming different discount functions (exponential function with discount rate $r = 0.2$, hyperbolic discount function with discount rate $k = 0.25$, quasi-hyperbolic discount function with parameters $\beta = 0.8$, $\delta = 0.9$).

Measuring Temporal Discounting

Most people prefer a higher reward to a lower reward, ceteris paribus. However, most people also prefer a reward received sooner to a reward of similar magnitude received at a later time. This introduces a trade-off in people's preferences between reward magnitude and the delay until the reward is received. One way to express this trade-off is a utility (or subjective value) function, a function that maps reward magnitude and delay onto units of utility. It is commonly assumed that the utility of a reward r_τ, received after delay τ, is given by:

$$U(r_\tau;\ k) = d(\tau; k)u(r_\tau)$$

where d is the so-called discount function with *discount rate* k, reflecting the strength of discounting, and u is the utility function. Higher values of k indicate stronger discounting (**Figure 1**).

Utilities can be used to rank rewards of different magnitudes received at different delays. A decision-maker is assumed to be indifferent between two rewards received after different delays if their utilities are the same. In experimental studies of intertemporal choice, the utility function u is often assumed to be linear, which means that the utility of a reward is given by its discounted value (Andersen et al., 2008).

A decision-maker's discount rate is not directly observable. It is typically estimated based on a person's choices. A common way to elicit a person's discount rate is an intertemporal choice task, in which a person is asked to make a number of pairwise comparisons between smaller, sooner and larger, later rewards. The smaller, sooner reward is often a fixed amount received immediately (e.g., "$20 now"). An example of such a pairwise comparison might be "$20 now or $30 in 1 month?" (Andersen et al., 2008). It should be noted, however, that specific implementations of intertemporal choice tasks vary, as will be demonstrated throughout the review.

Such tasks can not only be used to measure a person's discount rate but also the functional form of the discount function. Typically, at least three candidate functional forms are considered (**Figure 1C**): (1) an exponential discount function; (2) a hyperbolic discount function; and (3) a quasi-hyperbolic discount function. The exponential discount function takes the form $d(\tau; r) = 1 / (1 + r)^\tau$. The higher the discount rate r, the lower the value of the discount function, that is, the more future rewards are discounted (**Figure 1B**). In the hyperbolic model, the discount function is given by $d(\tau; k) = 1 / (1 + k\tau)$. The latter function is steeper than the exponential function for smaller delays. Another alternative is the quasi-hyperbolic model with discount function $d(\tau; k) = \beta\delta^\tau$, where β is typically referred to as "present bias," indicating a premium that decision makers put on immediate rewards (or a discount that they apply to any delayed reward, irrespective of delay), whereas δ captures the discount rate as a function of delay, $\delta(\tau) = 1 / (1 + r)^\tau$.

SOCIO-DEMOGRAPHIC FACTORS

Discount rates are associated with a number of fundamental socio-demographic factors. One important factor is age. Whilst temporal discounting decreases from childhood into adolescence and young adulthood (Olson et al., 2007; de Water et al., 2014; Achterberg et al., 2016), the overall evidence about the effects of aging is mixed. While some studies found no differences between older and younger adults (Green et al., 1999; Chao et al., 2009), others have shown either decreased (Meier and Sprenger, 2010; Eppinger et al., 2012) or increased temporal discounting (Read and Read, 2004) in older adults, although there may also be non-linear effects, with discount rates lower in middle age (41–50) compared to younger (19–40) and older (51–75) adults (Harrison et al., 2002). It has been suggested that this inconsistency in age-related differences in temporal discounting may stem from

TABLE 1 | Summary of the associations between temporal discounting and socio-demographic, psychological, neuroimaging, and molecular genetic variables.

Variables	Direction of association	Effect sizes
SOCIO-DEMOGRAPHIC VARIABLES		
Age	No association, Positive, Negative	Moderate
Gender	No association, Men discount more	Moderate
Education level	Negative	Moderate
Income	Negative	Moderate
Marital status	Singles discount more	Moderate
Limitations: Small sample sizes, low-powered studies, the correlation between socio-demographic variables and temporal discounting is prone to misinterpretations and should be considered together with other biological and psychological variables		
PSYCHOLOGICAL VARIABLES		
Personality		
Big Five		
Openness	Negative	Low
Extraversion	Positive	Low
Conscientiousness	Negative	Low
Neuroticism	Positive	Low
Agreeableness	No association	
Trait impulsivity	Positive	Low to moderate
Future oriented cognitive styles and imagery		
Ability to imagine (present, future)	Positive	Moderate to high
Future orientation	Negative	Low to moderate
Intelligence	Negative	Moderate
Inhibitory control	No association, Negative	Low to high
Limitations: Small sample sizes, low correlations, interaction effects are often not considered, effect of possible mediator and moderator variables not sufficiently explored (e.g., the role of risk preferences), impact of task specificities on the obtained results		
NEUROIMAGING		
Brain structure		
Gray matter volume of regions associated with valuation (vmPFC, striatum, PCC, OFC)	Positive, Negative	Low to moderate
Gray and white matter volume of regions associated with cognitive control (dlPFC, FP)	Positive, Negative	Low to high
White matter volume and cortical thickness of regions associated with memory and future oriented thinking (hippocampus/parahippocampus, entorhinal cortex)	Positive, Negative	Low to high
Connectivity strength of (inhibitory) corticostriatal tracts	Negative	Moderate to high
Brain function		
Neural sensitivity to rewards and delays (vmPFC, vS, OFC, dlPFC)	Positive, Negative	Low to high
Recruitment of PFC regions during reward anticipation, valuation, and choice	Negative	Not reported
Intrinsic connectivity strength between cortical regions associated with cognitive control and valuation (e.g., FP and vmPFC)	Negative	Low to moderate
Task-related functional connectivity between cortical and subcortical (e.g., dlPFC and striatum), cortical and limbic (e.g., ACC and hippocampus), and within cortical areas (e.g., dlPFC and vmPFC)	Negative	Not reported
Limitations: Low-powered studies, small sample sizes, inconsistent and non-replicated findings, moderator and mediator variables not thoroughly considered, dependence of the results on the methodology		
MOLECULAR GENETICS		
Genetic variations in the dopaminergic systems associated with DA hypofunction	No associations, Positive	Low to moderate
Single nucleotide polymorphism rs6528024 on the X chromosome (associated with internalization of a serotonin receptor)	No associations, Negative	Low
Minor allele of r13395777 (intergenic region) on chromosome 2	No associations, Positive	Low
Limitations: Low-powered studies, non-replicated findings, task impurity problem, no studies on environment × gene interactions		

Low effect sizes are considered d (or r) < 0.15; moderate effect sizes are considered 0.15 ≤ d (or r) ≤ 0.35; high effect sizes are considered d (or r) > 0.35. vmPFC, ventromedial prefrontal cortex; PCC, posterior cingulate cortex; OFC, orbitofrontal cortex; dlPFC, dorsolateral prefrontal cortex; FP, frontal pole; vS, ventral striatum; ACC, anterior cingulate cortex; DA, dopamine.

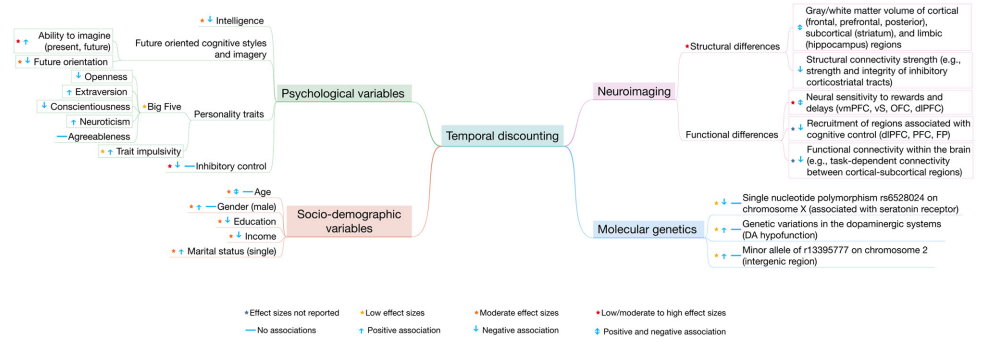


FIGURE 2 | Summary of the associations between temporal discounting and socio-demographic, psychological, neuroimaging, and molecular genetic variables. The figure in a simplified way summarizes how the different variables relate to (steep) temporal discounting. However, the relation of these variables to temporal discounting is far from being so simple and isolated (as it may appear in the figure) as these variables often interact with each other. Low effect sizes are considered d (or r) < 0.15; moderate effect sizes are considered 0.15 ≤ d (or r) ≤ 0.35; high effect sizes are considered d (or r) > 0.35. vmPFC, ventromedial prefrontal cortex; vS, ventral striatum; OFC, orbitofrontal cortex; dlPFC, dorsolateral prefrontal cortex; PFC, prefrontal cortex; FP, frontal pole; DA, dopamine.

variability in age-related decline of cognitive functions that may contribute to intertemporal choice (James et al., 2015; Huffman et al., 2019), in particular, declarative memory (Kable et al., 2019). Age-related mild-cognitive impairment has been shown to be associated with increased temporal discounting in older people (Kable et al., 2019).

Results of studies of sex differences in temporal discounting are not consistent either (Kirby and Maraković, 1996; Harrison et al., 2002; de Wit et al., 2007; Reimers et al., 2009; Steinberg et al., 2009; Meier and Sprenger, 2010), although a recent meta-analysis argued that men have higher discount rates than women (Gaillard et al., 2020). Lower discount rates are associated with higher educational attainment, higher income and wealth levels, as well as home ownership (Harrison et al., 2002; Meier and Sprenger, 2010; Yang, 2016). Considering marital status, singles appear to have higher discount rates than married people (Harrison et al., 2002).

Correlations of socio-demographic variables with discount rates need to be interpreted with care. An individual's behavioral, and neural phenotype such as temporal discounting at the moment of measurement is the product of a complex developmental process, during which genes, social experience, and cultural context interact with each other dynamically and reciprocally (Rippon et al., 2014). If not properly accounted for in the analysis, associations between discount rates and socio-demographic variables are prone to misinterpretation. Isolating the (causal) effect of individual factors on intertemporal preferences is difficult and requires careful consideration of hypotheses, sample size, independent and dependent variables, as well as type of statistical analysis (Rippon et al., 2014). Unfortunately, many existing studies fall short from a methodological perspective. Large-scale, population-representative studies are needed in order to dissect contributions of different socio-economic as well as other individual differences variables to temporal discounting.

PERSONALITY TRAITS

Impulsive decision making has been associated with a broad range of personality traits for a long time (Funder et al., 1983; Shoda et al., 1990). *Personality*, defined as characteristic patterns of thought, emotion, and behavior, is a key individual differences variable in psychology. Major theories of personality (Eysenck, 1947; Cloninger, 1986; Gray, 1987; Costa and McCrae, 1992) include dimensions that appear conceptually related to the ability to withhold or delay rewards, such as impulsivity or reward dependence. Accordingly, the most widely studied personality construct in the context of temporal discounting is *trait impulsivity*, often defined as "a predisposition toward rapid, unplanned reactions to internal or external stimuli without regard to the negative consequences of these reactions to the impulsive individual or to others" (Moeller et al., 2001, p. 1784). Within individual differences psychology, impulsivity is considered a broad construct composed of several distinct traits (cf. Whiteside and Lynam, 2001) and is measured with self-report scales such as the UPPS-P Impulsive Behavior Scale (Lynam et al., 2006; Cyders et al., 2014) and the Barratt Impulsiveness Scale (BIS; Patton et al., 1995).

