The Role of Cognitive and Motivational Processes in Food-Cue Reactivity:

Evidence from Behavioural and Electrophysiological Investigations

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Abstract

Overeating triggered by food cues is assumed to contribute to the rising numbers of overweight and obesity in obesogenic environments. Thus, food-cue reactivity has become a growing research topic. This thesis aims to contribute to a deeper understanding of cognitive and motivational processes involved in food-cue reactivity. In four studies, attentional, motivational, and learning processes in the context of food-cue processing and food choices were investigated. In *Study I*, food-elicited modulations of the attentional blink have revealed evidence for prioritised attentional processing of food cues. In *Study II*, event-related potentials (ERPs) of emotion-induced blindness elicited by food cues have indicated early attentional capture by task-irrelevant food stimuli. Further ERP evidence in *Study III* has shown that sustained attention towards food cues is affected by the food's calorie content and by the situational context in which food choices are made. Moreover, transient frontal cortical asymmetry as measured by frontal alpha asymmetry has suggested an influence of the food's calorie content on neural correlates of approach/avoidance motivation. In *Study IV,* the impact of newly learned food cues on food-seeking behaviour in terms of Pavlovian-to-instrumental transfer and the robustness of this effect against video-based manipulations of the food outcome's value have been shown. In sum, the findings support the assumption that cognitive and motivational processes play an important role in food-cue reactivity. They contribute to a comprehensive understanding of food-cue reactivity, which is essential for the development of treatments of overeating and eating disorders.

Zusammenfassung

Durch externe Essensreize ausgelöstes Überessen trägt vermutlich mit zu den steigenden Zahlen von Übergewicht und Adipositas bei. Daher rückte die Reaktivität auf Essensreize zunehmend in den Fokus von Forschungsarbeiten. Diese Arbeit soll zu einem tieferen Verständnis der kognitiven und motivationalen Prozesse, die an der Reaktivität auf Essensreize beteiligt sind, beitragen. In vier Studien wurden Aufmerksamkeits-, Motivations- und Lernprozesse im Zusammenhang mit der Verarbeitung von Essensreizen und der Essensauswahl untersucht. In *Studie I* lieferten durch Essensreize ausgelöste Modulationen des Aufmerksamkeitsblinzelns Evidenz für eine priorisierte Verarbeitung von Essensreizen auf Ebene der Aufmerksamkeit. In *Studie II* zeigten ereigniskorrelierte Potenziale (EKPs) der durch Essensreize ausgelösten emotionsinduzierten Blindheit eine frühe Anziehung der Aufmerksamkeit durch aufgabenirrelevante Essenreize. EKPs in *Studie III* zeigten außerdem, dass der Kaloriengehalt des Lebensmittels und der situative Kontext, in dem die Essensauswahl getroffen wird, die anhaltende Aufmerksamkeit gegenüber Essensreizen beeinflussen. Darüber hinaus deutete vorübergehende frontale kortikale Asymmetrie, gemessen durch frontale Alpha-Asymmetrie, auf einen Einfluss des Kaloriengehalts des Lebensmittels auf neuronale Korrelate der Annäherungs-/Vermeidungsmotivation hin. In *Studie IV* zeigte der *Pavlovian-to-instrumental* Transfereffekt die Auswirkungen neu erlernter Hinweisreize auf die Essensauswahl und erwies sich als robust gegenüber videobasierten Manipulationen. Insgesamt stützen die Ergebnisse die Annahme, dass kognitive und motivationale Prozesse eine wichtige Rolle bei der Reaktivität auf Essensreize spielen. Die Studienergebnisse leisten einen wertvollen Beitrag zu einem umfassenden Verständnis der Reaktivität auf Essensreize, welches für die Entwicklung von Behandlungsmethoden gegen Überessen und Essstörungen unerlässlich ist.

List of abbreviations

AAT	approach-avoidance task
AB	attentional blink
ABM	attentional bias modification (training)
BMI	body mass index
dlPFC	dorsolateral prefrontal cortex
EEG	electroencephalography
EIB	emotion-induced blindness
EPN	early posterior negativity
ERP	event-related potential
FAA	frontal alpha asymmetry
IST	Incentive-Sensitization Theory of Addiction
EIT	Elaborated Intrusion Theory of Desire
HC	high calorie
LC	low calorie
LPP	late positive potential
O	outcome (in the context of outcome-response theories)
PIT	Pavlovian-to-instrumental transfer
R	response (in the context of outcome-response theories)
RSVP	rapid serial visual presentation
S	stimulus (in the context of outcome-response theories)
SOA	stimulus onset asynchrony
T1	first target stimulus (in the RSVP paradigm)
T2	second target stimulus (in the RSVP paradigm)
tDCS	transcranial direct current stimulation
VTA	ventral tegmental area

One of the very nicest things about life is the way
we must regularly stop whatever it is we are doing
and devote our attention to eating.

Luciano Pavarotti in *My own story*, 1981
(written with William Wright)

1 Introduction

According to the World Health Organization, the worldwide prevalence of overweight (BMI ≥ 25 kg/m^2) and obesity (BMI ≥ 30 kg/m^2) has increased dramatically during the last decades. In 2016, 39% of the world's adult population were overweight and 13% were obese (World Health Organization, 2021a), and these numbers are continuously rising. This development poses a considerable problem to national health systems as increased BMI is known to have severe health consequences. For instance, overweight and obesity are major risk factors for cardiovascular diseases, the leading causes of death worldwide. Today already, overweight is linked to more deaths than underweight (World Health Organization, 2021a, 2021b).

The main cause of the global obesity epidemic lies in the energy imbalance between calorie intake and expenditure. While the overall intake of energy-dense foods has increased with the increase of prosperity in many parts of the world, physical activity and, thus, calorie expenditure has declined (World Health Organization, 2021a). These circumstances can be attributed to the easy access to convenience and takeaway foods, which are often high in fat and sugar, on the one hand, and the lack of physical activity in everyday life on the other hand. Besides personal lifestyle, environmental factors are crucial determinants of individual eating behaviour and the level of physical activity. Especially urban environments facilitate the intake of energy-dense foods as they provide access to fast-food shops, convenience stores, and takeaways. At the same time, public transportation, short distances, and sedentary work promote physical inactivity (Giskes et al., 2011). In short, living in modern urban areas means living in so-called *obesogenic environments* (Swinburn et al., 1999).

Obesogenic environments are characterised by "the sum of influences that the surroundings, opportunities, or conditions of life have on promoting obesity in individuals or populations" (Swinburn et al., 1999, p. 564). For instance, diverse temptations are omnipresent in everyday life: advertisements for snacks and drinks on TV, the smell of French fries in front of a takeaway, bakeries offering doughnuts and cake at every corner, and billboards displaying fast-food menus. In obesogenic environments, individuals are surrounded by an overwhelming number of cues signalling the availability of tasty, mostly energy-dense, and unhealthy foods.

2 Theoretical background

In parallel with the increase of overweight and obesity, the role of external cues in eating behaviour has attracted growing research interest during the last decades. This research is mainly motivated by the overarching goal to develop prevention and intervention programs against overeating. However, effective programs should be based on a profound understanding of the cognitive and motivational mechanisms involved in food-cue processing. In this respect, basic psychological research can make valuable contributions by investigating the mechanisms of attention, motivation, learning, and memory in the context of food cues.

2.1 Food cues and food-cue reactivity

The smell or the sight of food are examples of proximal food cues, which are directly linked to food intake. Furthermore, food intake is often accompanied by interoceptive cues like emotional states or food-related memories and distal cues such as the spatial and temporal context of food intake (Jansen et al., 2011). Through classical conditioning, cues that are repeatedly (and exclusively) paired with food intake can become conditioned stimuli when they reliably predict the unconditioned stimulus, that is, food intake. Consequently, food cues can trigger conditioned responses in terms of cephalic phase responses which are preparatory physiological processes of food intake optimizing the digestion and the absorption of nutrients (Mattes, 1997).

The cued (over)eating model refers to these physiological reactions elicited by food cues as *food-cue reactivity* (Jansen, 1998; Jansen et al., 2011). The model postulates that food-cue reactivity is perceived as appetite or craving on the subjective level, thereby fosters cue-induced food intake, and increases the likelihood of overeating in the absence of hunger (Jansen et al., 2011). In support of this model, a meta-analysis of 45 studies revealed a medium effect of food-cue reactivity (peripheral physiological activity or neural activity to food cues) and self-reported craving on eating behaviour and weight gain (Boswell & Kober, 2015)[1].

In general, any external or internal cue that is consistently present during or immediately before food intake can become a food cue. For instance, the people we usually share our meals with, the table we eat at, the radio show we listen to during lunch, or

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[1] If not otherwise stated, here and in the following, reported evidence stems from healthy, normal-weight, adult samples. Whenever evidence derived from eating disorder patients, overweight/obese samples, or children/adolescents is reported, this will be explicitly declared.

the “ding” sound of the microwave oven can be reliable predictors of eating and thus elicit food-cue reactivity. Obviously, these food cues result from individual and unique learning processes. The identification of such ‘personal’ food cues can be useful in the treatment of overeating (e.g., in the context of binge eating disorder). In cue-exposure therapy, repeated exposures to these specific food cues are combined with response prevention, that is, the prevention of eating (Jansen, 1998). Consequently, the cues lose their predictive value via extinction, which effectively contributes to the reduction of craving and cued overeating (Jansen et al., 2011; Schyns et al., 2020).

While it is essential to consider patients’ individual food cues for extinction treatment, for research on food-cue reactivity, universal food cues that are generally associated with food intake are most useful. We all share the learning experience that eating is preceded by the visual perception of the food. Thus, the sight of food is a universal predictor of food intake (although, of course, seeing food does not necessarily lead to eating). Therefore, besides odours, pictures of food can be considered one of the most basic forms of food cues (see Blechert, Meule, et al., 2014). In fact, food-cue reactivity elicited by visual food cues seems to be comparable to responses to real food. Both the exposure to visual food cues (i.e., pictures and videos) and to real foods have been shown to have medium-sized effects on subsequent eating (Boswell & Kober, 2015). One key benefit of visual food cues over real foods or odours is their ease of use and the possibility of a high degree of standardisation in controlled experimental settings. Overall, ample evidence speaks in favour of the validity of the “picture viewing approach” (Blechert, Meule, et al., 2014, p. 1), that is, the presentation of food images in psychological research on eating behaviour. For instance, Blechert, Meule, et al. (2014) pointed out the effects of food deprivation and hunger on the response to food images, the differentiation of individuals with disordered eating and healthy controls based on food-image responses, and the training effects of food-picture viewing on eating behaviour (see, e.g., Frank et al., 2010; Pursey et al., 2014 for related evidence from neuroimaging studies). Taken together, food images are the stimuli of choice in experimental psychological research on eating behaviour in general and food-cue reactivity in particular. In the course of this thesis, unless otherwise stated (for instance, in Chapter 5), the term *food cue* will be used as a synonym for food image. Accordingly, *food-cue reactivity* will refer to reactivity in response to visual food cues (that is, food images). It should also be noted that going beyond the definition of food-cue reactivity in the cued (over)eating model (Jansen, 1998; Jansen et al., 2011), which focuses on physiological, cephalic phase responses elicited by food cues, the term will be used in a broader sense in the course of this thesis. Thus, food-cue reactivity as used in the present thesis will include physiological responses, subjective food craving, as well as cognitive and motivational processes (assessed via behavioural measures, neuroimaging, and electrophysiological methods) elicited by food cues (see also van den Akker et al., 2014).

2.1.1 Characteristics of food images

When conducting behavioural, neuroimaging, and electrophysiological studies on food-cue reactivity, characteristics of the presented foods and physical image characteristics require careful consideration (Blechert, Meule, et al., 2014). First, foods differ in terms of nutrients contained, degree of processing, and calorie content. Regarding nutrients, especially macronutrients (i.e., proteins, carbohydrates, and fat) are more or less visible food characteristics and important determinants of food choices for many dieters (see, e.g., Freire, 2020). The degree of processing, which is closely linked to the visual appearance of food regarding shape and colour, strongly affects subjective palatability (see, e.g., Adams & White, 2015). Calorie content refers to the amount of energy contained in a specific food item. In weight-loss programs, the daily calorie intake is one of the most popular benchmarks (see Tsai & Wadden, 2005). It is widely understood that excessive calorie intake leads to weight gain and that weight loss can be achieved by reducing calorie intake. In European countries, the concept of calories is also known from the list of nutrients and Guideline Daily Amount labels on ready-meal packages (see Rayner et al., 2004). Consumers' understanding of such information seems to be generally high but is related to age, social grade, interest in healthy eating, and nutrition knowledge (K. G. Grunert et al., 2010). Several studies suggest that (estimated) calorie content and perceived healthiness of foods are closely linked. Low-caloric (LC) foods are perceived as healthy and as contributing to weight loss whereas high-caloric (HC) foods are considered unhealthy and contributing to weight gain (Carels et al., 2006; Carels et al., 2007; Larkin & Martin, 2016). At the same time, HC foods have naturally rewarding properties because of their energy density and oftentimes a high hedonic value in terms of pleasant salty or sweet taste. Their rather low health value in combination with their high hedonic value leads to an ambivalent nature of HC foods (Roefs et al., 2018). Depending on the situational context or the task in an experimental setting, both dimensions, health value and hedonic value, can influence food choices as well as neural food-cue reactivity. Therefore, when using the categorisation of food stimuli into LC and HC foods for the purpose of research, the experimental task should be unambiguous in terms of which type of value (i.e., health vs. hedonic value) is being studied in relation to measures of behavioural or neural responses (Roefs et al., 2018).

Second, like any other photograph, every food image has specific physical image parameters such as contrast, complexity, brightness, and colours. As in any other research that uses visual stimuli, these parameters should be considered as they are known to affect visual perception and related neural activity (e.g., Del Gatto et al., 2021; Knebel et al., 2008). Thus, especially when addressing research questions involving the contrast of food versus non-food images or HC versus LC food images, the stimuli in these categories should be carefully matched for physical image characteristics. Only then can findings be attributed to the concepts of interest rather than to purely perceptual differences.

Both dimensions of food images, the actual properties of the displayed food and the physical image parameters, are incorporated in food image databases that have been developed specifically for the use in investigations of (neural) food-cue reactivity. For the studies subsumed in the present thesis, stimuli from the databases *food-pics* (Blechert et al., 2019; Blechert, Meule, et al., 2014) and *FRIDa* (FoodCast research image database; Foroni et al., 2013) were used. Both databases provide photos of raw as well as processed foods with detailed information about image parameters, calories, nutrients, and normative ratings of valence, arousal, palatability, etc. By relying on validated picture databases, the characteristics of the food cues in terms of food properties and image parameters could be taken into account in the studies presented in this thesis.

