

Food on the Mind: The Influence of Stimulus Modality on Attentional and Inhibitory Control Processes in Aberrant Eating

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Abbreviations

<i>AB</i>	Attentional Bias
<i>ANOVA</i>	Analysis of Variance
<i>BED</i>	Binge Eating Disorder
<i>BMI</i>	Body-Mass Index
<i>dIPFC</i>	dorsolateral Prefrontal Cortex
<i>ED</i>	Eating Disorder
<i>EDA</i>	Electrodermal Activity
<i>EEG</i>	Electroencephalogram
<i>ERP</i>	Event-Related Potential
<i>EPN</i>	Early Posterior Negativity
<i>fMRI</i>	functional Magnetic Resonance Imaging
<i>fNIRS</i>	functional Near-Infrared Spectroscopy
<i>GLMM</i>	Generalized Linear Mixed Model
<i>LRT</i>	Likelihood-Ratio Test
<i>OFC</i>	Orbitofrontal Cortex
<i>PTSD</i>	Posttraumatic Stress Disorder
<i>RE</i>	Restrained Eater
<i>RIM</i>	Reflective-Impulsive Model
<i>RS</i>	Restraint Scale
<i>RSVP</i>	Rapid Serial Visual Presentation
<i>SSD</i>	Stop-Signal Delay
<i>SSRT</i>	Stop-Signal Reaction Time
<i>SST</i>	Stop-Signal Task
<i>URE</i>	Unrestrained Eater
<i>VAS</i>	Visual Analogue Scale

Zusammenfassung

Das Reflective Impulsive Model postuliert, dass Persönlichkeitsmerkmale und Zustandsfaktoren zu einer erhöhten Aufmerksamkeit auf und einer verringerten inhibitorischen Kontrolle bei Essensreizen führen, was zu Überessen beitragen kann. Es ist jedoch nicht bekannt, ob die Modalität in der Essen kognitiv repräsentiert wird zu dieser Art der Verarbeitung beiträgt. Um diese Lücke zu schließen, wurde in der vorliegenden Dissertation der Einfluss mentaler Repräsentationen von Nahrungsmitteln auf Überessen untersucht. Zu diesem Zweck untersuchten wir die essens- und modalitätsabhängige Aufmerksamkeitsverarbeitung und inhibitorische Kontrolle in einer Stichprobe von fastenden Personen und einer Stichprobe von restriktiven Essern (RE).

In einer ersten Studie zeigten elektrophysiologische Daten aus einer Rapid Serial Visual Presentation Aufgabe eine erhöhte Aufmerksamkeit auf Essensbilder relativ zu Nicht-Essensbildern, während die Aufmerksamkeit auf (Nicht-)Essenswörter gleich war. Unsere Verhaltensdaten zeigten jedoch, dass RE eine geringere Aufmerksamkeitsverzerrung gegenüber Essensbildern aufwies als URE. Dies könnte darauf hinweisen, dass RE eine verbesserte inhibitorische Kontrolle bezüglich Essensbildern besitzen.

In einer zweiten Studie zeigten wir, dass fastende Personen in einer Stoppsignalaufgabe eine ähnlich stark ausgeprägte inhibitorische Kontrolle bei Essenswörtern und -bildern aufwies, während sie eine geringere inhibitorische Kontrolle bei Nicht-Essensbildern als bei -wörtern hatten. Darüber hinaus fanden wir bei einer Reanalyse dieser Studie heraus, dass RE eine geringere inhibitorische Kontrolle bei Nicht-Essensbildern als bei -wörtern aufwies, während sie eine bessere inhibitorische Kontrolle bei Essensbildern als bei Essenswörtern zeigten.

Zusammengefasst sind Essenswörter entgegen der Erwartung mit einer geringeren inhibitorischen Kontrolle assoziiert, und zeigten RE eine bessere inhibitorische Kontrolle gegenüber Essensbildern. Wir nehmen daher an, dass Essenswörter und Essensbilder in einer ähnlichen Modalität mental repräsentiert werden. Darüber hinaus vermuten wir, dass Valenz und Diätziele die Repräsentation von (Nicht-)Essensreizen durch Annäherungs- und Vermeidungstendenzen beeinflussen könnten.

Summary

The Reflective Impulsive Model poses that trait and state factors can predispose individuals to increased attentional and decreased inhibitory processing of food cues, which can lead to overeating. It is unknown, however, whether the way that food is mentally represented contributes to this form of food cue processing. To fill this gap, the current dissertation aimed to uncover the contribution of mental representations of food to overeating. To this end, we investigated food- and modality-dependent attentional processing and inhibitory control in a sample of fasted individuals and a sample of restrained eaters (RE).