Numerous studies of associations between temporal discounting and impulsivity in relatively small clinical and/or non-clinical samples have reported inconsistent results, ranging from non-significant to moderate correlations between temporal discounting and impulsigenic traits (de Wit et al., 2007; Murphy and MacKillop, 2012; Stahl et al., 2014; Caswell et al., 2015; Steward et al., 2017; VanderBroek-Stice et al., 2017; Jauregi et al., 2018). Recently, a large-scale general population study (N = 1,252) indicated that only some impulsigenic traits are significantly related to discount rates (MacKillop et al., 2016). In that study, lack of premeditation and positive urgency from the UPPS-P as well as non-planning and motor impulsivity from the BIS were consistently and significantly related to

temporal discounting. However, effect sizes were low (r = 0.10) and comparable to those reported in meta-analyses on the relations between self-reported and laboratory measures of impulsivity (Cyders and Coskunpinar, 2011; Sharma et al., 2014). A recent study using genetic data also confirmed weak to moderate positive correlations between trait impulsivity and temporal discounting, with lack of premeditation showing the strongest association (Gustavson et al., 2020). Interestingly, a meta-analysis of the construct of self-control—typically defined as the opposite of impulsivity and often referred to in the context of impulsive decision making (Evenden, 1999)—in part found slightly higher correlations of self- and informant-report questionnaires with temporal discounting, dependent on the concrete temporal discounting task (average r = 0.15, range 0.08–0.39 for self-report; average r = 0.21, range 0.11–0.27 for informant-report; Duckworth and Kern, 2011).

Thus, although intertemporal choice is sometimes thought to represent a direct behavioral measure of choice impulsivity (Hamilton et al., 2015), associations with traits related to impulsivity are surprisingly low, and often non-significant in underpowered studies (Murphy and MacKillop, 2012; Stahl et al., 2014). It may be suspected that these low correlations are due in part to the heterogeneity of constructs referred to as impulsivity (Evenden, 1999; Strickland and Johnson, 2020) or reliability-related issues in the comparison of self-report and behavioral measures (Enkavi et al., 2019; Dang et al., 2020).

It has to be noted, however, that steeper discounting is generally related to impulsive behaviors such as substance use, gambling behavior, or obesity (Reynolds, 2006; Reimers et al., 2009; see Moreira and Barbosa, 2019, for a recent review) and, accordingly, to pathological behavior (Amlung et al., 2019). Since many personality traits are considered to be on a continuum with psychopathology (Widiger and Samuel, 2005; Coghill and Sonuga-Barke, 2012; Ettinger et al., 2014), these results are not surprising: By definition, some forms of psychopathology involve an extreme form of impulsivity (e.g., ADHD, bulimia nervosa), thus rendering the measurement of this construct very important. Indeed, Amlung et al. (2019) argued that temporal discounting may be a transdiagnostic marker.

Since Whiteside and Lynam (2001) based the original UPPS Scales in part on the Big Five, it has been investigated whether these major dimensions of personality are also related to temporal discounting. The strongest association appears to be between steeper discount rates and higher levels of extraversion (Daugherty and Brase, 2010; Mahalingam et al., 2014; Civai et al., 2016), perhaps due to higher susceptibility to (direct) rewards in extraverted individuals (Ostaszewski, 1996; Hirsh et al., 2010). Similar to impulsivity, however, this association is of small effect: In a study of N = 5,888 participants, Mahalingam et al. (2014) found a correlation of r = 0.10. Their results also revealed small effects of openness (r = −0.05), conscientiousness (r = −0.09), and neuroticism (r = 0.09), with higher discounting being predicted by lower openness and conscientiousness and higher neuroticism. Agreeableness was not related to temporal discounting. Interestingly, the influences of openness and neuroticism interacted with the magnitude effect (i.e., the effect that smaller rewards are discounted more strongly than larger ones), reflecting the fact that correlations were stronger for larger reward magnitudes (Mahalingam et al., 2014). However, as Mahalingam et al. (2014) point out themselves, the study only used two different delayed amounts and a single delay interval, thereby limiting the psychometric quality of the temporal discounting measure.

Apart from impulsivity and the Big Five, research into associations between temporal discounting and personality traits is scarce and less consistent. For instance, associations between steeper discounting and novelty seeking (Anokhin et al., 2011; Malesza and Ostaszewski, 2013), reward dependency (Malesza and Ostaszewski, 2013), or risk-relevant traits such as harm avoidance (Bobova et al., 2009; Malesza and Ostaszewski, 2013; Howe and Finn, 2020) and sensation seeking (Ostaszewski, 1996; Kirby and Petry, 2004; Stahl et al., 2014) remain unclear.

Notably, interactions between different personality traits such as harm avoidance and impulsivity (Howe and Finn, 2020) were recently highlighted and should be investigated in future studies. This notion is particularly important, given the observation that risk perception, which may to some extent be reflected by harm avoidance, plays an influential role in temporal discounting (Lopez-Guzman et al., 2018). Indeed, it is important to consider that delayed rewards, especially real-life rewards, are also *uncertain*. This may be especially true in socioeconomically-stressed populations (see Socio-demographic factors section) and possibly also moderates associations with various personality traits. Since models without consideration of risk attitudes overestimate discount rates of risk-averse individuals and underestimate discount rates of risk-seeking individuals (Lopez-Guzman et al., 2018), effect sizes of associations between temporal discounting and personality traits might be biased.

Additionally, different methods and measures of temporal discounting may lead to results varying between studies. For instance, both temporal discounting and the possible confounding effect of risk perception could be differentially influenced by different task parameters such as reward method (e.g., hypothetical vs. real rewards; though see Johnson and Bickel, 2002; Matusiewicz et al., 2013), reward magnitude (Prelec and Loewenstein, 1991), or trust toward the experimenter (Ma et al., 2018). For example, the association of temporal discounting with neuroticism might be particularly high when participants are confronted with real rewards, high reward magnitudes, and less trusted experimenters or online settings, partly due to confounds with probability discounting.

Therefore, risk perception factors should be accounted for (Lopez-Guzman et al., 2018, 2019) and the specific implementation of intertemporal choice tasks should be considered when investigating temporal discounting and its association with individual difference variables.

Overall, studies of the personality correlates of temporal discounting have yielded patterns that broadly agree with the construct validity of temporal discounting as measure of impulsivity. However, studies were not entirely consistent, and effect sizes tend to be small. More large-scale studies are required to both test specific hypotheses and replicate previous findings (possibly using the same vs. different temporal discounting

applications), whilst also accounting for the possible role of individual differences in risk perception.

FUTURE-ORIENTED COGNITIVE STYLES AND IMAGERY

Another important domain of individual differences concerns future-oriented cognitive styles and abilities, i.e., general temporal thinking (Zimbardo and Boyd, 1999) or mental imagery, which is defined as the ability to form and experience mental representations of stimuli without actually perceiving them (Pearson et al., 2015). Since both constructs involve subjective thinking styles and experiences, they are normally assessed with self-report questionnaires. Measures of temporal thinking include the Consideration of Future Consequences Scale (CFCS; Strathman et al., 1994) and the Zimbardo Time Perspective Inventory (ZTPI; Zimbardo and Boyd, 1999), whereas (visual) mental imagery is generally assessed with the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973).

Initially, it may appear straightforward that dispositions that emphasize thinking about the future should be positively associated with choosing larger future rewards over smaller immediate rewards. And indeed, as Teuscher and Mitchell (2011) observed, future orientation and discount rates are similarly related to behavioral and demographic variables and show significant associations with each other, with more future oriented individuals showing less temporal discounting. However, Teuscher and Mitchell (2011) also concluded that the correlation between the two constructs is only modest and that they are not identical. Most importantly, Steinberg et al. (2009), who investigated 935 individuals using a new scale of future orientation, only found a correlation of $r = -0.15$. Later studies assessing other and more widely used measures of future orientation in large samples found comparable effect sizes (Daugherty and Brase, 2010; Bruderer Enzler, 2015; Cosenza and Nigro, 2015).

Overall, although the term future orientation has been used in the context of many different constructs (Steinberg et al., 2009), the correlation of temporal discounting with measures of time perspective appears to be robust, consistently indicating that steeper temporal discounting is associated with stronger focus on present rather than future consequences (Daugherty and Brase, 2010; Guo et al., 2017; Macaskill et al., 2019). Recently, a study replicated these results but raised the question of whether temporal discounting is more strongly related to immediate than future orientation (Macaskill et al., 2019). The authors concluded that studies with relatively elaborate temporal discounting paradigms point to that finding (e.g., Charlton et al., 2011, Study 2; Joireman et al., 2008, Study 3). However, there were also studies finding comparable correlations (with even more participants) that used rather complex tasks as well (e.g., Cosenza and Nigro, 2015).

Thus, although future studies should investigate relations of temporal discounting with specific temporal thinking styles further, it seems that both future and present time orientation have an impact on temporal discounting, perhaps comparable in size. Macaskill et al. (2019) make an important, more general point, though, in emphasizing the impact of task complexity. While shorter temporal discounting tasks may entail an economic advantage enabling large-scale studies (e.g., single-shot paradigms; see Macaskill et al., 2019, Study 1), investigators should bear in mind that this comes at the expense of psychometric quality and might influence associations with individual difference variables.

Apart from thinking styles, the ability to imagine future events has been considered as a correlate of temporal discounting. Since *episodic future thinking*, i.e., making use of episodic memory to pre-experience future events (Atance and O'Neill, 2001), reveals that discounting can be reduced by inducing episodic imagery (Rung and Madden, 2018; Scholten et al., 2019), it is reasonable to assume that interindividual differences in the tendency and ability to imagine are related to temporal discounting. However, Parthasarathi et al. (2017) unexpectedly found that higher ability to imagine (measured using VVIQ, Marks, 1973; lower scores representing more vivid imagery) was associated with stronger temporal discounting (primary training study: $N_{\text{before_training}} = 48$, $r_{\text{before_training}} = -0.37$; $N_{\text{after_training}} = 38$, $r_{\text{after_training}} = -0.45$; additional study: $N = 154$, $r = -0.25$). Moreover, a 4-week visualization training, compared to a relaxation training control group, surprisingly led to a (weak) increase in discount rates ($N = 38$; $d_{\text{after_training}} = 0.71$)[1].