2.2 Cognition and motivation in food-cue reactivity

Besides physiological responses to food cues, cognitive and motivational processes are important aspects of food-cue reactivity. Cognitive processes involved in food-cue reactivity range from the perception of food and the allocation of attentional resources to complex problem solving and decision making in the context of food choices. Motivational aspects of food-cue reactivity encompass the mental states of hunger and desire as the main driving forces of food intake as well as motivational tendencies to approach or avoid specific foods.

2.2.1 The Elaborated Intrusion Theory of Desire

A cognitive approach to the emergence and perpetuation of (substance or food) craving is provided by the *Elaborated Intrusion Theory of Desire* (EIT; Kavanagh et al., 2005).

Within the EIT, the term *desire* is used synonymously with craving and is considered an "affectively charged cognitive event in which an object or activity that is associated with pleasure or relief of discomfort is in the focal attention" (Kavanagh et al., 2005, p. 447). Thus, going beyond the cued (over)eating model (Jansen, 1998; Jansen et al., 2011), in which craving is conceptualised as the subjective experience of physiological food-cue reactivity, the EIT is based on the assumption of a conscious, cognitive dimension in the experience of craving. Postulated core components of desire are intrusive thoughts and cognitive elaboration in the form of imagery. Intrusive thoughts are spontaneously elicited associations with internal or external cues that possibly interrupt ongoing tasks (e.g., concentrated reading is interrupted by the smell of freshly baked cake and the sudden wish to eat a piece of it). If intrusive thoughts are accompanied by strong affective reactions or a sense of deficit, cognitive elaboration involving allocation of attentional resources, memory retrieval of related information, and vivid sensory imagery of the desired target is likely to occur. For instance, one could ask themselves where the smell of cake comes from, try to identify the type of cake, and imagine enjoying a piece with a cup of coffee. These elaborations foster the subjective experience of desire and consume working-memory capacities. Thus, they interfere with ongoing cognitive tasks (e.g., distract attention from reading). Importantly, cognitive elaboration of the desired target is also supposed to enhance the saliency of desire-relevant cues in the environment, thereby further fostering associative processes and intrusive thoughts. Although the imagery aspect of elaboration can be initially pleasant, it also contributes to the extension of craving episodes and enhances their intensity (J. May et al., 2012). Eventually, imagery can lead to negative affect if the desire cannot be fulfilled. It is thus likely to motivate behavioural reactions aiming to acquire the desired target in order to reduce negative affect (J. May et al., 2015).

Evidence for the EIT in the context of food craving[2] came from studies that have demonstrated that sensory imagery is related to the strength of desire (e.g., Harvey et al., 2005) and impairs performance in competing visuospatial tasks (Tiggemann et al., 2010). Other studies have investigated strategies to reduce food craving by targeting intrusive thoughts and cognitive elaboration. For instance, olfactory and visual imagery tasks successfully reduced self-reported food craving by competing for working-memory resources with the mental imagery of desired foods (Kemps & Tiggemann,

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[2] It should be noted that the EIT is also applicable to substance craving for alcohol, nicotine, and other drugs (for an overview of related evidence, see J. May et al., 2015).

2007). Cognitive defusion (i.e., taking a distanced perspective on one's own thoughts) reduced the intrusiveness of thoughts, vividness of imagery, and food craving intensity in general, whereas guided imagery of a forest walk had this effect for chocolate-related food craving only (Schumacher et al., 2017). A single session of functional imagery training even led to a reduction in snack consumption and weight loss by fostering positive goal imagery (Andrade et al., 2016). Taken together, there is substantial empirical evidence that supports the assumption of a cognitive component in the emergence and maintenance of food craving.

2.2.2 The Incentive-Sensitization Theory of Addiction

Pleasant tastes and the fulfilment of basic needs make eating a rewarding experience and food a primary reinforcer. In the context of food (and drug) reward, the distinction between 'liking' and 'wanting'[3] has evolved within the theoretical framework of the *Incentive-Sensitization Theory of addiction* (IST; Robinson & Berridge, 1993, 2008). 'Liking' refers to the "hedonic reaction to the pleasure of a reward" (Berridge, 2009, p. 537), that is, its sensory pleasant experience. In contrast, 'wanting' is elicited by the *incentive salience* attributed to rewards or reward cues (e.g., food cues). The attribution of incentive salience implies enhanced motivational value and enhanced attentional salience of the target stimulus. Thereby, 'wanting' can manifest as the cue-triggered desire for an associated reward and can elicit the behavioural urge to acquire the reward but is not necessarily conscious (Berridge, 2009). In fact, conscious or cognitive wanting and 'wanting' often go together but can also be opposed to each other (Berridge & Robinson, 2016). For instance, a piece of cream cake can be unwanted on a cognitive level when thinking about dieting goals, but can be 'wanted' at the same time. Similarly, 'liking' and 'wanting' are linked in normal reward processing, but can also occur separately, e.g., when drug addicts experience craving ('wanting') without any pleasantness ('liking'; Berridge, 2009).

Most importantly, 'liking' and 'wanting' can be traced back to differing underlying neural systems. 'Wanting' is generated in a mesocorticolimbic circuit involving ventral tegmental area (VTA), nucleus accumbens core and shell, ventral pallidum, amygdala, lateral hypothalamus, dorsal striatum, insula, and orbito-frontal cortex (Morales & Berridge, 2020). In contrast, 'liking' generators are anatomically tiny, distributed, hedonic hotspots embedded in subregions of subcortical and cortical structures of the

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[3] As proposed by the authors of the theory, quotation marks are used to distinguish 'liking' and 'wanting' as conceptualised in the IST from the common understanding of liking and wanting (without quotation marks; see Berridge, 2009).

‘wanting’ network, for example, the rostrodorsal quadrant of the medial shell of the nucleus accumbens and the caudolateral half of the ventral pallidum (Berridge & Robinson, 2016; Morales & Berridge, 2020). ‘Liking’ and ‘wanting’ also differ in terms of neurochemistry: When stimulated via opioid or endocannabinoid neurotransmitters, hedonic hotspots reinforce ‘liking’ reactions (Berridge & Robinson, 2016). However, dopaminergic stimulation of hedonic hotspots fails to amplify ‘liking’ (e.g., Wyvell & Berridge, 2000; see Morales & Berridge, 2020). In contrast, ‘wanting’ is closely related to the dopaminergic system. In fact, incentive salience seems to be generated by dopaminergic projections from the midbrain to regions of the limbic system (see Morales & Berridge, 2020).

IST (Robinson & Berridge, 1993, 2008) postulates that the dopaminergic system can be permanently sensitised by drugs, which causes hyper-reactivity of the ‘wanting’ system to drug cues or contexts. Importantly, this mesolimbic dopaminergic sensitisation may also occur without drugs in the context of behavioural addictions (e.g., gambling, shopping, or eating addictions; see Berridge & Robinson, 2016; Temple, 2016). Accordingly, the food addiction model proposes parallels between compulsive overeating and drug addiction (see, e.g., Davis & Carter, 2009; García-García et al., 2020). Compulsive overeating mainly (but not only) occurs in the context of binge eating disorder and bulimia nervosa. While binge eating disorder involves compulsive overeating without compensating behaviour, episodes of overeating are followed by purging or other compensating strategies in bulimia nervosa. In fact, high scores on food addiction scales are most commonly reported by binge eating disorder and bulimia nervosa patients (Davis & Carter, 2009; Gearhardt et al., 2014). Compulsive overeating and drug abuse share behavioural patterns like loss of control over consumption, consumption despite awareness about negative health consequences, and the experience of craving (Davis & Carter, 2009; García-García et al., 2020). Moreover, the reinforcing effects of addictive drugs and palatable food seem to be mediated by the same mesocorticolimbic dopaminergic pathways (Gearhardt et al., 2011; G.-J. Wang, Volkow, Thanos, & Fowler, 2004). However, it has to be noted that related evidence from neuroimaging studies is inconsistent (García-García et al., 2020). In terms of IST, compulsive overeating could reflect excessive ‘wanting’ that may originate from sensitised hyperreactivity of the mesocorticolimbic system and is usually triggered by external food cues. In favour of this view, brain activation patterns of obese individuals in response to food cues seem to be compatible with the assumptions of the IST (Devoto et al., 2018).

2.2.3 The interplay of cognition and motivation in food-cue reactivity

The theories described above each focus on either cognitive or motivational aspects of food-cue reactivity. While the EIT (Kavanagh et al., 2005) highlights the role of cognitive processes (intrusive thoughts and cognitive elaboration), the IST (Robinson & Berridge, 1993, 2008) takes a motivational approach by emphasizing 'liking' and 'wanting' as (not necessarily conscious) mechanisms of food reward. This might create the impression that cognitive and motivational processes in food-cue reactivity act independently from each other. However, the opposite is the case. Food-cue reactivity is best characterised as a dynamic interplay between motivation, cognition, and action (see Figure 1).

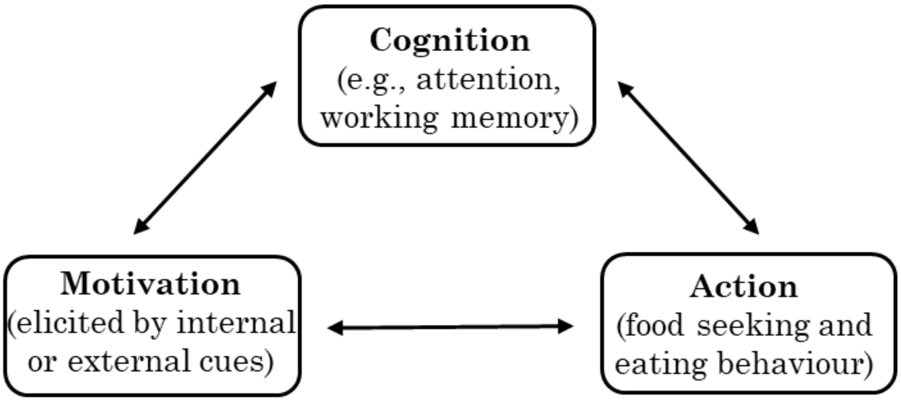

Figure 1. Interplay of motivation, cognition, and action in the context of food-cue reactivity (own representation based on Pineda & Leland, 2011, fig. 43.1, p. 646).

Motivation can be defined as the driving force of goal-directed behaviour, responsible for "its initiation, direction, intensity, and persistence in the face of obstacles" (Pineda & Leland, 2011, p. 646). The motivation for food seeking and eating can be triggered by internal cues of hunger as well as by external food cues. Internal cues are processed in relatively direct subcortical circuits that seem to be conserved across species (Forlano & Cone, 2007) and are responsible for maintaining the energy homeostasis of the organism (DiLeone et al., 2012). External food cues can also exert their influence subcortically via mesolimbic projections from the VTA to limbic structures (e.g., DiLeone et al., 2012; see chapter 2.2.2). Thus, the motivation to eat can initiate appetitive behaviour without cortical input or conscious cognition. However, cortical regions are connected to subcortical circuits and enable the integration of more complex dimensions like food preferences, the momentary inhibition of hunger, and dieting goals into motivation for food intake (Pineda & Leland, 2011). For instance, the insula and orbitofrontal cortex play an important role in the processing of food qualities (taste and texture), the conscious sensation of hunger, and the context-specific affective and motivational value of food (e.g., G.-J. Wang, Volkow, Telang, et al., 2004).

In order to transform motivation into flexible goal-directed behaviour while considering internal and external conditions, additional cognitive processes are needed as mediators between motivation and action (Pineda & Leland, 2011). One example of such a mediating cognitive process is selective attention. The conceptualisation of ‘wanting’ (see Berridge & Robinson, 2016) assumes that the attribution of incentive salience to ‘wanted’ food stimuli leads to a prioritisation of these stimuli in the allocation of attentional resources (e.g., Hickey & Peelen, 2015). This attentional bias for food stimuli may ensure the prioritised processing of goal-related information at the expense of competing information in order to promote food seeking and eating (Pineda & Leland, 2011). On the neural level, the attentional bias towards motivationally salient stimuli is assumed to lie in the disinhibition of cholinergic activity in the basal forebrain by dopaminergic projections from the VTA (e.g., St Peters et al., 2011). However, selective attention for food cues not only promotes the transformation of the motivation to eat into action, it can also cause the motivation in the first place. For instance, exposure to food cues reliably elicits food craving in binge eating disorder patients and healthy controls (e.g., Meule et al., 2018). Furthermore, thoughts about food and processing food-related information in working memory are also able to guide attention towards food cues in the environment (see Higgs, 2016), which again could increase consumption motivation. Thus, selective attention, working memory processes, and motivation mutually influence each other (Franken, 2003) and interactively contribute to the behavioural output of food seeking and eating.

2.3 Individual differences in food-cue reactivity

There is high inter- as well as intra-individual variability in eating behaviour concerning what, when, and how much people eat. Concurrently, there is also high variability in food-cue reactivity. This has been investigated intensively, particularly in the context of investigations into the causes of weight gain and eating disorders (see, e.g., Chami et al., 2019). In the following, a short overview of states and traits related to food-cue reactivity is given. It should be noted that this selective overview is by no means exhaustive but focuses on individual differences that were of particular interest in previous research and were included in the original studies introduced in the present thesis.

At the state level, appetitive motivational states in terms of hunger and food craving affect food-cue reactivity. Hunger can be defined as a “conscious sensation reflecting a mental urge to eat [that] can be traced to changes in physical sensations in parts of the body” (Blundell et al., 2010, p. 252). In contrast to the rather unspecific feeling of hunger, food craving refers to the intense desire to eat a particular food (Weingarten & Elston, 1990). Due to the subjective nature of appetitive states, self-report scales are the method of choice to assess the level of hunger and situational food craving. As revealed by meta-analyses, both hunger and food craving are associated with an attentional bias towards food cues (Hardman et al., 2020). This suggests an important role of appetitive motivational states not only for physiological but also for cognitive aspects of food-cue reactivity.

Besides differences in situational food craving, individuals differ regarding their predisposition to experience periods of food craving. Trait food craving was positively correlated with BMI, eating disorder symptomatology, and dieting (Meule et al., 2014). Furthermore, implicit approach tendencies towards food were stronger in high than low food cravers (Brockmeyer et al., 2015a).