It is unclear, however, why these effects occurred. Parthasarathi et al. (2017) provided several possible explanations, including the possibilities that the VVIQ is primarily related to present imagination; that imagery ability could also lead to an enhanced visualization of smaller, sooner options, thus providing an enhanced preference for them; that visualizing isolated future goals reduces motivation toward them. Furthermore, the above-mentioned risk preference issue might also have an influence here, as imagery ability has been shown to moderate the relationship between risk perception and risk taking (Traczyk et al., 2015), thus possibly leading to less influence of risk perception on discounting behavior and, ultimately, more discounting in people with stronger imagery ability. Also, methodological issues such as the dissociation of hypothetical and real rewards should be considered since the ability to imagine the receipt of money now or in future may play a differential role (e.g., a stronger role in hypothetical rewards because it might be generally harder to imagine receipt of pretend money or a stronger role in real rewards because it is more relevant to imagine receipt of real money). However, to date, no studies have been carried out to clarify these important open questions. Thus, future investigations should aim to replicate the effect found by Parthasarathi et al. (2017) and to give evidence for potential explanations. A promising population within which to address these questions consists of participants with extremely low or high voluntary imagery (aphantasics and hyperphantasics, respectively; Zeman et al., 2020). Moreover, investigating interactions between episodic future thinking and

[1]Since Parthasarathi et al. (2017) did not conduct repeated-measures ANOVA, only effect sizes of differences in discount rates between the groups before ($p = 0.09$, $d = 0.17$) and after ($p = 0.04$, $d = 0.71$) training can be reported.

self-report measures of imagery could help to determine the role of imagination abilities in temporal discounting.

INHIBITORY CONTROL

Inhibitory control refers to the ability to withhold or stop responses or thoughts that are unwanted in a given context. Within the influential model by Miyake et al. (2000), inhibitory control is a core dimension of cognitive control. *Cognitive control*, or *executive function*, refers to effortful, general-purpose control mechanisms that dynamically regulate thoughts and behaviors by modulating cognitive sub-processes (Miyake and Friedman, 2012; Diamond, 2013; Cohen, 2017). Cognitive control is required when automatic or impulsive responses have to be overridden. This ability is of relevance to mental and physical health, success in education, and other real-life outcomes (Egner, 2017). Inhibitory control itself is heterogeneous, but has been suggested to include response inhibition, resistance to distractor interference, and resistance to proactive interference from irrelevant memories (Friedman and Miyake, 2004).

Controlled inhibition of automatic processes and responses may also be a mechanism of intertemporal choice (Cohen, 2017). Accordingly, relationships between temporal discounting and inhibitory control have been examined in both humans and rodents (Dalley et al., 2011). Findings, however, are so far mostly inconclusive.

Urošević et al. (2016) found no significant correlations between temporal discounting and inhibitory control in a go/nogo task in healthy controls ($N = 32$), although a correlation emerged in bipolar patients ($r = 0.40$). A study of $N = 167$ students also failed to observe significant correlations of temporal discounting with go/nogo and stop-signal task performance (Jauregi et al., 2018).

There is, however, also evidence of significant associations. In a comprehensive analysis of impulsivity and inhibitory control in $N = 190$ healthy adults, Stahl et al. (2014) observed that a latent variable indexed by two temporal discounting tasks was correlated with a latent variable tapping inhibition of proactive interference. There was no correlation, however, with latent variables tapping stimulus interference, response interference, and information sampling.

Additionally, Lawyer and Mahoney (2018) found the individual rate of discounting (b) to be correlated modestly but significantly with the stop signal reaction time (SSRT) measure from the stop-signal task in $N = 296$ young adults. SSRT was not, however, correlated with another measure of temporal discounting, the area under the curve.

Moreover, Harden et al. (2017) observed in a large sample of $N = 810$ adolescents that temporal discounting loaded onto a "cognitive dyscontrol" factor that included, amongst others, the Tower of London task, a measure of general executive function. This suggests that associations between temporal discounting and aspects of cognitive control may exist, but that they may be of small magnitude and may benefit from latent factor approaches.

Overall, evidence of correlations between temporal discounting and inhibitory control is scant and relatively inconsistent. It should be noted that the lack of strong associations between temporal discounting and cognitive control is complemented by experimental data, which show that these seemingly related constructs do indeed reflect different processes (Scherbaum et al., 2018). Further work is thus clearly needed, particularly with larger samples and employing sophisticated data analytical techniques (Harden et al., 2017).

Future studies may also further explore this area by going beyond studying reaction times and error rates of inhibitory tasks, instead employing model parameters derived from models of task performance (e.g., Ulrich et al., 2015; Aponte et al., 2017) and relating these to temporal discounting parameters (Kvam et al., 2020).

INTELLIGENCE

Intelligence has often been investigated in relation to intertemporal choice. Mischel, the pioneer in the study of delay of gratification, and his colleagues reported that results of their marshmallow test of self-control covary with IQ (Mischel and Metzner, 1962) and longitudinally predict a broad range of competencies (Mischel et al., 1988; Shoda et al., 1990; though see Watts et al., 2018, for possible limitations). Interestingly, in the study of children's tendency to discount the value of a relatively more worthful candy (Mischel and Metzner, 1962), there was a positive correlation between self-control and intelligence ($r = 0.29$), comparable to the effect sizes found in more recent studies of more complex temporal discounting tasks in adults (Shamosh and Gray, 2008).

Indeed, Shamosh and Gray (2008) conducted a meta-analysis of 24 studies and found that higher intelligence was associated with lower temporal discounting (weighted mean using a random effects model: $r = -0.23$). They further found this effect to be independent of the type of temporal discounting measure, experimental paradigm, and domain of intelligence, although several other moderator variables may play a role. For instance, the relation between intelligence and temporal discounting was weaker when real monetary outcomes involved chance (i.e., when participants had a chance of winning a real reward or when one single trial was randomly chosen to assign a real reward to participants) compared to studies in which outcomes were continuously hypothetical or real. Furthermore, measures of verbal intelligence were correlated equally strongly with temporal discounting as combined measures of verbal and non-verbal intelligence, suggesting either a role of verbal strategies to maintain self-control (Olson et al., 2007) or influences of a general intelligence factor (Isen et al., 2014). Finally, the authors explored possible moderating variables such as publication year and sample characteristics [age, education level, socio-economic status (SES), and IQ]. The results suggest that the relationship between temporal discounting and intelligence was stronger in more recent publications as well as in older, more highly educated, and more intelligent samples and those with higher SES. It should be noted, however, that, given the relatively low number of studies involved in the meta-analysis, the exploratory nature of the majority of the moderator analysis, the liberal modeling methods, and the collinearity between some of the variables (e.g., age and education), the differential roles

of various background and moderating variables have to be examined further.

Regarding the basis of the observed correlation, Shamosh and Gray (2008) argued that it might be the result of either motivational processes, such as conscientiousness, or shared mechanisms, such as working memory (Hinson et al., 2003). Age-related cognitive decline may also play a moderating role here (Kable et al., 2019). Generally, studies point to a combination of several variables: For instance, since the relation between the Big Five and temporal discounting is significant but rather low (see Personality Traits section), it can be assumed to be of some relevance (Civai et al., 2016), but additional variables should be considered.

Shamosh et al. (2008) tested the hypothesis of shared working memory mechanisms, as represented by working memory capacity, which is the ability to actively maintain goal-relevant mental representations (such as future rewards), while suppressing irrelevant or competing information (such as immediate rewards; Engle, 2002, 2018). They computed a latent variable derived from four working memory span tasks and a three-back task and measured brain activity with fMRI. Behaviorally, controlling for intelligence, working memory had no unique contribution to temporal discounting. Moreover, the relation between intelligence and temporal discounting was partially mediated by working memory-related brain activity in the left anterior prefrontal cortex (aPFC), thereby confirming the hypothesis of shared working memory mechanisms but also indicating the relevance of other variables, such as demographic variables and levels of future orientation. In agreement with these findings, it has been discussed that, apart from higher executive control functions, more precise perception of future outcomes could be relevant for the observed association (Burks et al., 2009)—an assumption that also is related to working memory and future orientation (see sections above). In fact, Basile and Toplak (2015) revealed in $N = 99$ that executive function and dispositions to think toward the future together are able to render intelligence non-significant as predictor of temporal discounting. Furthermore, a recent study demonstrated that working memory training could possibly lead to lower discount rates (Felton et al., 2019; also see Rung and Madden, 2018; Scholten et al., 2019). In sum, executive functioning seems to be an important underlying process relating intelligence and temporal discounting, and a disposition toward future orientation could be relevant as well. However, to the best of our knowledge, to date, no large-scale study has compared several moderating or mediating factors to completely explain the correlation.

Since the meta-analysis by Shamosh and Gray (2008), numerous studies on the relation between temporal discounting and intelligence have been added to the literature. Amongst them are large-scale studies that, though addressing different primary research aims, generally confirm the significant association of temporal discounting and intelligence found by Shamosh and Gray (2008) with similar effect sizes (e.g., Isen et al., 2014: $r = |0.17|–|0.28|$; Steinberg et al., 2009: $r = |0.27|–|0.31|$). Based on the groundbreaking investigations by Mischel and colleagues and studies in later years (Isen et al., 2014), the association appears to be stable over the life course, suggesting that both intelligence and the tendency to choose larger, later over smaller, sooner rewards develop similarly. In fact, both could be represented in neural development, notably within PFC, again suggesting a role of executive functions (Shamosh et al., 2008; Wesley and Bickel, 2014). However, as mentioned above, further—large-scale or possibly meta-analytic—studies on the relation between temporal discounting and intelligence are needed to clarify the role of different measures of intelligence as well as of shared underlying processes and moderating variables.

BRAIN STRUCTURE AND FUNCTION

Associations of temporal discounting with brain structure and function may to some extent explain links between individual differences in temporal discounting and other psychological variables. In this section, we review neuroimaging evidence that relates variation in brain structure, activity, and connectivity patterns with individual differences in temporal discounting. It is important to note that our aim is not to thoroughly review the neural underpinnings of temporal discounting; this has been done in previous work (Peters and Büchel, 2011; Frost and McNaughton, 2017; Schüller et al., 2019).

Evidence from structural imaging studies suggests that regional gray (gMV) and white matter volumes can to some extent predict individual differences in discount rates. In general, temporal discounting correlates with (i) gMV of regions associated with valuation such as striatum, ventromedial prefrontal cortex (vmPFC), posterior cingulate cortex (PCC), and orbitofrontal cortex (OFC) (Cho et al., 2013; Tschernegg et al., 2015; Guo et al., 2017), (ii) gMV of regions associated with cognitive control and other more deliberate processes such as dorsolateral prefrontal cortex (dlPFC) and frontal pole (FP) (Bjork et al., 2009; Mohammadi et al., 2016; Wang et al., 2016), as well as (iii) gMV and white matter volume of regions associated with memory and future-oriented thinking (hippocampus/parahippocampus, entorhinal cortex; Yu, 2012; Wang et al., 2016; Lempert et al., 2020).

However, not only the strength, but also the direction of the reported correlations is inconsistent across studies. For instance, in $N = 34$ healthy individuals, Cho et al. (2013) found that discount rates correlate negatively with gMV of striatum (bilateral putamen, no correlation coefficient reported). On the other hand, employing a region of interest (ROI) approach, using a more detailed assessment of temporal discounting (more items, repeated testing), and a larger sample size ($N = 70$), Tschernegg et al. (2015) found a positive correlation between striatal gMV and discount rate (reported correlations for left caudate: $r = 0.28$, $p = 0.02$, uncorrected; and for right caudate: $r = 0.31$, $p = 0.01$, uncorrected). Similarly, while Bjork et al. (2009) ($N = 29$) reported negative correlations between gMV of regions associated with cognitive control and discount rate (inferior lateral PFC: $\beta = -0.37$, $p < 0.05$, uncorrected; dlPFC: $\beta = -0.42$, $p < 0.05$, uncorrected), Wang et al. (2016) ($N = 227$) demonstrated that gMV of similar regions (FP, OFC, lateral PFC) correlates positively with discount rate (prediction accuracy rates ranging from 0.17 to 0.24). These inconsistent findings may be attributed to several factors including sample heterogeneity across studies, differences in approach (whole brain vs. ROI), methods to assess temporal discounting, statistical analyses (e.g.,

differences in the chosen thresholds), and the anatomic specificity of the reported brain regions.