At the level of traits, the concepts of restrained, external, and emotional eating predominate the literature on food-cue reactivity. Due to the fact that the Dutch Eating Behaviour Questionnaire (DEBQ; van Strien et al., 1986; German version by S. C. Grunert, 1989) allows for a joint measurement of these trait-like eating styles, they are often examined in combination. The concept of restrained eating (see Herman & Mack, 1975; Polivy et al., 2020) refers to chronic dieting. Restrained (in contrast to unrestrained) eaters are constantly restricting their food intake in order to lose weight or maintain their current weight (Herman & Polivy, 1980). While some definitions of restrained eating are based on the assumption of successful dieting and weight management (e.g., restrained eating as measured by the DEBQ; van Strien et al., 1986), others include the assumption that strict dieting is intermittently disrupted by episodes of overeating that limit the dieting success or even lead to overweight (e.g., restrained eating as measured by the Restraint Scale; Herman & Polivy, 1980; see Polivy et al., 2020). In longitudinal studies, restrained eating was not associated with either prospective weight gain or weight loss (see M. R. Lowe et al., 2013 for a review). With respect to food-cue reactivity in restrained and unrestrained eaters, previous research has been inconclusive. Some findings support the assumption that restrained as compared to unrestrained eaters show stronger food-cue reactivity as evident in their eating behaviour as well as in attention and memory responses to food cues (Polivy & Herman, 2017). In other studies no differences in food-cue reactivity of restrained and unrestrained eaters were observed (see Werthmann et al., 2015). Most likely, divergent definitions and measures of the concept of restrained eating mainly contributed to these inconsistencies (P. Watson & Le Pelley, 2021).

External eating is characterised as eating in response to external food cues irrespective of internal signals of hunger or satiety. According to the *Externality theory* (Schachter & Rodin, 1974), this eating style is a risk factor for overeating and obesity (Rodin & Slochower, 1976). Empirically, there seems to be no direct association of external eating with overeating and weight gain (Snoek et al., 2013; van Strien et al., 2009). However, food craving was observed to mediate the relationship between external eating and BMI (Burton et al., 2007). Furthermore, external eating moderated the association between overeating and changes in BMI in a representative Dutch sample (van Strien et al., 2012). As external eating refers to eating triggered by food cues in the environment, food-cue reactivity should be enhanced in external eaters. This assumption is supported by findings of a positive association between an attentional bias towards food cues and external eating (Brignell et al., 2009; Hou et al., 2011) and enhanced electrophysiological responses to food cues in (female) high external eaters (Nijs et al., 2009; T. D. Watson & Garvey, 2013; Wolz et al., 2015).

The concept of emotional eating goes back to the *Psychosomatic theory* (Kaplan & Kaplan, 1957). It refers to habitual eating in order to cope with negative emotions, for instance, eating in response to states of anxiety, depression, and frustration (see Macht & Simons, 2011). Similarly to external eating, emotional eating was found to moderate the relation between overeating and changes in BMI (van Strien et al., 2012). Furthermore, it mediated the relationship between depression and BMI in young adults (Lazarevich et al., 2016). However, there is also accumulating evidence for a lack of enhanced food intake in negative moods in emotional eaters (see Bongers & Jansen, 2016). In terms of food-cue reactivity, some studies point to enhanced neural processing of food cues (Blechert, Goltsche, et al., 2014) and stronger visual attention for food cues (Hummel et al., 2018) in high as compared to low emotional eaters. However, there are also contradicting results, such as emotional eating being unrelated to food-cue processing (T. D. Watson & Garvey, 2013) and visual attention for food cues (Werthmann et al., 2014).

On a final note, it should be mentioned that restrained, external, and emotional eating are probably not independent from each other (see Nagl et al., 2016). For instance, it is reasonable to assume that strict periods of restrained eating foster outbursts of external and emotional eating (Herman & Mack, 1975) or that predispositions for emotional and external eating are inhibited by restrictive dieting.

2.4 Aims and outline of the present thesis

The present thesis aims to introduce an overview of existing work on cognitive and motivational processes in food-cue reactivity and to provide new insights to this field. Therefore, a series of behavioural and electrophysiological studies dealing with different aspects of food-cue reactivity has been conducted (see Table 1).

In *Study I* (Kirsten et al., 2019) and *Study II* (Kirsten et al., 2021) the attentional bias towards food cues was investigated in rapid serial visual presentation (RSVP) tasks by testing the effects of food cues on the attention blink (Raymond et al., 1992) and emotion-induced blindness (EIB; Most et al., 2005). In *Study I,* the effects of food cues on target identification performance in the RSVP paradigm were investigated. In *Study II,* event-related potentials (ERPs) were examined to provide insight into the neural mechanisms of EIB elicited by food cues. *Study III* (Kirsten et al., 2022) focused on motivational processes in response to food cues and their neural correlates. Here, ERPs were combined with time-frequency analyses of frontal cortical asymmetry. Thereby, the motivational tendencies of approach and avoidance in response to HC and LC food cues in different situational contexts were investigated. Finally, in *Study IV* (Kirsten et al., 2021), cognitive, motivational, and behavioural aspects of food-cue reactivity were brought together. This was realised in the investigation of the influence of videos with a pro- and anti-sugar message on snack choices in a Pavlovian-to-instrumental transfer (PIT) task.

In the following chapters, novel contributions of these studies to the existing literature in the respective areas of research will be presented and discussed. This thesis will focus on the main outcomes of the studies and their integration into existing research. Therefore, methodological details and the report of statistical analyses will be left out. The interested reader is invited to find the complete research reports in the original publications (see Table 1).

Table 1. Overview of publications included in the thesis

Study	Reference
I	**Kirsten, H.**, Seib-Pfeifer, L.-E., Koppehele-Gossel, J., & Gibbons, H. (2019). Food has the right of way: Evidence for prioritised processing of visual food stimuli irrespective of eating style. *Appetite*, *142*, Article 104372, DOI: 10.1016/j.appet.2019.104372
II	**Kirsten, H.**, Seib-Pfeifer, L.-E., Schmuck, J., Gibbons, H. (2022). Event-related potentials of food-induced blindness in the rapid serial visual presentation paradigm. *Appetite*, Article 106344, DOI: 10.1016/j.appet.2022.106344
III	**Kirsten, H.**, Seib-Pfeifer, L.-E., Gibbons, H. (2022). Effects of the calorie content of visual food stimuli and simulated situations on event-related frontal alpha asymmetry and event-related potentials in the context of food choices. *Appetite, 169,* Article 105805, DOI: 10.1016/j.appet.2021.105805
IV	**Kirsten, H.**, Seib-Pfeifer, L.-E., & Gibbons, H. (2021). Helpless against food cues: The influence of pro- and anti-sugar videos on instrumental food-seeking behaviour in a Pavlovian-to-instrumental transfer paradigm. *Psychology & Health*, 37:5, 633-657, DOI: 10.1080/08870446.2021.1907388

Note. The order of publications in the table corresponds to the order of their appearance in the thesis.

3 Attentional bias towards food cues

Visual selective attention plays an important role in the motivation for food consumption. Incentive salience of food cues is assumed to bias attention in favour of food cues in the environment (Berridge, 2009). Furthermore, attentional processing of food-related information is likely to elicit and foster the desire to eat (see Franken, 2003; Kavanagh et al., 2005).

One of the most important roles of attention is the selection of relevant as well as the deselection of irrelevant information from the overwhelming sensory input the individual is constantly confronted with. In preparation of goal-directed behaviour, relevant information is selected for higher-order processing at the cost of other information that is neglected (Driver, 2001; Krummenacher & Müller, 2019). As postulated within the framework of the IST (Robinson & Berridge, 1993, 2008), incentive salience of food cues makes them especially “attention grabbing” (Berridge, 2009, p. 538). Thus, incentive salience causes an *attentional bias* towards food cues, meaning that they preferentially capture and/or hold visual attention (Field et al., 2016).

3.1 Measurement of attentional bias towards food cues

The attentional bias towards food cues has attracted growing interest during the last two decades. It has been studied using a variety of paradigms of which the most popular are presented in the following. Among behavioural measures, a modified version of the Stroop task (Stroop, 1935) and the dot-probe task (C. MacLeod et al., 1986) are two of the most common used tasks (see Hagan et al., 2020). Moreover, eye-tracking and electroencephalography (EEG) are common psychophysiological methods used in this context.

3.1.1 Behavioural measures and eye-tracking

In the food-Stroop task, coloured food and non-food words are presented and participants are asked to name the colour of each word as quickly as possible while ignoring its meaning. Slower reaction times in colour naming of food as compared to non-food trials are assumed to reflect an attentional bias towards food cues. The underlying assumption is that the meaning of the food words captures attention more than the meaning of the non-food words does. Thus, the processing of the food word would consume cognitive resources, thereby impairing colour naming and causing slower reactions. In support of this assumption, several studies reported generally slower reaction times for food than for non-food words in the food-Stroop task (Black et al., 1997; Merson & Pezdek, 2016; Nijs, Franken, & Muris, 2010). Others have found this effect only for restrained eaters, dieters (Francis et al., 1997; Green & Rogers, 1993; Overduin et al., 1995; S. H. Stewart & Samoluk, 1997), and anorexia nervosa patients (Perpiñá et al., 1993; Sackville et al., 1998). However, there are also several reports that have failed to observe a food-related attentional bias using the food-Stroop task (Hodge et al., 2020; Wilson & Wallis, 2013). Moreover, meta-analyses have revealed that contrary to the expectations of most studies, neither overweight/obese individuals as compared to normal-weight controls (Hagan et al., 2020) nor restrained as compared to unrestrained eaters (P. Watson & Le Pelley, 2021) show greater attentional bias towards food stimuli in the food-Stroop task. In sum, the heterogeneity of the results raises doubts about the usefulness of the food-Stroop task. Furthermore, it is still unclear what mechanism causes the food-Stroop effect (see Werthmann et al., 2015). Early attentional capture by food-words, delayed disengagement, as well as attentional avoidance of food-related content, or a combination of all could explain the prolonged response latency in food trials (see also Field & Cox, 2008). Thus, the food-Stroop paradigm cannot provide information as to the underlying components of the attentional bias towards food cues.

Contrary to the food-Stroop task, the dot-probe (or visual probe) task (C. MacLeod et al., 1986) offers the possibility to distinguish early and late processes of attentional bias. During a dot-probe trial, two visual stimuli (words or pictures) are presented side by side for a fixed duration (typically between 100 and 2000 ms). The presentation of the two stimuli is followed by a small dot (the probe) that appears at the position of either the left or the right stimulus. Participants are asked to indicate the position of the probe (left or right) as quickly as possible by pressing the corresponding key. If the attentional focus was already oriented to the stimulus at the position where the probe appears, this should facilitate the probe's detection and shorten the response latency. Thus, an attentional bias towards food stimuli would be revealed by shorter mean reaction times when the probe replaces food rather than non-food stimuli. Via modification of the stimulus onset asynchrony (SOA) between stimuli and probe, early and late attentional processes can be distinguished. While short SOAs of ≤ 200 ms are assumed to measure a bias in initial attentional orienting, longer SOAs (usually ≥ 500 ms) are thought to assess biased disengagement in maintained attentional processing (see Field & Cox, 2008). Additionally, the calculation of an attentional bias score by subtracting the mean response latency in trials when the probe replaces food stimuli from the mean response latency in trials when the probe replaces non-food stimuli indicates the direction of the attentional bias. While positive bias scores signify an attentional approach bias towards food, negative bias scores represent an attentional avoidance of food (Mogg et al., 2004; Werthmann et al., 2015). Several dot-probe studies have confirmed the assumption of an attentional approach bias for food over non-food stimuli irrespective of body weight or restrained eating (e.g., Ahern et al., 2010; Nijs, Muris, et al., 2010; Werthmann et al., 2013). However, in the dot-probe literature, results are inconsistent with regard to the relationship between the attentional bias towards food and theoretically relevant constructs such as eating styles, body weight, and eating behaviour (for an extensive overview, see Freijy et al., 2014). In accordance with the results obtained with the food-Stroop task, recent meta-analyses on the attentional bias towards food as measured by the dot-probe task did not find differences between restrained and unrestrained eaters (P. Watson & Le Pelley, 2021) or between overweight/obese and normal-weight individuals (Hagan et al., 2020). In light of the finding that the reliability of the attentional bias score obtained using the dot-probe task with threatening stimuli has been found to be very poor (e.g., Schmukle, 2005), similar concerns have been raised with respect to the food dot-probe task (Franja et al., 2021; van Ens et al., 2019; Vervoort et al., 2021). As a consequence, the analysis of inter-trial variability of attentional bias scores has emerged as a new approach in the field (see Liu et al., 2019; Liu et al., 2021). Another promising approach to enhance reliability of the food dot-probe task is its combination with eye tracking.

In contrast to the sole analysis of reaction times, eye-tracking, that is, the recording of eye movements, provides a more direct measure of attention allocation (Duc et al., 2008). Eye movements during the dot-probe task can be analysed in terms of gaze direction bias, initial gaze duration bias and gaze dwell-time bias (see, e.g., Werthmann et al., 2013). Gaze direction bias for food is assessed by monitoring the relative amount to which the initial fixation (usually defined as a period of 100 ms without interruption by saccades or blinks) after appearance of the stimuli includes food versus non-food stimuli. Thereby, initial attentional orienting is measured. Via initial gaze duration bias, the early attentional maintenance is assessed as the duration of the initial fixation on food versus non-food stimuli. Finally, gaze dwell time bias is an indicator of the total attentional engagement with food over non-food stimuli as it measures the total dwell time on the respective stimuli. First evidence suggests better internal consistency and test-retest reliability of dwell-time over gaze direction bias in the food dot-probe task (van Ens et al., 2019). Using eye tracking indices of attentional bias, preferred initial orienting towards food cues, and preferred early as well as general maintained attentional engagement with food cues have been observed in a normal-weight sample (Werthmann et al., 2013). Another study confirmed the gaze duration bias only for participants in a fasted condition and obese participants independent of fasting status (Castellanos et al., 2009). In yet another study, overweight participants showed larger gaze direction but smaller gaze duration bias than healthy weight controls (Werthmann et al., 2011). However, overall, a meta-analysis of eye-tracking data again speaks against the assumption of larger attentional bias (initial orienting and maintained attention) in overweight/obese as compared to healthy weight individuals (Hagan et al., 2020).