Individual differences in temporal discounting may also be related to task-dependent neural activity differences (Seghier and Price, 2018). Specifically, it has been argued that the degree of PFC recruitment during temporal discounting may among others reflect differences in self-control and thus relate to temporal discounting. Supporting this, it has been shown that increased activity in cognitive control associated regions during temporal discounting relates to choosing larger, later rewards, whereas hypofunction in these areas is associated with impulsive choice (McClure et al., 2004; Peters and Büchel, 2011; Elton et al., 2017; Jimura et al., 2018).

Other studies have shown that individual differences in neural sensitivity to temporal delays and reward magnitudes may relate to differences in temporal discounting (Hariri et al., 2006; Kable and Glimcher, 2007; Ballard and Knutson, 2009; Cooper et al., 2013). Cooper et al. (2013) reported that steep and flat discounters exhibit opposite neural patterns in response to delays; while the former showed increased activity in ventral striatum (vS) and vmPFC in response to short delays, this pattern was observed for long delays in the latter. Furthermore, the authors demonstrated that neural delay sensitivity could account for ∼15% of variance in discount rates. This value is close to the reliable correlation between cognitive ability and temporal discounting (Shamosh and Gray, 2008), thereby supporting a significant contribution of neural delay sensitivity to differences in temporal discounting. Differences in vS sensitivity to rewards have also been implicated in temporal discounting. However, the exact nature of this association in healthy adults remains debatable (Hariri et al., 2006; Ballard and Knutson, 2009; de Water et al., 2017; Elton et al., 2017).

In addition to the sensitivity and recruitment of certain brain regions, the effectiveness of the structural, intrinsic, and functional connectivity between and within these regions has been shown to predict differences in temporal discounting (Li et al., 2013; van den Bos et al., 2014; Calluso et al., 2015; Mohammadi et al., 2016; Wang et al., 2016; Anandakumar et al., 2018; Ikuta et al., 2018; Xin et al., 2020). van den Bos et al. (2014) demonstrated that individual differences in discount rates were correlated with structural and functional connectivity between right dlPFC and dorsal striatum ($r = -0.66$, $p < 0.001$ and $r = 0.57$, $p < 0.01$ respectively; $N = 22$). More specifically, they found that stronger structural corticostriatal connectivity and stronger negative corticostriatal functional coupling during temporal discounting predict lower discount rates. Similarly, flat discounters have been found to exhibit stronger intrinsic (Wang et al., 2016) and task-dependent functional connectivity between cortical and subcortical, cortical and limbic (Peters and Büchel, 2010, 2011), and within cortical areas (Hare et al., 2014), than steep discounters. Considering that temporal discounting behavior is complex and engages several brain networks, future research should more precisely investigate how different neural networks interact during temporal discounting behavior, and whether inter-individual differences in these network interactions relate to differences in temporal discounting.

Brain features may also explain or mediate the link between psychological variables (such as personality traits and cognition) and temporal discounting. For instance, Shamosh et al. (2008) showed that working memory-related aPFC activity partially mediates the relationship between intelligence and temporal discounting (see Intelligence section), whereas Benoit et al. (2011) showed that activity in middle rostral PFC mediates the relation between temporal discounting and episodic future thinking. Relatedly, resting state functional connectivity (Guo and Feng, 2015) and intrinsic organization within PFC (Xin et al., 2020) have been shown to support the relation between temporal discounting and personality dispositions such as regulatory mode (Guo and Feng, 2015) and achievement motivation (Xin et al., 2020), respectively. Anterior and lateral portions of PFC have been associated with information integration (anterior/rostral portions of PFC; Ramnani and Owen, 2004) and executive functions of working memory and attention (lateral portions of PFC; Yuan and Raz, 2014). Thus, it could be speculated that differences in processes such as memory, attention, and information integration may underlie differences in temporal discounting. More powerful studies are needed to replicate these findings and to assess the possible mediating mechanisms underlying the correlations between temporal discounting and other psychological variables.

Taken together, neuroimaging studies provide evidence that structures and functional patterns in prefrontal, subcortical, and limbic regions associated with valuation, cognitive control, memory, and future-oriented thinking may partially account for individual differences in temporal discounting. However, more research is needed to replicate and validate the findings in large, representative samples.

These results should be interpreted with caution for several reasons. First and foremost, the results are not conclusive and are often derived from relatively low-powered studies. The correlation strength (effect size) between MRI measures (both structural and functional) and individual differences is typically very small, which renders small sample studies severely underpowered and prone to false negatives. This is especially the case for fMRI studies (the studies reviewed here have sample sizes ranging from $N = 12$ to $N = 103$), as more recent structural studies on temporal discounting have used relatively larger sample sizes (e.g., Wang et al., 2016, $N = 227$). Considering the low correlation between MRI measures and individual differences in temporal discounting, the inconsistent findings reported in this section, and more generally the replicability crisis in psychological research, future neuroimaging studies should use larger sample sizes to increase statistical power (Turner et al., 2018). In addition, larger sample sizes will make it possible to more thoroughly consider the effects of moderator or mediator variables such as age, sex, IQ, or SES and thus better discern the contribution of each to differences in temporal discounting behavior.

Second, a recent meta-analysis (Elliott et al., 2020) reported low test–retest reliability of commonly used fMRI measures, which hinders and limits the ability to use task-fMRI measures for individual differences research. While temporal discounting tasks were not included in the meta-analysis, previous research

indicates that they may not be immune to reliability issues (Vetter et al., 2017; Fröhner et al., 2019). Therefore, unless evidence of reliability is provided, task-fMRI studies linking individual differences in temporal discounting with brain features should be considered with great caution.

Third, findings appear to depend on approach and methodology. One example concerns differences when employing whole brain vs. ROI approaches. While the former may provide a broader overview of the brain regions associated with temporal discounting behavior, the latter may offer insights into the role of more specific brain regions, alas with additional limitations stemming from methods used to define specific ROIs. Moreover, recent work (Botvinik-Nezer et al., 2020) indicates that even within the same approach, differences in analysis pipelines may yield different findings. Therefore, combining different approaches and employing meta-analytic strategies may provide a better picture of the neural correlates underlying individual differences in temporal discounting.

Finally, many neuroimaging studies do not report effect sizes, making it difficult to compare findings across studies and to quantify the magnitude of the reported effects. To aid cross-study comparisons and to aid meta-analyses, future studies should support their conclusions with effect sizes [e.g., for fMRI studies, Poldrack et al. (2008) suggest mean % signal change and standard deviation].

MOLECULAR GENETICS

Converging evidence from animal (Anderson and Woolverton, 2005; Stein et al., 2012) and human studies (Isen et al., 2014; Anokhin et al., 2015) shows that temporal discounting is moderately yet significantly heritable. Building on this finding, several genetic polymorphisms have been associated with temporal discounting; however, the findings are inconclusive (Mitchell, 2011; MacKillop, 2013; Gray et al., 2019; Levitt et al., 2020).

Given the involvement of the neuromodulator dopamine (DA) in motivation and reward processing (Schultz, 2001) as well as clinical conditions associated with steep discounting (e.g., addiction; Le Folla et al., 2009; Mitchell, 2011), several studies have investigated how variations in genes coding for the synthesis, signaling, re-uptake, and metabolism of DA relate to temporal discounting (Boettiger et al., 2007; Eisenberg et al., 2007; Paloyelis et al., 2010; Sweitzer et al., 2013; MacKillop et al., 2015). Although these candidate-gene studies converge on the importance of the DA system in temporal discounting (Gray et al., 2019; Levitt et al., 2020), the results as to which genes and which variations relate to steeper discounting are largely inconsistent and have not been replicated in other studies. A major reason for this is the insufficient power of these studies to detect small effects (most probable in this case), which severely compromises the reliability and validity of the findings[2].

[2]Candidate-gene studies have been reported to additionally suffer from other more general issues. Considering the scope of our review, we do not discuss these issues in detail but instead refer the reader to Tabor et al. (2002), Zhu and Zhao (2007), Hart et al. (2013), and Farrell et al. (2015).

Currently, the most powerful approach in molecular genetics is the Genome Wide Association Study (GWAS) design. To date, there are two GWAS of temporal discounting (Sanchez-Roige et al., 2018; MacKillop et al., 2019). In the largest of these (Sanchez-Roige et al., 2018), steeper discounting was associated with a polymorphism (rs6528024) in the *GPM6B* gene (genome-wide significance $p = 2.40 \times 10^{-8}$, $\beta = -0.10$, SEM = 0.02, minor allele frequency = 0.03), which is involved in the internalization of a serotonin receptor. Importantly, these results were replicated in an independent cohort ($N = 928$; $p = 1.44 \times 10^{-8}$, $\beta = -0.10$, SEM = 0.02). In that study, the authors additionally showed that 12% of the variance in temporal discounting was accounted by genotype. By contrast, in a more recent GWAS in $N = 986$ healthy individuals, MacKillop et al. (2019) found an association between temporal discounting and a polymorphism (rs521674) in the *ADRA2A* gene coding for α2 adrenoreceptor (which did not survive correction for type I error rate), and an intergenic locus in chromosome 2 (genome-wide significant at $p = 2.8 \times 10^{-8}$, $\beta = 0.27$, SEM = 0.05, minor allele frequency = 0.33), whose function remains unknown. Interestingly, in addition to not reporting concurrent findings, these studies did not replicate previous findings from candidate-gene approaches.

Taken together, these findings suggest that the genetic underpinnings of temporal discounting are far more complex than may have been initially thought. Further research is needed to replicate these findings in well-powered studies with appropriate replication samples. Multi-center studies and large-scale consortia may be needed to achieve these goals.

Similar to brain features, genetic variations may explain, mediate, or moderate correlations between temporal discounting and different psychological variables. In line with this, Sanchez-Roige et al. (2018) found that the genetic signature of temporal discounting overlapped with neuroticism ($r_g = 0.18$, $p = 2.25 \times 10^{-2}$), years of education ($r_g = -0.67$, $p = 7.9 \times 10^{-15}$), childhood IQ ($r_g = -0.63$, $p = 1.63 \times 10^{-4}$), and college attainment ($r_g = -0.93$, $p = 3 \times 10^{-10}$), all of which have also been behaviorally associated with temporal discounting (see above). These findings have yet to be replicated in more powerful studies. A promising approach that could additionally complement these findings is using GWAS to investigate whether psychological variables and temporal discounting share common genetic variations. This approach has been used to assess the genetical relationship between major psychiatric disorders (Lee et al., 2013), and may provide additional evidence on the biological mechanisms underlying associations between psychological variables and temporal discounting.