3.1.2 Event-related potentials

ERPs originate from the summation of postsynaptic potentials from large groups of similarly oriented cerebral neurons (mainly pyramidal cells). The flow of current created by simultaneous postsynaptic potentials produces electrical dipoles that manifest as measurable voltage changes on the scalp surface (Luck, 2014). ERPs are derived from these voltage changes in the EEG by averaging the electrophysiological activity related to an event over multiple occurrences. Thus, they "provide a direct, instantaneous, millisecond-resolution measure of neurotransmission-mediated neural activity" (Luck, 2014, p. 12) in response to an event and therefore are perfectly suited for investigations of attentional processes. Multiple ERP components, that is, voltage changes that reflect specific neural or psychological processes (Kappenman & Luck, 2012), have been investigated in the context of attention. Usually, ERP components are distinguished and labelled based on their (relative) polarity, latency, and scalp distribution (see Kappenman & Luck, 2012). For instance, the first positive deflection within approximately 100 ms after event onset is known as P1 whereas the second negativity around 200 ms after event onset would be denoted as N2. ERPs can be analysed in terms of their size (amplitude) and timing (latency). To quantify the size, the approach of computing mean amplitudes in the time range of the component of interest is most common (Luck, 2014). Via quantifying the mean voltage of the component of interest separately per participant and experimental condition, the question whether different conditions lead to differences in the size of the component can be investigated. Increases of ERP amplitudes are usually interpreted as the result of greater neuronal activity devoted to an event (e.g., Polich, 2012).

In electrophysiological research on selective attention, both early components reflecting initial attentional allocation in the course of visual perception (e.g., P1, N1), and later, postperceptual components reflecting higher-order attentional and working-memory processing (e.g., P3b, late positive potential) have been investigated intensively (Gupta et al., 2019; Luck & Kappenman, 2012). However, ERP research on attentional processes in response to food cues seems to be still in its infancy (Hagan et al., 2020; for a review see Carbine et al., 2018). Up to now, only a few studies investigated food effects on early ERP indices of attentional allocation and their results have been inconclusive (see Carbine et al., 2018). In contrast, more research has focused on ERP indices of postperceptual attentional processing of food stimuli.

In this context, P3b and the late positive potential (LPP) have attracted special interest[4]. P3b (also referred to as P300) is a centro-parietal positivity that peaks between 300 and 500 ms after stimulus onset (Sutton et al., 1965). This component is known to be modulated by stimulus frequency and task relevance, with infrequent stimuli and targets usually eliciting larger amplitudes than frequent stimuli and non-targets (see, e.g., Verleger, 2020). According to Hajcak et al. (2010), P3b seems to reflect allocation of capacity-limited resources to motivationally salient stimuli. In accordance with this, amplitude increases in response to emotional stimuli, which can be considered inherently motivationally salient, have been reported (see Hajcak et al., 2012). Furthermore, P3b has often be interpreted as an index of context updating in working memory (e.g., E. K. Vogel & Luck, 2002). In this view, it reflects the transfer of the neural representation of new stimuli into working memory (Hajcak & Foti, 2020; Polich, 2012).

The late positive potential (LPP; also referred to as positive slow wave or late positive complex) is a longer lasting centro-parietal positivity occurring approximately 400-600 ms after stimulus onset (Hajcak et al., 2010). The LPP is modulated by emotional content, as it is larger after unpleasant and pleasant compared to neutral stimuli (Schupp et al., 2006). Importantly, LPP seems to be especially sensitive to emotional contents of high evolutionary significance. Amplitude increases in response to relevant biological stimuli (e.g., erotic image or pictures of threat and mutilations) are typically larger than to other stimuli of the same valence (see Hajcak et al., 2012; Schupp et al., 2006). In sum, LPP can be interpreted as an indicator of sustained attention to emotional, motivationally relevant content (Hajcak et al., 2012; Hajcak & Foti, 2020).

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[4] Some use P300, P3b, and late positive potential (LPP) as interchangeable terms for positive, centro-parietal deflections around 300 ms after stimulus onset. Based on the distinction proposed by Hajcak et al. (2010), LPP is used to refer to sustained positive complexes occurring after the time range of the P3b.

Studies investigating P3b and LPP as indices of postperceptual attentional processing of food cues in passive viewing and Go/No-Go tasks have concurrently reported generally larger amplitudes in response to food cues as compared to non-food objects (e.g., Carbine et al., 2017). Moreover, palatable foods elicited larger P3b and LPP amplitudes than less palatable or less emotionally charged foods (e.g., Asmaro et al., 2012; Schwab et al., 2017). These results suggest greater attentional capture by palatable foods than by less palatable foods or non-food objects (Carbine et al., 2018). In accordance with evidence from behavioural and eye-tracking studies, most EEG studies did not find differences in P3b and LPP variations in overweight/obese and normal-weight participants (see Carbine et al., 2018; Hagan et al., 2020).

3.2 Attentional bias towards food cues: Current state of research

In sum, concurring evidence from behavioural, eye-tracking, and ERP studies suggests that there is a general attentional bias towards food cues as compared to non-food stimuli. However, results have been inconsistent with regard to its association with theoretically related constructs like body weight and restrained eating. Results of recent meta-analyses do not suggest differences in attentional bias towards food between overweight and healthy weight individuals or an association with BMI (Hagan et al., 2020; Hardman et al., 2020) and restrained eating (P. Watson & Le Pelley, 2021). In contrast, there were weak associations with food craving and hunger (Hardman et al., 2020). Furthermore, systematic reviews suggest an increased attentional bias towards food cues in binge eating disorder patients (Stojek et al., 2018) and an association of external, emotional, and loss of control eating with sustained attention to HC food (Wolz et al., 2015). The attentional bias seems to be related to food intake in the near future (proximal) but not to distal food intake (Field et al., 2016; Hardman et al., 2020).

Besides methodological shortcomings and lack of reliability of the experimental paradigms used to investigate the attentional bias towards food cues (see Hagan et al., 2020; Werthmann et al., 2015), the strong focus on the spatial dimension of attention has been criticised (Neimeijer et al., 2013). In particular, behavioural studies mostly relied on indices of spatial attention (e.g., in the dot-probe task, visual search, exogenous cuing) to investigate the attentional bias towards food cues. However, attentional resources cannot only be allocated to specific locations but can also be distributed over time when it comes to the selection of information from simultaneously or rapidly incoming sensory input for further processing (Luck & Kappenman, 2012). For instance, motivationally salient information (e.g., affectively arousing words) is selected preferentially from a rapid serial presentation of stimuli, probably in order to facilitate working memory consolidation and initiation of appropriate reactions (Keil & Ihssen, 2004). Similarly, an attentional bias towards food cues has been reported in the temporal dimension in terms of preferential processing of food cues in the RSVP paradigm (G. R. Davidson et al., 2018; Neimeijer et al., 2013; Piech et al., 2010).

3.2.1 Attentional blink and emotion-induced blindness

In the RSVP task (Broadbent & Broadbent, 1987), 10-20 visual stimuli are presented sequentially without inter-stimulus intervals as a rapid visual stream (presentation duration of around 100 ms per stimulus). In the dual-target version of the task, in every sequence two stimuli are marked as targets which participants are supposed to report. When the second target (T2) follows the first target (T1) with an SOA of 200-500 ms, typically, an attentional blink (AB) effect emerges as an impairment in the ability to identify T2 (Raymond et al., 1992). This effect is largest when T1 and T2 are presented within 200-300 ms and declines with increasing lag (temporal distance) between the targets (see Martens & Wyble, 2010). Also when T2 directly follows T1 within 100 ms, no impairment of T2 identification occurs (lag-1 sparing; see Hommel & Akyürek, 2005).

There are divergent explanations for the phenomenon of the AB (bottleneck theories; see, e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; attentional gating theory; see Raymond et al., 1992) but they seem to converge on the idea that it is a relatively late, post-perceptual effect rather than a deficit in early perceptual processing (see Martens & Wyble, 2010). Due to the high temporal resolution, ERPs are excellently suited to investigate the underlying mechanism of the AB in more detail. A recent review of ERP evidence suggests that AB is caused by multiple factors and that disruption of attentional engagement, working-memory encoding, and semantic processing are all involved in the emergence of the AB effect (Zivony & Lamy, 2021). Apparently, ongoing processing of T1 impairs attentional engagement with T2 (indexed by reduced and delayed N2pc), prevents semantic processing (indexed by reduced N400), and reduces the probability that T2 is encoded in working memory (indexed by absent P3b).

Based on existing knowledge about the mechanisms of the AB, the RSVP paradigm cannot only be used to investigate the phenomenon of the AB itself. It can also serve as a diagnostic tool in the investigation of higher-order attentional processing of particular stimuli. More specifically, presenting food cues as T1 or T2 in a RSVP task could provide insight into their higher-order attentional processing in form of food-elicited modulations of the AB. Until now, only a few studies have taken this approach. First reports suggest that food cues elicit a larger AB effect than non-food stimuli when presented as T1 (Ballestero-Arnau et al., 2020; Neimeijer et al., 2013). Furthermore, food-T2 elicited a 'backward blink' in restrained eaters, that is, they impaired the identification of preceding non-food T1 (Neimeijer et al., 2013). In binge eating disorder patients, the AB effect was reduced when food words (as compared to non-food words) were presented as T2 (Schmitz et al., 2015). The first (and so far only) ERP study of food effects on the AB revealed smaller P3b amplitudes during the AB elicited by food T1 in obese adolescents compared to healthy controls (Woltering et al., 2021). This was interpreted as an impairment in working-memory updating of obese participants after their attention was captured by food stimuli.

Impairments in target identification do not only occur in the context of the AB elicited by T1 in the dual-target version of the RSVP task. In the single-target RSVP task, task-irrelevant emotional distractors can cause a deficit in subsequent target identification. This effect is known as *emotion-induced blindness* (Most et al., 2005)[5]. It can be elicited by highly arousing emotional stimuli such as threatening (Kennedy et al., 2014; Most et al., 2005) and erotic (Arnell et al., 2007; Most et al., 2007) words and pictures. EIB resembles the AB in terms of timing and duration as it is also most pronounced around 200-300 ms after distractor onset and gets weaker with longer lags (see McHugo et al., 2013). However, in contrast to the AB, EIB already occurs at lag 1 (no lag-1 sparing; Most & Jungé, 2008). On the ERP level, similarly to the absence or reduction of P3b in response to T2 in the AB (Kranczioch et al., 2003; Kranczioch et al., 2007), reduced P3b and N2 in response to targets that fall into the time window of the EIB have been reported (Kennedy et al., 2014). Moreover, emotionally arousing distractors that elicited an EIB effect were themselves accompanied by a P3b (Hoffman et al., 2020; Kennedy et al., 2014; J. MacLeod et al., 2017) although being task irrelevant. Furthermore, negative distractors elicited larger amplitudes of parieto-occipital N2 (Kennedy et al., 2014), a component peaking around 250 ms after stimulus onset that is associated with the attentional selection of relevant (emotional)

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[5] Note that emotion-induced blindness is also often referred to as 'emotional attentional blink' (see, e.g., McHugo et al., 2013). Here, the term emotion-induced blindness is preferred to take into account differences in the underlying mechanisms of the attentional blink in the dual-target RSVP task and the deficit in target identifications following emotional distractors.

stimuli. Emotion research often refers to the difference curve between emotional and neutral stimuli in the N2 time window as Early Posterior Negativity (EPN; see, e.g., Schupp et al., 2006).

Similarly to threatening and erotic stimuli, food cues were found to elicit EIB in anorexia nervosa patients (Neimeijer et al., 2017) and hungry participants (Piech et al., 2010) but also in healthy, satiated participants (G. R. Davidson et al., 2018; Neimeijer et al., 2013; Piech et al., 2010).

3.3 Attentional bias towards food cues: Novel contributions

Based on these first reports of food effects on the phenomena of the AB and EIB in RSVP studies, *Study I* was designed to replicate these findings and investigate the association of the attentional bias towards food in the temporal dimension with restrained, external, and emotional eating. Subsequently, neural correlates of EIB elicited by task-irrelevant food distractors were investigated in *Study II*.

3.3.1 Food-elicited modulations of the attentional blink

In *Study I*, the AB was used as a diagnostic tool to investigate the temporal dimension of the attentional bias towards food cues at the behavioural level. Therefore, food and non-food stimuli were implemented as T1, T2, and task-irrelevant distractors in a RSVP task. Based on the findings of a previous study (Neimeijer et al., 2013), we tested four hypotheses with regard to the effects of food cues on the AB. First, the AB should be more pronounced when food cues (as compared to non-food stimuli) are presented as T1. Second, the AB should be diminished when food cues (as compared to non-food stimuli) are presented as T2. Third, food T2 should interfere with the identification of preceding non-food T1 in terms of a backward interference. Fourth, task-irrelevant food (but not non-food) distractors should elicit an AB effect in terms of EIB. We expected these effects to be more pronounced in high as compared to low scorers on the restrained, external, and emotional eating scales.

We found evidence in support of the assumption that food cues gain preferential access to limited processing resources, which was apparent in modulations of the AB. In support of hypothesis 1, food T1 caused larger AB effects, that is, stronger impairment in the identification of subsequent T2 than non-food T1. Thus, attentional resources seem to be preferentially allocated to food cues which causes an interference with competing tasks such as the identification of T2. Furthermore, food T2 caused a backward interference in form of an impairment to report the preceding T1. However, there was no evidence for the assumption that food T2 are able to ‘overcome’ the AB. Thus, even though food T2 could not be reported more often than non-food T2, they still had an impact on task performance. In combination, these observations suggest that although presented during the AB and not always fully processed, food cues gain attention to some extent, also in situations of limited cognitive resources. Lastly, food distractors led to an impairment in subsequent target identifications. This effect was not specific for the interval of the AB but also affected targets that were presented with substantial time lag to the distractors. As food cues were task irrelevant in these trials, their impact on target identification can be interpreted as an automatic bottom-up capture of attentional resources. Taken together, these results support the assumption that the attentional bias towards food also affects the temporal dimension of visual attention via giving food cues preferred access to limited cognitive processing resources.

We did not find evidence for a stronger attentional bias in high restrained, external, and emotional eaters. Moreover, the food effects on the AB were not affected by hunger and time of day. Therefore, we concluded that the prioritisation of food cues in situations of limited processing capacities seems to be a universal phenomenon that might be explained by the generally high relevance of food for human well-being.

3.3.2 ERPs of emotion-induced blindness elicited by food cues

Going beyond the analysis of target identification rates on the behavioural level in *Study I*, with *Study II* we aimed to get a deeper understanding of the neural mechanisms involved in the temporal attentional bias towards food cues. Here, we focused on the attentional capture by task-irrelevant food cues, that is, the food-elicited EIB. To investigate the neural correlates of this effect, the EEG was recorded during a single-target RSVP task with food and non-food distractors. Given that food cues are usually rated as positive and affectively arousing (Blechert et al., 2019), they can be considered emotional stimuli. Thus, ERP studies of EIB elicited by emotional distractors (see chapter 3.2.1) provided a sound basis for the formulation of expectations for ERPs of the food-elicited EIB. Consequently, we expected smaller amplitudes of P3b and N2 in response to targets presented shortly after food distractors than in response to targets presented after non-food distractors. In contrast, P3b and N2 amplitudes elicited by food distractors should be larger than P3b and N2 elicited by non-food distractors. Correct target identifications were expected to be preceded by smaller distractor and larger target ERPs than incorrect target identifications. Taken together, the food-elicited EIB should be accompanied by a trade-off between distractor and target ERPs.

In accordance with the assumption of a food-elicited EIB, the identification rate of targets that followed shortly after food distractors (lag 2) was reduced compared to the identification rate of targets that followed shortly after non-food distractors. Thus, task-irrelevant food distractors must have captured attentional resources automatically and thereby impaired subsequent target identification. With larger lags (lag 8) between distractor and target, this effect disappeared.

With respect to target ERPs, we found larger centro-parietal target P3b (340-440 ms after target onset) for correctly identified targets compared to targets that were not correctly identified. This result is in accordance with previous AB and EIB studies (e.g., Kennedy et al., 2014; Kranczioch et al., 2003; Woltering et al., 2021) and emphasises the role of neural mechanisms reflected in the P3b for categorisation and working-memory consolidation processes. Against our assumptions, there was no evidence for a modulation of the target P3b by preceding distractors in lag-2 trials. Thus, the food-elicited EIB was not reflected in a reduction of respective target P3b. Parieto-occipital target N2 (190-270 ms after target onset in lag-2 trials) was specifically reduced for incorrectly identified targets as compared to correctly identified targets preceded by food distractors. In contrast, there was no difference in N2 amplitude between correctly and incorrectly identified targets preceded by non-food distractors. Presumably, this pattern of results reflects differences in the emergence of target-identification errors occurring after food and after non-food distractors. On the one hand, attentional processing of food distractors may have caused a reduced availability of cognitive resources needed for attentional processing of the target (as reflected in the N2). On the other hand, target identification errors that occurred after non-food distractors may have been the result of general inattention or errors on the motor response level, thus, errors that are not necessarily related to attentional processing of the target and therefore are not reflected in the target N2.

Against our expectations and in contrast to ERP effects observed with negative distractors (Kennedy et al., 2014), no centro-parietal positivity in terms of a P3b was apparent in the distractor ERP. Instead, a centro-parietal negativity emerged 320-370 ms after distractor onset. As timing and topography differed from the distractor N2 observed in previous EIB studies, we referred to this component as the *Distractor Negativity* instead of N2. The Distractor Negativity was larger in response to food as compared to non-food distractors but was not related to subsequent target identifications in lag-2 trials. This component can be attributed to the family of attention-related N2 components (Folstein & van Petten, 2008) and seems to reflect automatic attentional capture by the task-irrelevant food distractors (comparable to N2/EPN effects in other RSVP tasks; see, e.g., J. MacLeod et al., 2017). Moreover, exploratory analyses revealed differences between food and non-food distractors in the food-non-food difference curve. A parieto-occipital, P1-like *Early Food Positivity* emerged 150-200 ms after distractor onset in terms of a positive deviation of the food-distractor ERP from the non-food distractor ERP. However, this difference was not associated with target identification. Based on its resemblance to the P1 component, the Early Food Positivity can be interpreted as an early index of visual selective attention (Di Russo et al., 2003) which could be a precursor of later limited-capacity processes involved in the food-elicited EIB.

To conclude, distractor ERPs in terms of Distractor Negativity and Early Food Positivity suggested automatic capture of visual attention by task-irrelevant food cues. However, their attentional selection did not lead to higher-order processing in terms of working-memory consolidation as indexed by the absence of a distractor P3b. Also, the expected trade-off between distractor and target ERPs was not observed. The amplitude of target P3b reflected performance in target identification but was unaffected by preceding distractors. In this respect, the food-elicited EIB seems to differ from EIB elicited by emotional distractors. Based on the postulation of a functionally earlier mechanism of EIB than consolidation into working memory (L. Wang et al., 2012), the impairment of target identification after food distractors could have emerged on the level of Distractor Negativity. This then might have contributed to the specific reduction of the target N2 for incorrectly identified targets presented after food distractors.

For the analyses of individual differences, we included self-reports of hunger, restrained, external, and emotional eating into the study. While hunger, external, and emotional eating were not related to the behavioural EIB effect and the ERP effects, a positive correlation between restrained eating and the size of the EIB on the behavioural level emerged. Thus, a more restrictive eating style seems to be associated with a stronger attentional bias towards task-irrelevant food cues. However, based on the present study it is not possible to determine whether the restrained eating style is a coping strategy for the attentional bias or if restrictive eating causes the attentional bias in the first place.

3.4 Attentional bias towards food cues: Conclusion

Study I and *Study II* contributed to the hitherto rather small field of research on the attentional bias towards food cues in the temporal dimension by making use of the RSVP paradigm. The findings confirmed previous observations of food-elicited modulations of the AB and food-elicited EIB (e.g., Neimeijer et al., 2013). Thereby, they provide further evidence of prioritised processing of food cues at the expense of competing information and tasks. The emergence of this clear attentional bias towards food cues in healthy, young, normal-weight, and educated samples further supports the assumption that an attentional bias towards food is a universal phenomenon (Werthmann et al., 2013; Werthmann et al., 2015) rather than a particular characteristic of disordered eating, dieting, or overeating. Most likely, this effect can best be explained by a combination of evolutionary importance of food for human survival and well-being on the one hand and the rewarding qualities and thereby emotional connotation of food on the other hand.

Going beyond a mere replication of behavioural findings, in *Study II* one of the first investigations of ERPs and, thus, underlying neural mechanisms, of the temporal attentional bias towards food cues was realised. First, it provides evidence for early ERP indices of attentional capture by food cues in form of the so-called Early Food Positivity and Distractor Negativity which can be broadly classified as P1 and N2 effects. Second, the results suggest differences in the neural mechanisms of EIB elicited by food cues and EIB elicited by other (especially negative) emotional stimuli (see Kennedy et al., 2014). However, more research is needed before further conclusions regarding the implications of these first results can be drawn.

4 Food-related approach/avoidance motivation

According to the IST, the attentional bias towards food cues is part of the incentive salience resulting from the activation of the ‘wanting’ system and serves the goal of obtaining a ‘wanted’ reward (Berridge & Robinson, 2016). ‘Wanting’ thereby also implies the stimulation of *approach* motivation towards food in order to access and consume palatable foods. Approach motivation can be defined as the “energization of behavior by, or the direction of behavior toward, positive stimuli (objects, events, possibilities)” (Elliot, 2006, p. 111). In the traditional approach-avoidance distinction, approach motivation is complemented by *avoidance* motivation, the “energization of behavior by, or the direction of behavior away from, negative stimuli” (Elliot, 2006, p. 111). In the context of eating, not only avoidance of inedible food but in light of dieting goals or the pursuit of a healthy lifestyle, also avoidance of palatable, but unhealthy food can be a reasonable strategy.

4.1 Measurement of food-related approach/avoidance motivation

On the behavioural level, food-related approach and avoidance motivation are usually assessed via reaction times in an approach-avoidance task (AAT; Rinck & Becker, 2007). Going beyond the behavioural level, neural correlates of approach and avoidance motivation can be assessed in terms of asymmetrical activity of the frontal cortex. The theory of frontal cortical asymmetry postulates relatively stronger left-frontal cortical activity in the context of approach motivation and relatively stronger right-frontal cortical activity in the context of avoidance motivation (e.g., Harmon-Jones & Gable, 2018). In EEG research, the amount of left- and right-hemispheric frontal alpha frequency can be used as a measure of asymmetrical cortical activity.

4.1.1 Approach-avoidance task

In the AAT, participants respond with pull- (approach) or push- (avoidance) movements (e.g., via computer mouse, joystick, or touchscreen) to stimuli from different categories (e.g., food and non-food; see, e.g., van Alebeek et al., 2021). Shorter reaction times of approach than of avoidance responses to stimuli of the category of interest (and this to a larger extent than to the stimuli of another category) are interpreted as an approach bias. In the *relevant-feature* version of the task, the approach and avoidance responses have to be performed based on the stimulus categories (e.g., approach food and avoid non-food stimuli). Thus, the categories of interest are in the focus of attention during the task. In the *irrelevant-feature* AAT, features that are unrelated to the categories of interest define whether a stimulus should be approached or avoided (e.g., approach stimuli with a red frame, avoid stimuli with a blue frame). Thereby, the true categories of interest remain task-irrelevant (see Lender et al., 2018). Meta-analytic evidence suggests that approach biases are measured more reliably with the relevant-feature AAT (Phaf et al., 2014). In accordance with this assumption, only a relevant-feature joystick AAT but not differing versions of the irrelevant-feature joystick AAT revealed a robust approach bias towards food cues (Lender et al., 2018). A touch-screen based variant of relevant- and irrelevant-features AAT yielded similar results (Meule et al., 2019). Nevertheless, the majority of food AAT studies relied on the irrelevant-feature AAT. This might be due to the fact that automatically elicited motivational tendencies in an incidental confrontation with food stimuli were of interest in most investigations (van Alebeek et al., 2021).

Some of these feature-irrelevant food AAT studies suggest that overweight/obese individuals, but not normal-weight controls show an automatic approach-bias towards food cues (Kakoschke et al., 2017b; Mehl et al., 2018). In an overweight sample, this bias was positively related to subsequent consumption in high external and emotional eaters (Kakoschke et al., 2017b). Another study reported an avoidance bias in response to LC food in binge eating disorder patients and healthy controls (Paslakis et al., 2017). Additionally, in normal-weight individuals, an approach bias towards HC food was positively correlated with food craving (Brockmeyer et al., 2015a) and reward sensitivity (C. N. May et al., 2016). Finally, a strong approach bias in combination with low inhibitory control resulted in elevated snack consumption (Kakoschke et al., 2015). The probably more reliable feature-relevant food AAT revealed positive associations of a food-approach bias with food craving, external eating, food liking, and desire to eat (Kahveci et al., 2020; van Alebeek et al., 2021).

4.1.2 Frontal cortical asymmetry

At the neural level, approach and avoidance motivation have been associated with asymmetrical activity of the frontal cortex. In the framework of the theory of frontal cortical asymmetry, relatively stronger left- than right-hemispheric frontal cortical activity indicates approach motivation whereas relatively stronger right- than left-hemispheric activity is interpreted as an index of avoidance tendencies (R. J. Davidson, 1998b; Harmon-Jones & Gable, 2018). Traditionally, this asymmetry is measured electrophysiologically by quantifying the difference of power (defined as squared amplitude) of the alpha frequency band (8-12 or 8-13 Hz) at left- and right-frontal sites. For a long time, alpha frequency was simply interpreted as an indicator of inactivity or resting state of a cortical region as it is negatively correlated with cortical activity (see, e.g., Allen et al., 2004). An updated view of this rather simplistic assumption is provided by the asymmetric inhibition model of frontal asymmetry (Grimshaw & Carmel, 2014). This model postulates that negative, withdrawal-related distractors are inhibited by the left dorsolateral prefrontal cortex (dlPFC) and positive, approach-related distractors are inhibited by the right dlPFC. Based on the association between alpha power and the dorsal fronto-parietal network which plays an important role in executive control of attention (Corbetta & Shulman, 2002), the model proposes that "EEG asymmetries reflect the integrity of executive control mechanisms that inhibit interference from irrelevant emotional distractors" (Grimshaw & Carmel, 2014, p. 3).

However, independent of the assumptions regarding its functional role, alpha power is used as an inverse measure of cortical activity. To quantify frontal cortical activity, frontal alpha asymmetry (FAA) scores are computed as the difference of alpha power at right- minus homologous left-hemispheric frontal sites. Thus, positive FAA scores indicate relatively greater right-hemispheric alpha power but relatively greater left-hemispheric cortical activity, which is interpreted as an index of approach. In contrast, negative FAA scores indicate relatively greater left-hemispheric alpha power but relatively greater right-hemispheric cortical activity, thus being an index of avoidance (e.g., Allen et al., 2004).

Studies investigating FAA in the context of motivation typically follow a dispositional model which postulates that resting state FAA is an indicator of a trait-like personal predisposition or affective style to approach or avoid stimuli in the environment (R. J. Davidson, 1998a). Following this approach, FAA is best measured at rest, without any sensory input in order to capture an individual's 'baseline' asymmetry in frontal cortical activity. Typically, this is realised by recording approximately eight minutes of resting state EEG (Allen et al., 2004). However, after inconsistent results have raised doubts concerning the validity of the dispositional model (see, e.g., Wacker et al., 2010), a capability model (Coan et al., 2006) has been proposed as an alternative theoretical framework for FAA. The capability model postulates that individual differences in FAA emerge from differences in the regulatory capabilities to react to emotional situational demands (Coan et al., 2006). In this sense, motivational demands of the (experimental) situation are crucial in order to capture elicited approach or avoidance tendencies in terms of asymmetrical frontal activity (Rodrigues et al., 2021). Although the current state of research rather speaks in favour of the capability model (see, e.g., Kuper et al., 2019; Rodrigues et al., 2021; J. L. Stewart et al., 2014), the majority of studies still follows the dispositional model by investigating resting state FAA.

For instance, in research on approach and avoidance motivation in the context of eating behaviour, the association of resting state FAA with restrained eating (Ochner et al., 2009; Silva et al., 2002), hunger (Ochner et al., 2009; Winter et al., 2016), binge eating, disinhibition, and appetitive responsivity (Ochner et al., 2009) has been investigated. Relatively greater left frontal activity at rest, indicating a predisposition for approach behaviour, was related to hunger, disinhibition, and appetitive responsivity (Ochner et al., 2009; Winter et al., 2016). In contrast, relatively greater right-frontal activity at rest, indicating avoidance tendencies, has been linked to restrained eating (Silva et al., 2002; Winter et al., 2016). However, this relationship did not emerge in another study (Ochner et al., 2009). There were no associations between resting state FAA and BMI or eating behaviour (Morys et al., 2020).