Several considerations should be taken into account in this context. First, evidence from behavioral genetics (Anokhin et al., 2011, 2015; Isen et al., 2014) confirms that temporal discounting is not completely genetically determined. Moreover, other factors may mediate and/or moderate the molecular genetic effects reviewed here. For instance, Gianotti et al. (2012) demonstrated that baseline activity in PFC mediated the association between Catechol-*O*-Methyltransferase (*COMT*) Val158Met polymorphism and temporal discounting. These and similar findings could point to a potential "third variable problem," considering that the same genes and the same areas

are associated with other variables such as for example working memory (in the case of PFC activity, see Lara and Wallis, 2015). Therefore, it is imperative to employ more integrative approaches, whereby several influences are considered together such that genetic contributions to temporal discounting can be more clearly defined.

Second, an important aspect in this line of research is employing a framework which will help in understanding how molecular genetic variation, temporal discounting, and psychiatric illness phenotypes co-occur. An increasingly promising framework proposes that temporal discounting may play the role of an endophenotype, viz. a marker of the genetic liability for a clinical disorder (Gottesman and Shields, 1973; Gottesman and Gould, 2003). While discussing the endophenotypic nature of temporal discounting is beyond the scope of this review (for a review see MacKillop, 2013), it is important to highlight that understanding the genetic underpinning of temporal discounting in healthy individuals may also provide invaluable insights in further elucidating the endophenotypic nature of temporal discounting and, by extension, the etiology, and pathophysiology of major clinical disorders (Amlung et al., 2019).

Finally, as discussed throughout this review, temporal discounting is a complex behavior determined by several genetical and environmental factors. Surprisingly, however, interactions between genes and environment in temporal discounting remain unexplored.

Overall, the methodological shortcomings, inconsistencies and gaps in the literature discussed here should inspire future research to employ more integrative and innovative approaches that could ultimately paint a more comprehensive picture of temporal discounting.

DISCUSSION

We have provided a comprehensive narrative review of temporal discounting from an individual differences perspective. Here, we (i) briefly summarize the key findings and (ii) discuss both limitations of previous studies and implications for future research (**Table 1**, **Figure 2**).

Summary of Key Findings

The first key finding is that temporal discounting, despite its ubiquity in human and non-human animals alike, is subject to considerable individual differences; i.e., people generally discount future rewards, but they vary in the extent to which they do so. Importantly, this variation is not due to random fluctuations but is both temporally stable and significantly heritable.

Second, individual differences in temporal discounting are associated with a number of socio-economic and health-related variables. Where replicable findings are observed, the direction of these associations is unambiguous: Steeper discount rates are associated with less economic success and greater levels of health problems.

Third, large studies within the domain of personality have shown that steeper temporal discounting is associated with higher levels of self-reported impulsivity and extraversion; however, effect sizes are small. Steeper discounting may also be related to lower openness and conscientiousness as well as higher neuroticism. Relations of temporal discounting with constructs such as novelty-seeking, reward dependence, harm avoidance, or sensation seeking are less consistent.

Fourth, cognitive styles related to future orientation show overlap with temporal discounting in studies of large samples, again with small effect size. Investigations of the relation between temporal discounting and the ability to imagine future events are scarce and have not yielded conclusive results yet.

Fifth, not many studies have investigated correlations between temporal discounting and inhibitory control, and findings are not entirely consistent. However, large studies point to overlaps of small magnitude between temporal discounting and facets of inhibitory control.

Sixth, there is consistent evidence of an association between steeper temporal discounting and lower intelligence. The strength of the association appears greater than those with personality or cognitive variables and is robust regarding various measurement features. However, likely moderator variables include age, education, sample's level of intelligence, and SES.

Seventh, individual differences in brain structure and function have been related to temporal discounting in a growing number of studies. However, findings are as yet not consistent, both with regard to areas involved and direction of effects.

Finally, following early candidate gene studies, more recent work has used GWAS. Findings are inconsistent and suggest that the molecular genetic architecture of temporal discounting is more complex than initially thought.

Limitations and Implications

The above reviewed body of work has produced many important and replicable findings; however, no studies or research fields are without limitations. The limitations of these studies will now be discussed, combined with suggestions for future research.

First, significant test–retest reliabilities have been interpreted as evidence that variance in temporal discounting has a trait component. However, no study has formally modeled the state and trait components underlying variance in temporal discounting. These can be separated from each other and from measurement error using statistical techniques derived from latent state-trait (LST) theory, which allow the estimation of amounts of variance in a measurement due to stable trait, situational fluctuations (state) and person × situation interactions, and measurement error (Geiser et al., 2015). LST modeling of temporal discounting may inform further individual differences studies with regards to the amount of variation in temporal discounting that is in fact due to traits rather than states or measurement error.

Second, despite replicable correlations between socio-demographic variables and discount rates, their origins are unclear. An area of particular need of further investigation concerns the vexing issue of the direction of effects, i.e., whether steeper temporal discounting causes

socio-economic disadvantage or vice versa. Combined cross-sectional and longitudinal designs are needed to disentangle these relationships.

Third, a take-home message of work in personality is that correlations with temporal discounting are of small magnitude, often approximately $r = 0.10$ (Mahalingam et al., 2014; MacKillop et al., 2016). An implication, which cannot be stressed enough, is that large samples are needed to detect such effects with high confidence. To provide a simple guideline, an a priori power calculation (Faul et al., 2009) for a correlation with an expected effect size of rho = 0.10, alpha level of 0.05 (one-tailed) and power of 0.90 yields a required sample size of $N = 850$. To obtain 0.95 power, a sample size of $N = 1{,}073$ is needed. While some studies fulfill these demands, many in the field do not. Accordingly, findings from smaller studies are often inconsistent or negative, and the likely robust estimates of small correlations come from large samples (e.g., Steinberg et al., 2009; Mahalingam et al., 2014; MacKillop et al., 2016; Harden et al., 2017).

A further suggestion for personality research is that future studies should be clear about whether correlations were planned a priori and hypothesis-driven or exploratory. Both approaches have their place (Behrens, 1997; Wagenmakers et al., 2012). However, not only given that psychometric personality questionnaires can be easily administered and yield numerous variables, pre-registered (replication) studies are sorely needed to consolidate and advance the field.

A fundamental issue concerns the important question of why correlations are so low. This particularly concerns psychometric self-report measures of impulsivity given that temporal discounting has often been considered a measure of impulsivity (Padhi et al., 2012; Patton and Stanford, 2012). The problem is, however, not unique to intertemporal choice. For example, correlations between psychometric self-report measures of impulsivity on the one hand and task-based measures of inhibitory control on the other hand tend to be similar in magnitude to those observed here (approximately 0.10–0.15; Cyders and Coskunpinar, 2011; Aichert et al., 2012). A number of reasons have been proposed for this phenomenon, relating both to methodological and theoretical issues. A methodological criticism that has been made of task-based measures is their low reliability (Hedge et al., 2018), which puts an upper limit on the correlation that can be observed with a psychometric self-report measure. In the case of temporal discounting, that criticism is not likely to play a major role, given that temporal discounting shows good-to-high test–retest reliabilities (Beck and Triplett, 2009; Kirby, 2009; Jimura et al., 2011; Matusiewicz et al., 2013; Martínez-Loredo et al., 2017). A more substantial, theoretical criticism relates to the constructs themselves (Dang et al., 2020). Specifically, even though two measures may share the same name, they may not measure the same construct (a problem known as the jingle-jangle fallacy; Marsh, 1994). This is particularly pertinent for constructs as heterogeneous as impulsivity. Thus, correlations between temporal discounting and psychometric self-report measures of impulsivity may be low, because they tap different aspects of the broad construct of impulsivity.

Other reasons for low correlations include differences in measurement approaches. Specifically, whilst temporal discounting involves choices made at a specific point in time with potentially real consequences at this moment (i.e., being informed of an immediate or later reward), self-report questionnaires typically ask about general cognitive, affective, and behavioral tendencies and preferences. Moreover, even when examining only temporal discounting, measurement methods differ. For example, time frames (e.g., date/delay effect; Read et al., 2005), reward magnitudes (e.g., magnitude effect), reward types (e.g., money, food, health etc.; Odum et al., 2020), number of trials (e.g., single-shot paradigms vs. comprehensive tasks involving several hundred trials), or measures derived from intertemporal choice tasks (e.g., discount rate vs. area under the curve) can lead to variation between temporal discounting tasks. The convergent validity of different measurement methods and factors has to be investigated further. It is likely, however, that such differences could contribute to inconsistent findings concerning the covariation with individual differences variables (i.e., differential external validity). A further issue that may lower the expected correlations is the task impurity problem (Miyake et al., 2000). This refers to the problem that any behavioral task measures not just the construct of interest, in this case sensitivity to magnitude and timepoint of reward, but also other, related or unrelated constructs. For example, intertemporal choice tasks may also tap into processing related to mathematical skills. The extent to which these account for correlations with other variables is unknown; latent factor modeling approaches may be instructive in this regard (Miyake et al., 2000).

Another important issue is related to risk. Rewards received in the future are always uncertain. However, temporal discounting tasks typically do not control for participants' perceived level of uncertainty of the rewards they are presented with, nor their level of risk aversion. Thus, studies of intertemporal choice ideally would simultaneously assess risk preferences and, potentially, preferences for early resolution of uncertainty to isolate intertemporal from risk preferences (Kreps and Porteus, 1978; Andersen et al., 2008; Lopez-Guzman et al., 2018, 2019).

Fourth, our review of the literature on cognitive styles showed that future studies would benefit from addressing the issue of task complexity. Additionally, a valuable approach would be to extend correlational designs in unselected samples to specific sub-populations with extreme expressions of relevant phenotypes, e.g., aphantasics or hyperphantasics (Zeman et al., 2020). Moreover, combinations of individual differences approaches with experimental challenges may be particularly informative in this context. Specifically, the interactive effects of cognitive styles such as future-orientation and theoretically related experimental manipulations such as episodic future thinking should be characterized.

Fifth, although numerous studies have shown steeper temporal discounting to be associated with lower IQ, multivariate designs are needed to reliably identify moderators of the relationships between IQ and temporal discounting. Such work would be important to clarify why the observed correlations emerge.

Sixth, functional neuroimaging has produced replicable findings of the neural activation patterns accompanying intertemporal choice at group-level (Peters and Büchel, 2011; Frost and McNaughton, 2017). However, there is less work on correlations between discounting and measures of brain function as well as structure, and findings are generally inconsistent. These inconsistencies likely arise in part from low power due to small sample sizes and the low reliability of some of the obtained measures. Larger samples may not, however, be the panacea in this field. A host of issues from task-related factors such as difficulty to sample-related factors such as levels of impulsivity have to be considered to aid interpretation of the direction and strength of correlation.

Seventh, studies have begun to shed light onto the molecular genetics of temporal discounting. Whilst initial candidate gene studies have been seminal in launching this work, they tended to suffer from low power to detect the likely very small effects of individual gene variants and they lack independent, large-scale replications. Indeed, later GWAS approaches have not confirmed these early findings. Generally, this work is most likely to progress through large-scale studies, such as multi-center consortia (Thompson et al., 2014). These large-scale studies are also needed to assess possible genetic links between temporal discounting and psychological variables.