In event-related designs, FAA is investigated in response to the presentation of appetitive or aversive stimuli. For instance, the presentation of dessert pictures elicited greater left- than right-hemispheric frontal activity in individuals with high dessert liking (Gable & Harmon-Jones, 2008). Additionally, cooking a tasty dish was associated with greater left-hemispheric activity whereas cooking with disgusting ingredients elicited greater right-hemispheric frontal activity (Brouwer et al., 2017).

4.2 Food-related approach/avoidance motivation: Current state of research

Taken together, AAT investigations of approach biases towards food cues yielded rather mixed results. Most likely, this can (at least partly) be explained by methodological variations between studies in terms of response devices (keyboard, mouse, joystick, touchscreen), simulation of approach and avoidance movements (zoom or distance effects versus actual movements), and differences between task instructions in terms of relevant-feature versus irrelevant-feature AATs (see Kahveci et al., 2021; van Alebeek et al., 2021). In the context of ‘wanting’, one would assume an overall approach bias for palatable, HC food. However, recent research using an updated touchscreen, relevant-feature AAT points to an important role of individual momentary preferences and questions the widely held assumption of a general approach bias towards HC food (Kahveci et al., 2021).

Going beyond reaction time measures, the concept of FAA offers the possibility to investigate approach and avoidance motivations in response to food at the neural level. Studies employing this method have revealed promising results (see above) but they also share an important shortcoming. Based on the dispositional model, most studies measured FAA at rest and tested for correlations between the resulting FAA scores and self-reports of eating behaviour (e.g., Ochner et al., 2009; Winter et al., 2016). In terms of analysing techniques, this is realised by calculating the frequency representation of the resting-state EEG signal in a frequency analysis (for instance by means of a *fast Fourier transform*, e.g., Cohen, 2014) and thereby extracting the alpha power. However, frequency analyses only provide information about the alpha power averaged over several seconds of EEG data but do not show dynamic changes in the frequency structure of the signal (Cohen, 2014). Although internal consistency of FAA scores derived from the fast Fourier transform is generally satisfactory (Towers & Allen, 2009), the temporal resolution of this method is rather poor and information about temporal fluctuations in FAA are lost. Nevertheless, even event-related FAA elicited by food cues, which is most likely temporally more dynamic than resting FAA, has been solely investigated by means of frequency analyses (e.g., Brouwer et al., 2017; Gable & Harmon-Jones, 2008).

4.2.1 Time-frequency analysis

By means of time-frequency analyses, the frequency structure of the EEG signal can be calculated while conserving a similar amount of temporal precision as provided by ERPs (Cohen, 2014). For instance, performing a complex Morlet wavelet convolution (see Cohen, 2014) of EEG data can reveal stimulus- or task-elicited changes in alpha power and thus FAA, with high temporal precision (see, e.g., Messerotti Benvenuti et al., 2019; Shevorykin et al., 2019). However, until now, time-frequency analyses have rarely been used to study temporal dynamics of FAA. However, in the context of resting activity, they revealed “transient bursts of asymmetry” (Allen & Cohen, 2010, p. 1) that would have remained undetected by frequency analyses. Furthermore, in event-related designs, transient motivational responses to emotional stimuli have been revealed by time-frequency analyses (Messerotti Benvenuti et al., 2019; Schöne et al., 2016). For instance, there was a reduction of left-frontal alpha power in response to erotic pictures only in the time window of 500-1000 ms after stimulus onset that indicated relatively greater left than right frontal cortical activity and thus temporary approach motivation (Schöne et al., 2016).

4.3 Food-related approach/avoidance motivation: Novel contributions

With *Study III*, we aimed to investigate the neural correlates of food-related approach and avoidance motivation, as measured by FAA and its temporal dynamics by means of time-frequency analysis. In the course of this, the influence of the food's calorie density and the situational context of food choices were taken into account. The approach bias towards HC versus LC food was investigated in prior studies (e.g., Paslakis et al., 2016; Paslakis et al., 2017), which pointed towards an approach bias towards both HC and LC food in healthy participants. In contrast, influences of the situational context of the food encounter, for example, in terms of current personal goals or mindset, have been widely neglected in previous research. Thus, this study was designed to gain insight into the interplay of the situational context and stimulus properties regarding food-elicited approach and avoidance motivation.

Participants completed a food-choice task that consisted of three blocks, each block representing a different situational context. First, in the 'baseline situation', participants were instructed to imagine coming home after an ordinary day of school or work. Second, in the 'reward situation', they were asked to imagine coming home after having donated blood, now desiring to reward themselves with a tasty meal without thinking about the consequences of their consumption. Finally, in the 'diet situation' they should imagine being on a diet in order to reduce weight by eating more healthy and light instead of sweet and fatty foods. In every block, a selection of HC and LC food pictures was presented and participants were asked to decide for every presented food whether they would eat it in the given situational context or not. By means of time-frequency analysis, FAA scores were calculated separately for the six combinations of calorie content and situational context. Additionally, respective ERP analyses of P3b[6] and LPP as measures of sustained attention for motivationally relevant stimuli were conducted.

At the behavioural level, we expected more HC than LC food choices in the reward situation and more LC than HC food choices in the diet situation. At the neural level, food choices in the reward situation should be accompanied by greater (more positive)

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[6] In the original article, this component is referred to as P300. To be consistent with Chapter 3.1.2, here, the term P3b is used.

FAA scores in response to HC than LC foods, which would indicate relatively greater activity in the left than right frontal cortex and thus signal stronger approach tendencies to HC foods. In contrast, food choices in the diet situation should be accompanied by smaller (more negative) FAA scores in response to HC but greater FAA scores in response to LC foods as compared to the baseline and the reward situation. Due to the novelty of the approach, we had no prior knowledge about the timing of FAA effects in this context. Therefore, we applied the procedure of collapsed localisers (Luck & Gaspelin, 2017) to determine the time window for the analyses. FAA scores averaged across all experimental conditions were maximal between 950 and 1175 ms after stimulus onset, thus, this time window was subjected to further analyses. For ERPs, larger P3b and LPP amplitudes in response to HC than to LC foods were expected based on prior research (Biehl et al., 2020; Schwab et al., 2017). In both the reward and the diet situation, amplitudes should be larger than in the baseline situation as food choices should be more demanding in terms of attentional resources given the specific requirements of these situations.

As expected, participants chose more HC than LC foods in the reward situation and more LC than HC foods in the diet situation. The sample showed a general preference for LC food, which was apparent from more LC than HC food choices in the baseline situation. In accordance with this preference for LC food, there was a main effect of calorie content on FAA that suggested temporary more pronounced approach motivation towards LC than towards HC food. More specifically, LC foods elicited greater FAA scores between 950 and 1175 ms after stimulus onset than HC foods did. Thus, there was relatively greater right- than left-frontal alpha power, that is, relatively greater left- than right-frontal cortical activity in response to LC foods. However, against our expectations, there was no effect of the situational context on FAA. In accordance with our assumptions, LPP amplitudes were larger for HC than for LC food. Thus, LPP reflected the greater intrinsic rewarding value of HC compared to LC food, which was also apparent from the sample's rating of the stimuli. Moreover, also in accordance with our assumptions, the specific situational context seemed to have caused enhanced recruitment of attentional resources for the processing of the food stimuli, which was reflected in larger amplitudes of both LPP and P3b in the reward and diet as compared to the baseline situation. However, the effect of calorie content on the P3b differed from the pattern observed for LPP. P3b amplitudes were generally larger in response to LC than to HC food, thereby reflecting the preference for LC food choices rather than the rewarding value of the food. Moreover, an interaction effect pointed towards a specific enhancement of P3b in response to HC stimuli in the diet situation. Presumably, ‘incongruent’ pairings of food stimuli and situational context (i.e., HC in the diet context and LC in the reward context) were especially difficult to process and thus required more attention than ‘congruent’ pairings. Also in this study all effects were unrelated to hunger. Neither were there any associations with trait food craving.

4.4 Food-related approach/avoidance motivation: Conclusion

In *Study III*, approach and avoidance motivation in the context of food choices were investigated. Going beyond previous studies, which mainly focused on behavioural effects in the AAT, we measured frontal cortical asymmetry as an indicator of motivational tendencies in a food-choice task. Similar to the relevant-feature AAT, the task required participants to make food choices based on the characteristics of the presented foods. Another extension of previous studies was the inclusion of three different simulated, situational contexts that should be taken into account when deciding which food to consume.

ERP indices of sustained attention reflected influences of both the calorie content and the situational context on food-cue processing. Moreover, a relatively novel approach for the analysis of FAA was used by applying time-frequency analysis on the EEG data. Thereby, a high temporal resolution could be preserved when quantifying left- and right-hemispheric alpha power. In prior studies, the time course of FAA was not considered as frequency-analysis techniques were used almost exclusively. Here, time-frequency analysis revealed temporarily stronger approach motivation towards LC foods in form of stronger left-frontal activity around 1000 ms after stimulus onset. Against our expectations, no influence of the simulated diet and reward situations on FAA emerged. Presumably, the artificiality of an imagined situational context and the fast switch between the three different conditions both contributed to the lack of effects. As knowledge about the temporal distribution of event-related FAA is still scarce, it is difficult to draw conclusions from the timing observed in this study and the time-frequency analysis must be considered a rather exploratory approach in this context. However, the first application of this method revealed promising first findings and gives rise to interesting future directions for research on event-related FAA in the context of food choices.

5 Influence of food cues on behaviour

In the previous chapters of this thesis, evidence in support of the assumptions that food cues are preferentially processed on the cognitive level and elicit approach tendencies on the motivational level has been discussed. These cognitive and motivational aspects of food-cue reactivity are supposed to contribute to food craving and consequently to overeating and weight gain (see cued overeating model; Jansen, 1998; or EIT; Kavanagh et al., 2005). In order to do so, food cues must further trigger food-seeking and eating behaviour. Thus, there must be a transfer of cognitive and motivational food-cue reactivity to the behavioural level. Based on associative learning theories of goal-directed actions, food-seeking actions can be considered instrumental responses that result from the learned association between the response (R) and the following outcome (O; Wit & Dickinson, 2009). If the outcome reliably follows the executed response, contingency is experienced. As a consequence, representations of the outcome can trigger the associated responses in terms of direct O-R priming on future occasions (see, e.g., Elsner & Hommel, 2001). Going beyond direct O-R priming, a stimulus (S) that has repeatedly been paired with the outcome by classical conditioning and thus is predictive of its occurrence can trigger the respective response via indirect S-O-R priming (Wit & Dickinson, 2009). For instance, a fast-food billboard at the side of the highway (S) could lead us to head to the next drive through (R) in order to buy hamburgers and fries (O). In this sense, associative learning mechanisms can play an important role in food-cue reactivity.

5.1 Measurement of the influence of food cues on behaviour

The influence of food cues[7] on food-seeking behaviour in terms of S-O-R priming mechanisms can be investigated by means of the PIT paradigm (Estes, 1948). The PIT task typically comprises three parts. First, participants learn that different responses (key presses) yield different outcomes in an instrumental training (O-R learning). Second, each outcome is repeatedly presented with a a-priori meaningless cue (e.g., geometrical pattern) in the Pavlovian training (S-O learning). Finally, in the transfer test, participants can perform free button presses to gain the associated outcomes they know from the instrumental training. During the transfer test, the Pavlovian

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[7] Note that in this chapter, the term ‘food cue’ is used in a slightly different sense than in previous chapters. In terms of S-O-R priming, a food cue (S) can be any stimulus that is predictive of a food outcome (O). Thus, the conception of food cues in this context is not confined to pictures of food.

cues that have been paired with the respective outcome are present in some trials. Typically, in these cued trials, S-O-R priming in terms of higher response rates for the outcome associated with the presented cue can be observed. Thus, the cues alter responses in favour of the associated outcome although no S-R connection has been established in the training phases. For instance, in the instrumental training of a PIT study by P. Watson et al. (2014) participants learned that they can gain smarties by pressing the left of two specified keys and popcorn by pressing the right key. In the following Pavlovian training, smarties and popcorn were paired with different black-and-white patterns. In the transfer test, participants pressed the left key for smarties more often than the right key when the pattern that had been paired with smarties was presented on screen. When the pattern that had been paired with popcorn was shown, they pressed the right key for popcorn more often than the left key. This effect is known as the *outcome-specific PIT effect* (see, e.g., P. Watson et al., 2018). Presumably, the Pavlovian cue activates the representation of the associated outcome and thus elicits the respective response (e.g., Wit & Dickinson, 2009). This effect illustrates how even previously unknown stimuli can influence food-seeking behaviour by associative-learning mechanisms.

In the context of food-seeking behaviour and food choices, an outcome-specific PIT effect of food cues has been observed in multiple previous studies and populations. Normal weight, healthy as well as obese individuals and anorexia nervosa patients showed an outcome specific PIT effect for healthy and unhealthy food outcomes (Quail et al., 2017; V. Vogel et al., 2019; P. Watson et al., 2017). While the PIT effects for HC and LC food did not differ in normal weight, adult participants, there was a larger PIT effect for HC than LC food in obese participants and adolescents (P. Watson et al., 2016; P. Watson et al., 2017).

5.2 Influence of food cues on behaviour: Current state of research

Existing evidence supports the assumption that food cues influence food choices and eating via PIT mechanisms. Additionally, some studies suggest that (at least for adolescents and obese adults) this effect might be stronger for HC than for LC food (P. Watson et al., 2016; P. Watson et al., 2017). Consequently, the question arises how the influence of food cues on food-seeking behaviour could be altered in terms of preventing unhealthy and facilitating healthy food choices.

To this aim, effects of the manipulation of the outcomes' motivational value have been investigated in previous studies (for a review, see P. Watson et al., 2018). For instance, outcome-specific satiation (P. Watson et al., 2014), health warnings (Verhoeven et al., 2018), and mindset manipulations in terms of health versus palatability rating tasks (Frank-Podlech et al., 2021) have been used as outcome devaluation procedures. However, in the transfer tests of the respective PIT tasks, only response rates in non-cued trials (i.e., trials in which Pavlovian cues were absent) were reduced by these manipulations. The outcome-specific PIT effect, thus the response rates in the presence of Pavlovian cues remained unaffected by the devaluation procedures (Frank-Podlech et al., 2021; Verhoeven et al., 2018; P. Watson et al., 2014). Only very strong outcome devaluations (e.g., aversive taste manipulations) seem to reduce cued food-seeking responses in the PIT task (e.g., Eder & Dignath, 2016; Mahlberg et al., 2019). However, such strong aversive interventions are unsuitable measures to fight unhealthy eating triggered by food cues in everyday life.