Specific suggestions for future genetic studies also include the observation that temporal discounting is a complex phenotype. Therefore, future work may wish to focus instead on subprocesses or neural measures, e.g., activation levels in specific areas of the temporal discounting network. Additionally, it is likely that genetic effects depend on environmental variables; therefore, gene × environment interactions should be considered in future studies.

CONCLUSIONS

The study of temporal discounting is a mature research field that has produced a number of replicable experimental (Rung and Madden, 2018) and neuroimaging (Frost and McNaughton, 2017) findings. Individual differences approaches have also generated some replicable findings; however, the field is still developing and many important questions are still unexplored.

General recommendations to the field include the issue of statistical power; correlations tend to be of small magnitude, necessitating large samples, clear a priori hypotheses, and independent replications. Given the task impurity problem, the field may also benefit from application of latent trait analyses; these have been applied with success in other areas of cognitive psychology (Friedman and Miyake, 2004). Fundamentally, evidence of reliability from test–retest studies should be supplemented by LST modeling, to properly separate trait from state variance and measurement error, as a fundamental basis for further individual differences work.

A final recommendation is to combine individual differences and experimental approaches. Various experimental manipulations reliably alter discount rates, including episodic future thinking manipulations or framing effects (Rung and Madden, 2018). Individual differences in these experimental effects, however, remain to be systematically explored. Such work would also be able to provide a more fine-grained picture of the patterns of correlations between temporal discounting under different conditions and personality, cognitive or neurobiological variables.

AUTHOR CONTRIBUTIONS

UE, CM, and BW developed the idea of the review. KK, QR, CM, and UE decided on the concrete conception and did the literature research. KK, QR, CM, and UE wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Appendix G | Review II

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Temporal Cognition, Impulsivity and Intertemporal Choice

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Introduction

Temporal cognition refers to the processes relating temporal characteristics of the physical world to the subjective experience of time (Matthews & Meck, 2016). Time is an essential and pervasive dimension in virtually all aspects of cognition and behaviour. Much of our thought, experience and behaviour is anchored in time, ranging from the recollection of past memories via present experiences such as pain or boredom, to plans and expectations about the future (Droit-Volet & Meck, 2007). Neurophysiological studies have failed so far to identify a single brain region solely dedicated to our capacity for temporal cognition, in notable contrast with the functional specialisation of areas processing auditory or visual information. Instead, a number of brain structures are thought to process time-related information, such as hippocampus, striatum, insula, fronto-parietal cortex and cerebellum, and there are numerous theoretical models of how these areas and connectivity among them may represent time (Wittmann, 2013).

One domain of cognition that is almost by definition highly sensitive to aspects of time is decision making. Decision making refers to a set of perceptual and cognitive processes that unfold over time and result in the choice of one response or course of action over another (or several others). Decisions are usually evaluated with regards to the (subjective) consequences for the decision maker or others. Various scientific disciplines have contributed to our understanding of decision making, most prominently psychology, economics, neuroscience and philosophy. Within these interdisciplinary decision sciences, the cognitive and neural processes underlying decision making are frequently investigated in situations of risk or uncertainty, i.e., when the probability of obtaining an expected outcome is known (but not 0 or 1) or poorly specified, respectively (Pleskac et al., 2015).

The temporal dimension inherent in the decision-making process has also been studied intensively (Kalenscher & Pennartz, 2008; Read & Scholten, 2017). Specifically, not only the decision-making process itself but also the consequences of one's decisions always unfold over time, thereby placing decision-making squarely in the domain of temporal cognition. Notably, depending on the specific situation, the consequences of one's decisions may be experienced almost immediately, within a few hundred milliseconds, such as in the decision where to look next (Noorani & Carpenter, 2016), or much later, after years and decades, as in the decision which profession to take up or which insurance scheme to invest in (Malkoc & Zauberman, 2019; Sutter, 2014).

One type of decision task that is particularly relevant in the context of temporal cognition is intertemporal choice (Frederick et al., 2002). Intertemporal choice tasks model situations, abundant in everyday life, in which people have to decide between rewards of different magnitudes which are available at different times in the future. One example is the decision whether to spend money on an immediately rewarding activity, such as a night out, or to save it towards a future, and potentially more rewarding activity, such as an overseas holiday. In a typical intertemporal choice task, participants choose between smaller rewards that are available sooner and larger rewards that are available later. In general, people prefer

rewards that are available earlier over rewards of the same size but available at a later time, thereby devaluing future rewards. This cross-species phenomenon is known as temporal discounting, or delay discounting (Ainslie, 1975; Frederick et al., 2002).

A number of theoretical explanations have been suggested to explain temporal discounting, including reward- or value-based accounts, cognitive accounts (focussing on representations, cognitive control, and prospection), personality-based accounts and (perceived) time-based accounts (B. K. Kim & Zauberman, 2009; Peters & Büchel, 2011; Zauberman & Urminsky, 2016). In this chapter, we focus on time-based accounts of temporal discounting, given that time perception itself and its effects on intertemporal choice have recently gained considerably in interest (Zauberman & Urminsky, 2016). In doing so, we also explore the relationship between intertemporal choice and impulsivity, as impulsivity has been hypothesised to reflect altered perception of time (Paasche et al., 2019) and given that the widely reported finding of increased temporal discounting in individuals with higher levels of impulsivity (Keidel et al., 2021) may be mediated by individual differences in temporal processing (Paasche et al., 2019).

We will first introduce intertemporal choice tasks as a prototypical paradigm of temporal cognition. We will then review studies of the effects of temporal processing manipulations on discounting behaviour, such as designs involving episodic future thinking or framing of temporal information. Next, we will discuss explanations of the temporal discounting phenomenon that are based on temporal cognition rather than other aspects of cognition (such as risk preferences). Finally, we will summarise and discuss evidence on the interrelationships between temporal processing, intertemporal choice and impulsivity.

Fundamentals of Intertemporal Choice

In its most canonical form, intertemporal choice refers to the choice between a smaller reward that is to be received sooner and an alternative, larger reward to be received at a greater delay. Thus, both decision options have two attributes: reward size and delay. Examples include the Marshmallow Test ("Would you rather have one marshmallow now or two in 15 minutes' time?") (Mischel, 2014; Mischel et al., 1989; Shoda et al., 1990; Watts et al., 2018) and the so-called consumption-savings problem ("How much of my income or wealth should I consume now and how much should I save and consume more at a later date?") (Choi et al., 2006; Hall, 1988; Modigliani & Brumberg, 1954).

For most decision-makers, the two attributes of decision options in an intertemporal choice task induce a trade-off: larger rewards are typically preferred over smaller rewards and rewards received sooner are typically preferred over rewards received later, ceteris paribus. Research on intertemporal choice is concerned with the modelling of this trade-off and the factors that influence it (Frederick et al., 2002).

A central issue in negotiating the trade-off between reward size and delay is the (non-)commensurability of the two attributes – how to compare an increase in one unit of

reward to a decrease in one unit of delay? Typically, a decision-maker's preferences for reward size and delay are inferred from their choices. The latter can be used to infer a ranking of different options that were available to the decision-maker, which is usually referred to as preferences. Under certain conditions, this ranking can be represented by a so-called utility function, a mapping of reward size and delay into utility (Mas-Colell et al., 1995). Thus, a utility function transforms the individual attributes of decision options – reward size and delay – into a common unit. The assumption is that in a given decision situation, a decision-maker would choose the option with the higher utility.

A utility function allows comparing a unit of reward, say 1 Euro, received at some delay, with a reward of similar size received immediately. The conversion of a future reward into its immediately-received equivalent, using a utility function, is called discounting and the value of a future reward discounted to the present is referred to as present value. Presenting a decision-maker with a series of decisions involving choices between rewards received immediately and rewards of different sizes received at varying delays allows inference of the so-called discount rate, the rate at which the decision-maker discounts future rewards per unit of time. A higher discount rate implies steeper discounting, that is, stronger devaluation of future rewards. Discount rates are often considered to be a measure of impulsivity (Keidel et al., 2021).

Differences in temporal discounting can manifest not only in the discount rate, the degree of discounting per unit of delay, but also in the functional form of the discount (utility) function. Different functions, such as exponential, hyperbolic and quasi-hyperbolic functions, typically differ in the weight they assign to different delays (Frederick et al., 2002). An important discount function is the exponential discount function. As its name indicates, future rewards are discounted as an exponential function of time: the utility (or discounted value) today of a future reward is given by $R/(1+r)^t$, where R is the value of the future reward, r is the discount rate per unit of time and t is the delay. This function assumes that the utility of delaying receipt of a reward is compounded over time: utility of delaying does not only accrue from the initial reward but also from additional utility gained in intermediate periods. This is reflected in the exponential form of the discount factor (Fig. 1).

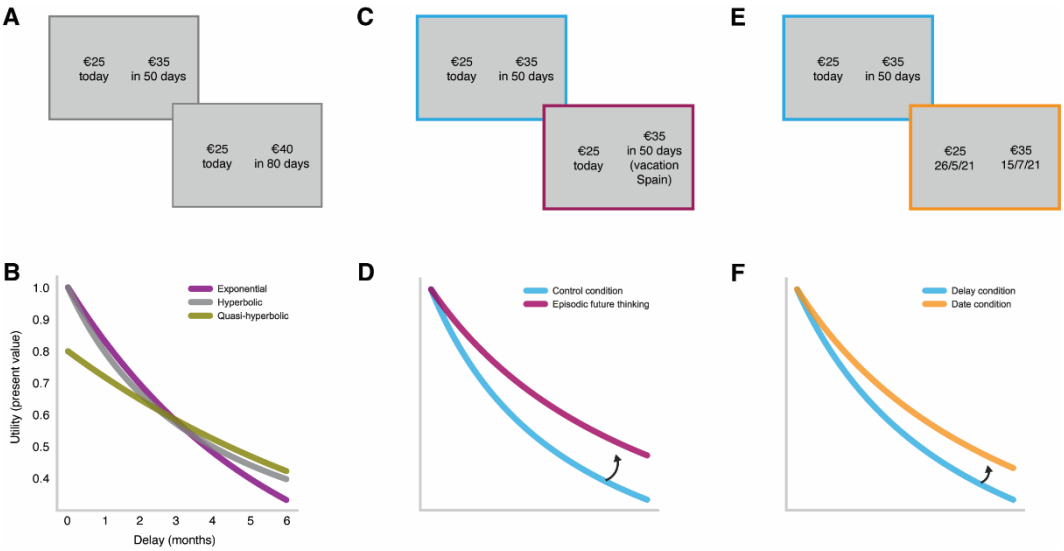


Figure 1 | The Intertemporal Choice Task. *Legend*: (A) Examples of choices in an intertemporal choice task. (B) Different discount functions, mapping delay until a $1 reward is received into utility (present value). (C) Examples of choices in an intertemporal choice task investigating the role of episodic future thinking in temporal discounting. (D) Illustration of the effect of episodic future thinking condition on the discount function. (E) Examples of choices investigating the role of different ways of presenting delays in an intertemporal choice task. (F) Illustration of the effect of date vs. delay condition on discount function.

Empirical research has demonstrated that human intertemporal choices are better described by a hyperbolic discount function, where the utility today of a future reward is given by $R/(1 + kt)$ (Kable & Glimcher, 2007, 2010). As the term indicates, this discount function assumes that utility only grows linearly over time. Compared with exponential discounting, a hyperbolic function discounts rewards more steeply at shorter delays and less steeply at longer delays. It can lead to so-called 'preference reversals': A person who prefers $20 received today to $30 received in three months may also prefer $30 received in one year and three months to $20 received in one year's time. Such behaviour is inconsistent with exponential discounting and is sometimes considered to be "irrational" (Frederick et al., 2002).

The discount functions discussed so far take as their arguments objective quantities, in particular, reward size and delay, and transform them directly into utility units, which in turn can be mapped into behaviour. Other approaches convert objective quantities into subjective values before mapping them into utilities. One motivation for the latter approach is to take properties of the perceptual system, e.g., number perception, into account when mapping stimulus properties (e.g., reward size, delay) into behaviour. A prominent example is the application of Weber's law to interval timing in scalar expectancy theory (Takahashi, 2005; Zauberman et al., 2009), which we discuss in more detail below. Other models take into account behavioural heuristics (Lempert & Phelps, 2016). At this point, it is still an

open question which factors determine the functional form of an individual's discount function.

Utility (or discount) functions have also been useful for identifying and characterising brain processes associated with intertemporal choice (for recent reviews, see Frost & McNaughton, 2017; Peters & Büchel, 2011; Schüller et al., 2019). The parameters of these functions, in particular, the discount rate, can be estimated based on the choices a person makes, for example, in an intertemporal choice task. Subsequently, these functions can be used to compute the utility of individual decision options that a person is presented with. Brain imaging techniques such as functional magnetic resonance imaging (fMRI) have been used to locate brain areas and networks in which activation is correlated with the utility of decision options during intertemporal choice (for meta-analysis, see Bartra et al., 2013).

This work has not only identified a network of brain regions associated with intertemporal choice but also structural and functional neural properties associated with individual differences in intertemporal choice (Keidel et al., 2021). The evidence so far suggests that certain structures and functional patterns in prefrontal, striatal, and subcortical brain regions associated with valuation, cognitive control, memory and future-oriented thinking, can, to some degree, account for individual differences in temporal discounting. It has been suggested that some of these structural and functional differences may serve as neural biomarkers of temporal discounting, that is, an objective biological measure of temporal discounting (Cho et al., 2013; Guo et al., 2017; Ikuta et al., 2018).

Time-related Experimental Effects

The previous sections have highlighted the importance of temporal processes in decision making, in particular in intertemporal choice, both in theory and experimental design. This section will add to this notion by focusing on two influential experimental effects on intertemporal choice behaviour.

Generally, experimental manipulations in intertemporal choice paradigms can help to elucidate the psychological and neural mechanisms of intertemporal choice that lead to non-rational, hyperbolic discounting behaviour. Within the context of temporal cognition, research has aimed primarily at two different processes, namely the perception of outcome values at different points of time and the perception of time itself (Ballard & Knutson, 2009; B. K. Kim & Zauberman, 2009). On the one hand, subjective valuation of objectively smaller, sooner and larger, later outcomes can be differentially influenced by visceral or emotional processes (Loewenstein, 1996) or by cognitive representations of outcomes (H. Kim et al., 2013; Malkoc & Zauberman, 2006). On the other hand, though possibly related, people are insufficiently sensitive to future time, and manipulations of time sensitivity can modulate intertemporal choice behaviour (Ebert & Prelec, 2007; B. K. Kim & Zauberman, 2009; Zauberman et al., 2009). Specifically, Zauberman et al. (2009) showed that

participants' subjective estimates of prospective time duration (marks on a line ranging from "very short" on the left end to "very far" on the right end) were not reflected by a linear function of objective time but by its logarithmic transformation. Interestingly, this is consistent with both hyperbolic discounting in intertemporal choice tasks and the Weber-Fechner law (Takahashi, 2005; also see Dehaene, 2003, who found that firing patterns of 'number neurons' follow the Weber-Fechner law).

Based on these important general findings, two specific experimental effects on intertemporal choice shall serve as examples to illustrate how manipulations of time-dependent valuation of outcomes and/or subjective time perception can influence intertemporal choice behaviour and, ultimately, reduce temporal discounting: Episodic Future Thinking (EFT) effects (Peters & Büchel, 2010) and the date/delay effect (LeBoeuf, 2006; Read et al., 2005) (Fig. 1).

EFT is defined as the ability to simulate experiences of one's own future (Atance & O'Neill, 2001). It plays a beneficial role in different cognitive and emotional functions including decision making, emotion regulation and spatial navigation (Schacter et al., 2017). In the context of intertemporal choice, EFT has been used to modulate discounting behaviour. In typical study designs, participants are first instructed to imagine and describe (positive) personal events at different points of time in the future. Subsequently, they complete a temporal discounting task in which the larger, later reward of each trial is cued by the self-generated event referring to that delay (Peters & Büchel, 2010). Although concrete induction methods of EFT (e.g., instructions) and control conditions (e.g., standard task without cues or cues referring to present/recent instead of future events) vary between studies, EFT has been shown to reduce temporal discounting relatively consistently and with moderate effect sizes (see Rung & Madden, 2018; Scholten et al., 2019, for reviews).

While the effectiveness of EFT in reducing temporal discounting is well documented, the underlying psychological mechanisms remain to be fully understood. Noël et al. (2017) and Rung and Madden (2018, 2019) summarize several possible and interconnected explanations.

First, EFT effects can be interpreted in terms of construal-level theory (Trope & Liberman, 2003), according to which near future events are mentally represented as lower-level construals (more concrete) whereas events further into the future events are represented as higher-level construals (more abstract). While this explains the so-called present bias, which puts a 'premium' on rewards received immediately (Trope & Liberman, 2003), in EFT, future rewards are rendered relatively more concrete and thus gain a comparable construal-level as immediate rewards, which facilitates option comparison and reduces temporal discounting (H. Kim et al., 2013; Rung & Madden, 2018; Yi et al., 2017). This explanation is supported by the idea that better visualization abilities moderate EFT (Peters & Büchel, 2010) and might also be linked to altered time perception (see below). Second, EFT might evoke an expanded temporal horizon (Lin & Epstein, 2014; Snider et al., 2016), which means that the time perspective in considering consequences of one's behaviour is

shifted towards the future, possibly moderated by working memory capacity (Lin & Epstein, 2014). However, a recent study did not find extension of temporal horizon to be a mediator of EFT (Rung & Madden, 2019). Third, given that humans' time sensitivity is often inadequate and strongly susceptible to manipulation (Ebert & Prelec, 2007), time perception rather than time horizon may play an important role in EFT. For instance, it has been suggested that EFT may lead to enhanced attention to episodic events rather than time (Radu et al., 2011; Rung & Madden, 2019). Thus, it could elicit lower sensitivity for duration until receipt of a larger, later reward, ultimately leading to less temporal discounting. Fourth, EFT manipulations that require the imagination of positive future events may enhance positive mood and thus indirectly strengthen cognitive control and working memory mechanisms (Noël et al., 2017). In this case, the possibly moderating role of positive valence of EFT serves as important evidence (Liu et al., 2013). Fifth, it has been argued that demand characteristics may drive EFT effects (Rung & Madden, 2018). However, recent studies provided evidence against this notion (Rung & Madden, 2019; Stein et al., 2018).

In sum, several non-exclusive mechanisms of EFT have been discussed and it is of course conceivable that several of these might combine to contribute to EFT effects. For instance, EFT, mediated by working memory mechanisms, may lead to more concrete positive future representations, which at the same time shift attention away from duration and enhance positive mood, resulting in less discounting behaviour. Future studies are required to separate these contributions in order to elucidate the psychological mechanisms of EFT effects in temporal discounting.

Another robust effect in the experimental intertemporal choice literature directly refers to time framing, namely, the date/delay effect (LeBoeuf, 2006; Read et al., 2005). In studies examining this effect, participants complete a temporal discounting task in which time until receipt of rewards is specified either as units of delay (e.g., 0 days vs. 23 days) or as dates equivalent in delay from the date of assessment (e.g., 1st of March 2021 (= today) vs. 24th of March 2021). The date condition has repeatedly been found to lead to a lower degree of temporal discounting than the delay condition, with moderate effect size (see Rung & Madden, 2018; Scholten et al., 2019, for reviews), both in studies using between- (e.g., Read et al., 2005) and within-subject designs (e.g., Dshemuchadse et al., 2013; though see Lempert et al., 2016). Interestingly, Read et al. (2005) also found this manipulation to reduce hyperbolic discounting, i.e., decision making became more consistent with 'rational' behaviour specifying delays in terms of specific dates (see DeHart & Odum, 2015, however, who found that hyperbolic/hyperboloid models provided a better description of choices).

Like EFT effects, the date/delay effect has often been replicated but the underlying mechanisms are not entirely clear, and several explanations have been offered (e.g., Rung & Madden, 2018; for additional approaches see LeBoeuf, 2006; Read et al., 2005). First, like in EFT effects, construal-level theory has been drawn upon to suggest that the more concrete date framing might lead to a lower-level construal than delay framing (especially

in larger, later rewards). This could make construal levels of choice options more similar, facilitate option comparison and thereby reduce temporal discounting (H. Kim et al., 2013). Second, while delays and rewards are presented as continuous numeric variables, thus enabling a direct computational strategy (i.e., estimating exchange rates), presenting delays in terms of dates requires additional cognitive operations. For example, dates would either need to be transformed into delays to perform computations or people might generally change their cognitive strategy, for example, by deciding primarily based on reward magnitude, which is considered more important (Read et al., 2005). Third, and relatedly, the date condition may lead to attentional shifts away from durations towards the reward options and their difference (Dshemuchadse et al., 2013; Read et al., 2005), which increases the relative importance of reward values and diminishes the role of delay for choices (lowered time sensitivity). Fourth, estimates of time duration may be reduced with dates in comparison to delays because they are more concrete (Jiang & Dai, 2021; Lempert et al., 2016; Read et al., 2005; Zauberman et al., 2009). Indeed, both Zauberman et al. (2009) and Jiang and Dai (2021) showed that dates led to lower subjective estimates of objective time than delays. Fifth, risk perception, which is partly confounded with temporal discounting (Lopez-Guzman et al., 2018), might also be altered by dates in comparison to delays: Uncertainty of receiving rewards might be higher with delays than with concrete dates (DeHart & Odum, 2015; Jiang & Dai, 2021), possibly as a consequence of differences in time perception (Jiang & Dai, 2021). Sixth, subadditivity (i.e., subdivision of elements into units, which are evaluated individually instead of in their entirety) increases discounting behaviour (Read, 2001) and might also contribute to the effect because only delays (and not dates) can directly be subdivided into units (DeHart & Odum, 2015; however, see LeBoeuf, 2006, Experiment 5; Read et al., 2005, Experiment 1). Seventh, a date could be emotionally valued with stronger positive valence than a delay, as it focuses less on duration and is more concrete, eliciting positive mood and thereby causing less discounting (LeBoeuf, 2006; Lempert et al., 2016).