5.3 Influence of food cues on behaviour: Novel contributions

With *Study IV* we aimed to investigate the effect of an ecologically more valid manipulation of the outcome value on the outcome-specific PIT effect. In modern obesogenic environments, confrontations with food-related information often occur in the form of videos on social media or TV. Both, advertisements for (mostly unhealthy) snacks and health communication campaigns use these communication channels. To operationalise the influence of food-related videos on (cued) food-seeking, we included a video-based manipulation of the outcome value as a between-subjects variable into the PIT task. Going beyond prior studies that focused mainly on outcome devaluation (decrease of the outcome value), we further implemented an outcome upvaluation condition (increase of the outcome value).

Study IV was announced as a snack contest in which participants could win differently desirable snacks. Chocolate cookies were used as a sugary, desirable snack and rice wavers as a sugar-free, less desirable snack. In the instrumental training of the PIT task, participants learned by trial-and-error that each of both snacks could be obtained by a certain number of key presses on the key associated with the respective snack. Subsequently, chocolate cookies and rice wafers were paired with meaningless, geometrical patterns in the Pavlovian training phase. Participants were asked to remember the associations between snacks and the response keys as well as between snacks and patterns (Pavlovian cues) in order to win snacks in the last phase of the task. After the trainings, they watched either an anti-sugar video (devaluation group), a pro-sugar video (upvaluation group), or a control video (control group) unrelated to food. In the following transfer test, participants could win cookies and rice wafers by pressing the keys associated with the snacks as often as they wanted. In some trials, the Pavlovian cues associated with the snacks were presented in the background. However, participants were told to ignore the cues and did not know which snack they could win in a given trial. As they were told that they would have to eat the snacks they won immediately after the task, their response rates could be interpreted as actual food-seeking behaviour for sugary versus non-sugary snacks. We expected reduced response rates for the sugary snack in the devaluation group and enhanced response rates for the sugary snack in the upvaluation group as compared to the control group. Based on previous research, this effect was only expected in non-cued trials of the transfer test but not in the presence of the Pavlovian cues.

In accordance with previous research, an outcome-specific PIT effect occurred. We observed higher response rates for cookies when the Pavlovian cue that had been paired with cookies was present and higher response rates for rice wafers in the presence of the cue that had been paired with rice wafers. The PIT effects for the sugary and the sugar-free snack did not differ from each other in size. Thus, the cues enhanced the snack-seeking behaviour for the respective snacks to a similar degree. In the analyses of the raw sums of key presses for both snacks in non-cued trials, an effect of the videos on the key presses for the sugary snack emerged. When no Pavlovian cue was present, the devaluation group pressed the key associated with chocolate cookies significantly less often than the upvaluation group. Non-cued key presses for the sugar-free snack remained unaffected by the presented videos. This could be explained by the fact that only the consumption of sugary but not sugar-free snacks was addressed in the devaluation video. An upvaluation effect was only apparent in terms of higher response rates for the sugary compared to the sugar-free snack within the upvaluation group. In line with previous studies, the outcome-specific PIT effect (cued responses for both snacks) did not differ between the groups that watched the anti-sugar, pro-sugar, and control video. The PIT effects for both snacks were unrelated to hunger, BMI, and impulsivity. Trait food craving was negatively correlated with the PIT effect for rice wafers.

5.4 Influence of food cues on behaviour: Conclusion

In accordance with previous research (e.g., Verhoeven et al., 2018; P. Watson et al., 2014), the results of *Study IV* demonstrate how quickly a meaningless external stimulus can become a food cue. A small number of paired presentations is able to convert a black-and-white pattern into a food cue that has an actual impact on food-seeking behaviour. This impressively illustrates the important role of associative learning mechanisms in the context of food choices and eating behaviour.

In light of these findings, strategies to reduce unhealthy food choices triggered by food cues have become an urgent research issue. With *Study IV*, we took a new approach by investigating the influence of a video-based devaluation procedure on (cued) food-seeking behaviour in the PIT paradigm. Extending existing research, we also included an upvaluation procedure which was thought to operationalise the impact of food advertisements. However, in accordance with previous findings (see P. Watson et al., 2018), evidence for devaluation (and upvaluation) effects only occurred in non-cued trials. In cued trials, participants seemed to be helpless against the influence of the food cues. These findings suggest that external cues predictive of tasty food outcomes might also trump the effects of video-based health campaigns in everyday life. Future research is needed to find a way to reduce the impact of food cues on food-seeking behaviour. One promising approach might be the reduction of the predictive value of the cue rather than the motivational value of the outcome (Jeffs & Duka, 2017) or the reduction of the cue's motivational value (Jeffs & Duka, 2019).

6 Conclusion and outlook

For several millennia, food scarcity has been one of the major issues for human survival and unfortunately is still a life-threatening factor in many parts of the world. In stark contrast to this, the abundance and omnipresent availability of (cheap and unhealthy) food has become a threat to the populations of modern industrial countries. Around the globe, obesity has tripled during the last four decades and is known to be one of the most important risk factors for noncommunicable diseases (World Health Organization, 2021a).

In light of these developments, the influence of external food cues on food choices and eating behaviour has become a growing field of research. Cognitive psychology can make valuable contributions to this endeavour by transferring validated paradigms and concepts from basic research to the applied context of food-cue reactivity. Following this approach, 'classic' principles and methods of cognitive psychological research were applied to the investigation of food-cue reactivity in the studies that are integrated in the present thesis. Namely, the AB in the RSVP paradigm, motivational tendencies reflected in frontal cortical asymmetry, and S-O-R priming in the PIT paradigm have provided insight into cognitive and motivational aspects of food-cue reactivity.

6.1 Integration of findings

Taken together, the presented studies shed light onto cognitive and motivational processes of food-cue reactivity from different perspectives. First, the results of *Study I* have demonstrated prioritised processing of food cues at the expense of other information in situations of rare cognitive resources. *Study II* has revealed a possible explanation for this phenomenon in terms of ERP indices of early capture of attentional resources by task-irrelevant food cues. ERPs in *Study III* have further shown that sustained attention towards food cues is affected by the food's calorie content as well as by the situational context in which food choices are made. Moreover, transient frontal cortical asymmetry suggests an influence of the food's calorie content on neural correlates of motivational tendencies. Finally, the findings of *Study IV* have demonstrated the enhancing effect of food cues on food-seeking behaviour and the robustness of this effect against video-based manipulations of the food outcome's value.

6.1.1 Cognitive and motivational aspects of food-cue reactivity

The research conducted within the framework of this thesis was based on the assumption that cognition and motivation play an important role in food-cue reactivity. At the beginning of this thesis, it was postulated that food-cue reactivity goes beyond mere physiological responses elicited by food cues but involves a complex interplay of processes at the cognitive, motivational, and behavioural level. The question how the findings of the presented studies can be interpreted with regard to this postulation can best be answered by referring back to the theoretical framework of the EIT and IST.

EIT (Kavanagh et al., 2005) posits a cognitive, conscious component of food craving ('desire') in the form of intrusive thoughts and subsequent imagery (cognitive elaboration) which consumes working-memory resources. The observed effects of food cues on the AB and EIB in *Study I* and *II* are compatible with these predictions of the EIT. They have shown that food cues capture and absorb attentional resources at the expense of competing tasks (target identification in the RSVP task). In light of the EIT, this attentional bias towards food cues could be interpreted as an 'intrusion' at the attentional level which might be a precursor of intrusive thoughts and imagery and thereby ultimately result in the (cognitive) experience of craving. Moreover, we observed that higher-order attentional processing of food cues (reflected in P3b and LPP in *Study III*) differs depending on food properties and the situational context. This indicates that external as well as internal conditions influence the amount of cognitive resources that are devoted to food stimuli (see also Carbine et al., 2018). Presumably, these factors will subsequently also affect the intensity of intrusive thoughts in the same way. For instance, food stimuli that are processed intensively at the attentional level because of their rewarding value, their fit with individual food preferences, and fit or misfit with current dieting goals are more likely to elicit strong intrusive thoughts than food stimuli that are processed less intensively. Thus, mechanisms at the level of sustained attention might be seen as moderators between rapid and early attentional orienting towards food cues and the slower and later elicitation of intrusive thoughts (see Figure 2).

This assumption is also well in line with the IST (Robinson & Berridge, 1993). As postulated by the IST, the concept of 'wanting' implies the attribution of incentive salience which includes a prioritisation of 'wanted' foods in the allocation of attentional resources (Berridge & Robinson, 2016). Cue-triggered 'wanting' should further imply the urge to acquire the 'wanted' food. This means, approach tendencies should be elicited at the motivational level. Based on the theory of frontal cortical asymmetry (e.g., Harmon-Jones & Gable, 2018), motivational approach and avoidance tendencies are reflected in asymmetrical activity of the frontal cortex, as measured by FAA. In concert with these assumptions, *Study III* provided first indications of transient approach motivation in response to LC foods reflected in temporarily greater left-frontal activity that matched the LC food preference of the study sample and thereby might reflect approach tendencies towards 'wanted' food.

Furthermore, 'wanting' at the motivational level is assumed to be closely linked to associative learning in the context of reward (Berridge & Robinson, 2003). For instance, cues that have repeatedly been paired with food can trigger 'wanting' for the associated food reward as a consequence of Pavlovian S-O learning. Consequently, instrumental food-seeking behaviour can be initiated. This association can be measured in *conditioned incentive experiments* (Berridge & Robinson, 2003), also known as the PIT task. In this sense, cue-triggered 'wanting' was demonstrated in form of the outcome-specific PIT effect in *Study IV*. Black-and-white patterns that had been paired with either cookies or rice wafers in a Pavlovian training triggered the response associated with the respective food outcome that had been learned in an instrumental training. Importantly, the PIT effect emphasises that cognitive and motivational processes involved in 'wanting' or food craving are not only elicited by food itself or pictures of food but also by a priori meaningless cues (e.g., black-and-white patterns in *Study IV*) that have become predictors of food outcomes via Pavlovian conditioning.

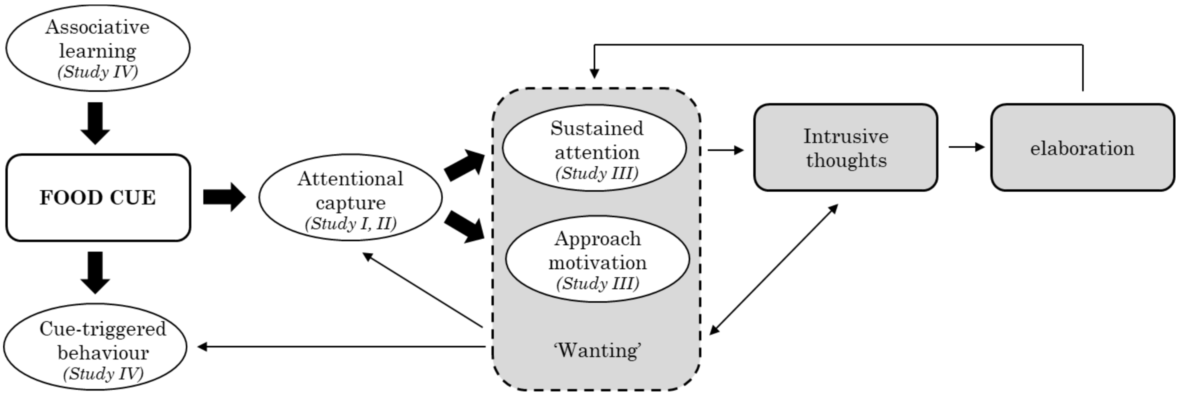

Figure 2. Model of cognitive and motivational aspects of food-cue reactivity based on the findings of *Study I-IV* embedded in the EIT and IST. Ellipses and thick arrows indicate concepts and associations that have been investigated in the *Studies I-IV*. Grey boxes represent components of EIT (solid frames) and IST (dashed frame). Thin arrows represent predicted relationships that have not been investigated in the *Studies I-IV*.

In sum, the *Studies I-IV* complement previous research (see, e.g., Carbine et al., 2018; Hagan et al., 2020; Hardman et al., 2020; Higgs, 2016) in emphasizing the role of attentional processes, motivational tendencies, and learning mechanisms in food-cue reactivity. Furthermore, the results are in accordance with the assumptions of the EIT and the IST. They also speak in favour of the initial assumption that food-cue reactivity is characterised by a dynamic interplay of cognitive and motivational processes (e.g., as postulated in Figure 2). However, more research is needed to support the assumed relationships between the single aspects of cognition and motivation in response to food cues and to identify further contributing factors and neural mechanisms of food-cue reactivity (see Chapter 6.4 on ideas for future research).

6.2 Implications

Besides their contribution to our understanding of food-cue reactivity, the results of the presented studies can be discussed in terms of their implications for everyday life and for intervention programs targeting overeating. In accordance with previous research, the results of *Study I* and *II* suggest a general attentional bias towards food cues at the expense of competing information in young, healthy, normal-weight participants. In times of food scarcity, the automatic attentional capture by food stimuli in the environment in a bottom-up way could have facilitated food seeking and eating (see Pineda & Leland, 2011). From an evolutionary perspective, the attentional bias towards food hence was advantageous for survival. Thus, the attentional bias towards food cues might be seen as a remnant of the hunter-gatherer culture. However, in modern, urban environments, the omnipresence of food cues makes the attentional bias towards food redundant. In combination with other factors, it might even be detrimental by fostering overeating and weight gain in obesogenic environments. Although there seems to be no direct relationship between the attentional bias towards food and overweight (Hagan et al., 2020; Hardman et al., 2020), sustained attention to HC food seems to be associated with external, emotional, and loss of control eating (Wolz et al., 2015).

Study III has provided insight into motivational processes involved in food-cue reactivity. First, the results demonstrate that (hypothetical) food choices are flexibly adjusted to situational circumstances. Based on the integration of contextual demands into food-cue processing (as indicated by ERP indices of sustained attention), participants modified the amount of HC and LC foods they chose to eat. Food choices in the baseline situation indicate a preference for LC foods (see Chapter 6.3 for a discussion).

In accordance with the effect at the behavioural level, temporarily stronger approach motivation was reflected in momentarily greater left-hemispheric frontal activity in response to LC foods independent of the situational context. However, due to the novelty of time-frequency analyses in this context, this finding should be treated with caution. A preliminary interpretation could be that more than situational demands or the rewarding value of food (in terms of calorie content), personal preferences influence whether specific foods elicit approach motivation. Consequently, individually preferred foods could be especially hard to resist.