Again, some of these explanations could be integrated. As argued above, the date condition is more concrete than the delay condition, i.e., may reflect a lower-level construal. This in turn might lead to differential perceptions of durations and risk, general shifts in attention towards the rewards, and/or changes in strategy, causing higher valuation of rewards and/or less time sensitivity. Additionally, a more positive (or rather less negative) valence of duration and better mood might be elicited when dates are specified. As a result, people engage in less temporal discounting. Future studies will need to examine whether such an integrative explanation or only specific parts of it apply.

It should be noted that both the EFT and the date/delay effect may have direct implications on our daily lives. For example, they could be used in persuasion strategies in politics (e.g., conveying a better picture and creating better acceptance of energy-efficient measures by inducing EFT or speaking of specific dates) or offers of investments and saving schemes (e.g., engaging in EFT of a wealthy future, referring to specific dates on which profits are returned) (LeBoeuf, 2006; Read et al., 2005). Importantly, given that temporal discounting

is increased in a number of mental disorders (Amlung et al., 2019), these manipulations could possibly be integrated into psychotherapy settings in order to reduce impulsive choice behaviours. For instance, EFT has been shown to be an effective intervention in reducing both obesity (Sze et al., 2017) and cigarette smoking (Stein et al., 2016, 2018).

In conclusion, EFT effects and the date/delay effect represent two important experimental effects in the intertemporal choice literature that illustrate how aspects of time influence temporal discounting behaviour. These manipulations not only improve our understanding of the cognitive and neural mechanisms underlying intertemporal choice but may also be used to optimize strategies in daily life and therapeutic contexts.

Intertemporal Choice, Temporal Processing and Impulsivity

Intertemporal choice and the role of temporal processes in delay discounting has not only been studied using experimental or framing manipulations. There also exists a large literature on individual differences in intertemporal choice (for review, see Keidel et al., 2021). In this section, we turn to a particular trait correlate of temporal discounting, namely impulsivity. Specifically, we will first turn to time-relevant aspects of impulsivity and will then explore the role that sensitivity to temporal information might play in the often-reported relationship between intertemporal choice and impulsivity.

Impulsivity is a broad and rather poorly specified term that has been defined most generally as "a predisposition toward rapid, unplanned reactions to internal or external stimuli without regard to the negative consequences of these reactions to the impulsive individual or to others" (Moeller et al., 2001, p. 1784). Theoretical criticisms of the very construct of impulsivity aside (Strickland & Johnson, 2021), impulsivity is widely studied in psychology, psychiatry and neuroscience. Impulsive symptoms, traits and behaviours can be assessed with clinical diagnostic instruments, psychometric personality inventories and experimental tasks, respectively (MacKillop et al., 2016; Sharma et al., 2014). However, correlations between these different levels of measurement are typically low (Aichert et al., 2012; Cyders & Coskunpinar, 2011), likely reflecting the heterogeneity of the impulsivity concept (Evenden, 1999).

Theoretical models of impulsivity generally accept the heterogeneity of the construct, but differ with regards to the number and nature of dimensions they postulate. For example, in one of the historically most influential conceptualisations and assessments of impulsivity, Barratt distinguished between attentional impulsiveness (such as difficulties in focussing on a task at hand and suppressing distracting thoughts), motor impulsiveness (such as acting on the spur of the moment or having an inconsistent lifestyle) and non-planning impulsiveness (such as a low tendency to think ahead carefully or engage in challenging mental tasks), resulting in the Barratt Impulsiveness Scale (Patton et al., 1995). Another widely adopted psychometric model and questionnaire is the UPPS Impulsive Behavior Scale by Whiteside and Lynam (2001). The original UPPS contains four dimensions,

namely, negative urgency (the tendency to act rashly during intense negative affect), lack of premeditation (the tendency to act without thinking), lack of perseverance (the tendency to be distracted and give up on boring or difficult tasks) and sensation seeking (the tendency to seek new and exciting experiences). Lynam et al. (2006) later added the positive urgency dimension (the tendency to act rashly during intense positive affect), thereby creating the UPPS-P Impulsive Behavior Scale which has since been used and validated in numerous studies. It should be noted that other models and measurements of impulsivity have also been proposed (Dickman, 1990; Eysenck et al., 1985).

Findings from intertemporal choice tasks are often interpreted within an impulsivity framework in mind (Peters & Büchel, 2011), and temporal discounting is sometimes explicitly regarded as a behavioural measure of impulsivity in both humans and non-human animals (Hamilton et al., 2015; Scholten et al., 2019). Evidence for this interpretation comes inter alia from large-scale studies of healthy individuals, showing that individual differences in self-report, psychometric impulsivity are consistently albeit weakly associated with temporal discounting (e.g., Keidel et al., 2022; MacKillop et al., 2016). Further support comes from studies of patients with clinical disorders that are known to involve impulsive symptoms, such as drug abuse or attention deficit hyperactivity disorder (ADHD). Numerous studies have provided evidence that those disorders are reliably characterised by increased temporal discounting (Amlung et al., 2019).

Of particular relevance to this chapter is the observed association between intertemporal choice and impulsivity, albeit of small magnitude (Keidel et al., 2021), which has been explained theoretically with reference to models of time processing (Paasche et al., 2019; Wittmann & Paulus, 2008). Specifically, both temporal discounting and impulsive actions may be interpreted as the choice of immediate, smaller gratification (with negative consequences) over delayed, larger gratification (Paasche et al., 2019). Indeed, the ability to delay gratification in time has been considered to be a hallmark feature of self-control (Mischel et al., 1989), and impulsive behaviour is often conceived of as the opposite of self-control (Rachlin & Green, 1972).

To illuminate the role of time processing in impulsivity and in the relationship between impulsivity and temporal discounting, theoretical models of how objective time flow is subjectively perceived should first be considered. Several such models exist (for review, see Matthews & Meck, 2016). An influential, early model is that by Treisman (1963), who proposed an ‘internal clock’ mechanism based on the existence of pacemaker and accumulator units. The pacemaker produces a series of pulses travelling along a pathway at a constant rate. Their number is recorded by a counter, or accumulator, with the number of pulses corresponding to temporal duration. An additional component is the attentional gate, with pulses counted only when attention is oriented towards the passing of time. Importantly, time sensitivity is not rigid but instead is subject to external and internal influences (Droit-Volet & Meck, 2007); anecdotally, it is well known to us that time seems to pass very quickly when having fun but seems to extend endlessly in a state of boredom. These state influences on temporal processing can be explained by two mechanisms

(Wittmann & Paulus, 2008). First, the production rate of the pacemaker has been postulated to increase with heightened arousal, leading to a greater number of pulses produced and thus the experience of a longer duration of time. Second, increased attention to time (as may happen in boredom, but which is unlikely to happen when one is engaged in a fun, attention consuming task) is similarly postulated to lead to a greater number of produced pulses and, thereby, a longer perceived duration.

Of relevance to the present discussion, it has been proposed that impulsive behaviour may result from altered time processing, specifically from an overestimation of the flow of time (Wittmann & Paulus, 2008). Thus, for a highly impulsive individual, a given time interval would subjectively feel longer than for a less impulsive person. For that reason alone, highly impulsive individuals may be expected to display greater temporal discounting, as a given delay interval would represent a higher cost against which the reward must be traded off than for those with less contracted time perception.

Evidence in support of this hypothesis comes from a number of sources. First, otherwise healthy individuals with higher levels of impulsivity have been observed to overestimate the duration of time intervals compared to less impulsive individuals (Lawrence & Stanford, 1998). Second, sleep deprivation, which has been shown to transiently induce impulsive behaviours and disinhibition (Anderson & Platten, 2011; Kumari & Ettinger, 2020; Meldrum et al., 2015), has been found to cause both increased temporal discounting and alterations in timing task performance suggestive of faster subjective time experience (Reynolds & Schiffbauer, 2004). Finally, patients with borderline personality disorder, drug dependence or frontal lobe damage show both impulsive behaviours and faster subjective time processing, and often associations between the two (Berlin et al., 2004; Berlin & Rolls, 2004; Wittmann et al., 2007).

In conclusion, there is evidence of interrelationships between heightened impulsivity, faster subjective experience of time and increased temporal discounting. Put simply, these associations may be interpreted to suggest that impulsive individuals show enhanced temporal discounting due to a faster subjective sense of time flow. However, it should be noted that the relationship between time processing and impulsivity is likely to be complex and has not yet been fully understood. Specifically, the reasons for faster subjective time experience in people with high levels of impulsivity remain unclear, with both a faster pacemaker and enhanced attention to time as well as interactions amongst them postulated as explanations, whereas impaired inner clock mechanisms per se are considered less likely (Wittmann & Paulus, 2008). It should also be noted that the overlap between psychometric, self-report impulsivity and temporal discounting is of small magnitude (Keidel et al., 2021), suggesting that substantial variance in either measure remains unexplained by a postulated, shared alteration in temporal processing sensitivity.

Conclusions and Outlook

In this chapter, we focussed on intertemporal choice as a manifestation of temporal cognition. In particular, we introduced key methodological approaches and concepts in the study of intertemporal choice and provided an overview of both experimental and individual differences-based findings that relate intertemporal choice to aspects of temporal information processing.

With regard to experimental effects, we discussed framing effects in which temporal information processing is experimentally manipulated, namely, the episodic future thinking (EFT) and date/delay manipulations. The effects that result from those manipulation underscore the importance of temporal information processing in intertemporal choice. Specifically, both detailed thinking about specific, often positive future events and a change from the common expression of a reward delay as a time period to a specific date in the future cause reduced temporal discounting. These effects are well replicated in the experimental literature (Rung & Madden, 2018) and thus present an ideal starting point for further research into processes of temporal cognition that may underlie temporal discounting. Specifically, the specific psychological mechanisms underlying these effects remain unclear. Whilst a number of hypotheses have been put forward (see above), it remains unclear how exactly temporal discounting is affected by EFT and the date/delay manipulation – both at the psychological and the neural level.

Following our discussion of group-level effects of temporal manipulations on intertemporal choice, we summarised evidence that individual differences in temporal discounting, impulsivity and their association may to some extent be explained by inter-individual variation in sensitivity to time. Specifically, we followed the argument that both temporal discounting and impulsive behaviour may be viewed as choosing immediate, smaller gratification over delayed, larger gratification, and outlined the hypothesis that impulsive actions may result from an overestimation of durations. Within this framework, a highly impulsive person would experience a given time interval as longer than a less impulsive individual, which could underlie the observed, greater temporal discounting in highly impulsive individuals.

A number of caveats remain in this area of research. First and foremost, impulsivity is increasingly recognised as a poorly defined, heterogeneous construct (Strickland & Johnson, 2021), necessitating careful consideration of which aspect of impulsivity is being investigated. Second, associations between impulsivity and intertemporal choice tend to be of only small magnitude, requiring samples with appropriate statistical power (Keidel et al., 2021). Third, the cognitive and neural mechanisms that underlie these associations remain to be characterised in more detail. More research is needed in this area.

To conclude, intertemporal choice is a decision-making task that yields the widely reproducible, cross-species phenomenon of temporal discounting. The task can be placed firmly in the temporal cognition literature and both group-level experimental effects and individual differences studies point to a substantial role of temporal perceptual and

cognitive processes in intertemporal choice. More refined characterisation of the cognitive and neural mechanisms that underlie these findings is required in the future.

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