Going beyond the effects on the cognitive and motivational level, food cues elicited an outcome-specific PIT effect at the behavioural level (see *Study IV* in accordance with previous research). This demonstrates that food cues can enhance actual food-seeking behaviour. Most importantly, this effect was observed after very short instrumental and Pavlovian learning phases (24 trials each). This shows how easily associative learning can turn previously unknown stimuli into food cues that are able to elicit cue-trigged food-seeking behaviour. Moreover, in *Study IV*, the PIT effect was robust against a video-based outcome devaluation procedure. In previous studies, satiety or written health warnings did not reduce cued food-seeking behaviour (Verhoeven et al., 2018; P. Watson et al., 2014). Thus, it can be speculated that cue-triggered eating behaviour in everyday life may be comparably robust against information-based intervention strategies. For instance, health education might not prevent the consumption of sugary snacks that is triggered by respective advertisements on social media, in magazines, on TV, and on billboards.

6.2.1 Implications for the treatment of overeating

Basic research on the cognitive and motivational aspects of food-cue reactivity serves the ultimate goal of furthering the development of effective cognitive trainings that could be applied in the treatment of eating disorders or in obesity intervention programs. Respective interventions targeting food craving and food intake can be broadly categorised into four groups: (1) cue-exposure treatments that are based on associative learning theory, (2) cognitive regulation strategies (e.g., reappraisal, acceptance, or imagination), (3) cognitive control techniques (attentional bias modification training, approach/avoidance training, inhibitory control training), and (4) bio- and neurofeedback trainings (see Wolz et al., 2020 for a meta-analysis). In a broad sense, the presented findings could be of relevance for attention bias modification (ABM) training, approach/avoidance training, and cue-exposure treatment.

ABM training is usually realised as a modified dot-probe task in which participants are trained to direct their attention away from food in general or from unhealthy food items in particular (Hardman et al., 2013; Smith et al., 2018; Zhang et al., 2018). Single ABM training sessions were able to reduce subsequent (HC) food intake in obese and HC food-craving samples (Smith et al., 2018; Zhang et al., 2018). A meta-analysis of four studies revealed a medium sized effect of ABM training in reducing unhealthy food intake in healthy samples (Turton et al., 2016). However, the long-term effectiveness of the intervention and their benefit in the context of eating disorders are still unclear (see, e.g., Stott et al., 2021). Based on our interpretation of the attentional bias towards food as a universal, evolutionary mechanism that manifests in early automatic attentional capture one might at least question the usefulness of unspecific single-session ABM training (see also Hardman et al., 2013).

For approach/avoidance training, a modified version of the AAT that requires avoidance responses (e.g., push movements) to target cues and approach responses (e.g., pull movements) to control cues is used. In that way, avoidance of unhealthy food can be practiced (e.g., Becker et al., 2015; Brockmeyer et al., 2015b). For instance, avoidance training of unhealthy food has shown positive effects in terms of reduced food intake, healthier food choices, and reduced craving (Becker et al., 2015; Brockmeyer et al., 2015b; Fishbach & Shah, 2006; Kakoschke et al., 2017a). In light of the assumption that approach and avoidance motivation in response to food cues are associated with asymmetrical activity of the prefrontal cortex as investigated in *Study III*, non-invasive brain stimulation might be a useful addition to approach/avoidance training. In fact, there is evidence of beneficial effects of transcranial direct current stimulation (tDCS) and repetitive transcranial magnetic stimulation of the dlPFC in the reduction of food craving (for reviews and meta-analytical evidence, see C. J. Lowe et al., 2017; Sauvaget et al., 2015). Although brain stimulation treatments have been developed largely independent from research on frontal asymmetry, there are interesting parallels between the approaches. For instance, in tDCS studies, anodal stimulation (causing excitation) of the right dlPFC in combination with cathodal stimulation (causing inhibition) of the left dlPFC reduced food craving (e.g., Fregni et al., 2008; Goldman et al., 2011). In contrast, anodal stimulation of the left dlPFC and cathodal stimulation of the right dlPFC improved eating disorder and depressive symptomatology in a pilot study of anorexia nervosa patients (Khedr et al., 2014). These observations are in accordance with the asymmetric inhibition model of frontal asymmetry (Grimshaw & Carmel, 2014) that postulates inhibition of withdrawal-related distractors by the left dlPFC and inhibition of approach-related distractors by the right dlPFC. However, for the moment, this association remains an interesting observation that could give rise to future developments. There is still need for further research on both the role of frontal cortical asymmetry in food-cue reactivity and the effects of non-invasive brain stimulation on craving and consumption behaviour.

Finally, food-cue exposure treatment can be seen as the clinical analogue of experimental extinction (van den Akker et al., 2018). By combining cue exposure with response prevention, learned associations between food cue and food intake are sought to be uncoupled. Thus, through the prevention of eating in response to food cues, the cues lose their predictive value (see Jansen, 1998). Repeated sessions of in-vivo cue exposure have been found to effectively reduce body weight, binge eating frequency, and snacking of exposed foods in overweight and obese females (Schyns et al., 2020). Compared to cognitive regulation (e.g., reappraisal, acceptance) and cognitive control (e.g., ABM, approach/avoidance training), in-sensu cue exposure (repeated imagined eating; see, e.g., Morewedge et al., 2010) was most effective in reducing food intake (Wolz et al., 2020). In most studies and first clinical applications, either real foods or the imagination of food was used for food-cue exposure treatments. As exposure effects do not transfer to non-exposed food items, clinically relevant effects can only be achieved by including as many relevant foods as possible in the treatment (van den Akker et al., 2018). Based on the outcome-specific PIT effect observed with newly learned food cues and its robustness against motivational outcome manipulation (see *Study IV*; Verhoeven et al., 2018; P. Watson et al., 2014), it seems important to also identify contextual food cues and include them into the exposure treatment to reduce cued overeating.

Finally, it should be noted that the abovementioned approaches targeting overeating in particular and the treatment of overweight/obesity in general all focus on the affected individual. However, the individual is not solely responsible for their overweight (e.g., Reidpath et al., 2002) and therefore cannot be made solely responsible for its treatment. The obesity pandemic is a public health problem that can only be solved by the joint effort of policy makers, society as a whole, and individual behavioural changes (Swinburn et al., 2011).

6.3 Limitations

Although the studies presented in this thesis were carefully planned and conducted, they include some shortcomings that should be kept in mind when interpreting the results. First, it has to be noted that in all studies, cognitive and motivational mechanisms in the context of food-cue reactivity were investigated by studying respective mechanisms in response to pictures of food. Even though convincing evidence speaks in favour of this “picture viewing approach” (Blechert, Meule, et al., 2014, p. 1), it can still only be an approximation of the confrontation with actual food. Most importantly, food pictures lack the sensory components of sound, touch, taste, and smell. Especially smell has a strong influence on appetite, food preferences, and food-seeking behaviour (see Fine & Riera, 2019; Shepherd, 2006). Obviously, in controlled laboratory experiments, the sensory modality of vision is much easier to investigate than the modalities of smell or taste. This has led to a strong focus on visually elicited food-cue reactivity in psychological research, which also applies to our studies. Previous research revealed that exposure to visual food cues had similar effects on eating behaviour and craving as exposure to real food and stronger effects than olfactory cues (Boswell & Kober, 2015). Thus, there is no reason to assume that cognitive and motivational mechanisms elicited by real food differ drastically from those elicited by visual food cues. However, it has to be noted that our findings are restricted to visually elicited cognitive and motivational processes in the context of food-cue reactivity.

Second, the artificiality of the laboratory setting in general requires consideration. We strived for high ecological validity by using authentic representations of food stimuli and everyday examples of situational contexts (*Study III*) and motivational manipulations (*Study IV*). At the same time, a high level of standardisation and objectivity was preserved in the computer-based experiments. Nevertheless, hypothetical food choices executed via key presses can only be seen as a rough approximation of food choices in the supermarket, the restaurant, or at home. Similarly, experimental tasks like the RSVP task (*Study I, II*) represent only a rough approximation of attentional processing of food in everyday life. Although, of course, this criticism can be put forward for almost all types of experimental psychological research, it is especially important to mention these limitations in the context of investigations in the applied context of food-cue reactivity. Nevertheless, basic research of this kind is important to understand the underlying mechanisms of attention and motivation in the context of food choices and eating and thereby can serve as a solid foundation for more applied research.

Finally, the generalizability of our results is clearly impaired by the specific characteristics of the studied samples. As mostly psychology students took part in the studies, our findings are restricted to a group of young, well-educated, mainly female adults with predominantly healthy body weight and lifestyle. The resulting lack of representativity and diversity of study samples is a known problem in psychological research in general which is oftentimes generously overlooked. However, in the context of research on eating behaviour it must be particularly emphasised. For instance, gender is known to be associated with choice of diet and nutritional knowledge. In a questionnaire study, more women than men indicated that they had tried low-fat or low-carb diets, that they acquired nutritional knowledge from different sources and that they wanted to lose weight (Davy et al., 2006). Moreover, an association between emotional eating and attention for food was only found in female but not in male participants (Hummel et al., 2018). Even at the neural level, gender differences were found. There is evidence of greater activation of brain circuits involved in behavioural control and self-referential cognition in women and greater activation of regions processing affective and appetitive value in men in response to pictures of HC (as compared to LC) foods (Killgore & Yurgelun-Todd, 2010). Besides gender, socioeconomic status plays an important role in eating behaviour. For instance, high socioeconomic status has been associated with healthy eating habits (Mullie et al., 2010). In light of these findings, sample characteristics are most likely (at least partly) responsible for the unexpected preference for LC food in *Study III*. Thus, although not representative of the broader population, young women are an interesting subpopulation for research on food-cue reactivity. Particularly with regard to eating disorder symptoms that are most prevalent among young women, basic research in this group is especially important (Galmiche et al., 2019).

6.3.1 Limitations regarding individual differences

Besides sociodemographic variables, individual traits and states are known to play an important role in food-cue reactivity. In our studies, we controlled for the influence of hunger (*Studies I-IV*) and included analyses of restrained, external, and emotional eating (*Studies I, II*) as well as food craving (*Studies III, IV*). To preclude influences of personal diet, we made sure to use mostly vegetarian/vegan food examples or to exclude vegetarians and vegans from participation whenever animal products were presented.

Hunger did not influence the effects in any of the studies. However, this cannot be interpreted as hunger being generally irrelevant for attentional and motivational food-cue processing or cued food seeking. In contrast, previous findings confirmed the intuitive expectation that hunger plays an important role in these contexts (Hardman et al., 2020; Piech et al., 2010; Stockburger et al., 2009). Rather than hunger being irrelevant, a generally low hunger level within our samples can explain the absence of effects.

Except for rather unsystematic single correlations, the observed effects were also unrelated to trait food craving and restrained, external, and emotional eating. However, these findings should be treated with caution as the limited variability in the very homogeneous samples could be responsible for the lack of findings. A lack of variability also made informative analyses of body weight unfeasible although respective data were collected in the form of BMI values. As a general note, it should be pointed out that all information about individual differences were obtained from self-reports. Therefore, limited construct validity of the questionnaires (see Chapter 2.3) could have biased the results. Moreover, self-reports in the context of eating habits might be especially prone to social desirability.

Going beyond the mentioned states and traits, other concepts that are also likely to affect food-cue reactivity have not been considered. For instance, food preferences, eating habits, and life-style apart from nutritional aspects are likely to play a role in cognitive and motivational reactions to specific food cues.

6.4 Ideas for future research

The studies presented within the framework of this thesis have revealed interesting findings that call for further investigations and give rise to new research questions. With respect to the attentional bias towards food, *Study I* and *II* show the usefulness of the RSVP paradigm for extending existing knowledge about spatial attention to the temporal dimension. In this context, *Study II* provides insight into the neural correlates of EIB elicited by task-irrelevant food cues. The first observations of the Distractor Negativity and the Early Food Positivity call for replication and extended investigation to enable a deeper understanding of the mechanisms behind the food-elicited EIB. Future studies should also include non-food emotional stimuli into the task design to compare ERPs of the food-elicited EIB with ERPs of the 'original' EIB elicited by highly arousing negative or positive non-food stimuli.

With the time-frequency analysis of FAA in *Study III,* we presented one of the first attempts to gain better insight into temporal dynamics of frontal cortical asymmetry in the context of approach and avoidance motivation for food. However, the exploratory nature of the approach makes replication studies indispensable to allow for firm conclusions. The imagined situational context for food choices implemented in *Study III* can be criticised as overly artificial and could have been a reason for the lack of effects. Therefore, an improved approach for future studies could be the use of a between-subjects design with participants that actually pursue different dieting goals.

The results of *Study IV* left behind the open question how food-seeking behaviour triggered by food cues could be reduced. As video-based manipulations of the outcome value and previous approaches using written health warning and satiation (Verhoeven et al., 2018; P. Watson et al., 2014) seemed to be mostly ineffective, future approaches could involve new techniques for the devaluation of the cue (see Jeffs & Duka, 2019). New findings in this area could also be useful for the continued improvement of the cue-exposure treatment of overeating.

Going beyond specific extensions of the presented studies, there is more need for research with respect to the relationship between elements of the EIT and elements of the IST in the context of food-cue reactivity. For instance (as outlined in figure 2), intrusive thoughts and elaboration are supposed to be mutually connected to 'wanting' (see also Berridge & Robinson, 2003) as supported by findings of intensified food craving after vivid food imagination (Harvey et al., 2005). As the two approaches have been developed independently from each other and focus on different aspects of (food) addiction, combining both perspectives could help to get a more holistic understanding of cognitive and motivational food-cue reactivity. In a next step, physiological mechanisms of food-cue reactivity measured by metabolic parameters should be included into the investigation of cognitive and motivational aspects in the course of interdisciplinary research (e.g., Vargas-Alvarez et al., 2022). Only a joint consideration of cognitive, motivational, and physiological mechanisms allows for a comprehensive understanding of food-cue reactivity.

Eventually, this kind of basic research in healthy populations should serve the overarching goal to be transferred to clinical populations of eating disorder patients. A profound understanding of healthy food-cue reactivity can help understand pathological deviations in the context of eating disorders and ultimately contribute to improved treatments.

6.5 Final conclusion

The presented studies contribute to the understanding of cognitive and motivational aspects of food-cue reactivity. Behavioural and electrophysiological findings provided insights into attentional processing of food cues, approach/avoidance tendencies in the context of food choices and the role of associative learning mechanisms in food-seeking behaviour. In light of rising numbers of overweight and obesity in obesogenic environments, this kind of basic research on food-cue processing is of great importance to provide a sound basis for the development of evidence-based countermeasures against overeating.

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