In the first study, electrophysiological data from a rapid serial visual presentation task indicated more motivated attention towards food pictures than non-food pictures, whereas attention was the same towards food and (non-)food words. Our behavioral data, however, indicated that RE had a smaller attentional bias towards food pictures than URE.

In the second study, results indicated that fasted individuals have similar inhibitory control for food words and pictures, whereas they had worse inhibitory control for non-food pictures than words on a stop signal task. Additionally, in a reanalysis of this study, we found that RE have worse inhibitory control for non-food pictures than words, while they had better inhibitory control for food pictures than food words.

Taken together, food words were unexpectedly associated with lower levels of inhibitory control, while RE had better inhibitory control to food pictures than food words. We therefore postulate that food words are represented in a similar modality as food pictures. Moreover, in RE we theorize that valence and dieting goals may mediate the representation of (non-)food cues through approach and avoidance motivational orientations.

List of publications

a) Accepted publications

van den Hoek Ostende, M. M., Gawrilow, C., Kaup, B., & Svaldi, J. (2026). Less distracted, more restrained: Attentional differences on the Rapid Serial Visual Presentation task in restrained eaters to food words and pictures. *Appetite*, 217, 108356 <https://doi.org/10.1016/j.appet.2025.108356>

van den Hoek Ostende, M. M., Schwarz, U., Gawrilow, C., Kaup, B., & Svaldi, J. (2024a). Modality Matters: Fasted Individuals Inhibit Food Stimuli Better Than Neutral Stimuli for Words, but Not for Pictures. *Nutrients*, 16(14), e2190. <https://doi.org/10.3390/nu16142190>

van den Hoek Ostende, M. M., Schwarz, U., Gawrilow, C., Kaup, B., & Svaldi, J. (2024b). Practice makes perfect: Restrained eaters' heightened control for food images. *European Eating Disorders Review*, 32(1), 90-98. <https://doi.org/10.1002/erv.3023>

Personal contribution statement

DFG funding for the current studies was acquired by Prof. Dr. Jennifer Svaldi and Prof. Dr. Caterina Gawrilow within project B2 of the research unit FOR 2718 on modal and amodal cognition. The original ideas of the current studies were conceived by Prof. Dr. Jennifer Svaldi. Formal conceptualization and alteration of the study protocols to accommodate for altered participant recruitment during the SARS-CoV-2 pandemic was completed by Prof. Dr. Jennifer Svaldi and Mechteld van den Hoek Ostende under consultation of Prof. Dr. Barbara Kaup. Development and testing of study materials (i.e., task paradigms) was completed by Mechteld van den Hoek Ostende under supervision of Prof. Dr. Jennifer Svaldi. Data collection and analyses were completed by Mechteld van den Hoek Ostende under supervision of Prof. Dr. Jennifer Svaldi. The studies contained in the current dissertation were completed at the University of Tübingen. Mechteld van den Hoek Ostende wrote the original drafts and revisions of the manuscripts in collaboration with Prof. Dr. Jennifer Svaldi. All authors contributed to the interpretation and revision of the manuscripts.

Introduction

Food Environment and Obesity

The social infrastructure provided by western societies is thought to contribute to the overconsumption of (unhealthy) food (Nicolaidis, 2019). In part, this is due to exposure to high-calorie foods, which increases food intake (Norman et al., 2016) by eliciting non-homeostatic eating (i.e., eating in the absence of hunger) as opposed to homeostatic eating (i.e., eating to replenish energy deficits; Olszewski et al., 2019). This non-homeostatic eating can lead to an energy surplus, which contributes to the development of overweight and obesity.

Worldwide, rates of overweight and obesity have been rising for the past decades (Ng et al., 2014; Wang et al., 2020). In Germany, over 50% of adults are overweight or obese (Schienkiewitz et al., 2017). Overweight and obesity are associated with an increased risk for mental health problems (Kasen et al., 2008; Sarma et al., 2021), as well as an increased risk for type 2 diabetes, cardiovascular disease and certain types of cancer (Hruby et al., 2016). This translates to increased mortality risk and loss of healthy life-years compared to normal weight peers (Grover et al., 2015) and is associated with rising healthcare and unemployment costs (Effertz et al., 2016). Understanding how the modern food-environment contributes to overeating is therefore of critical importance.

Aberrant Eating

There are several approaches to understand the influence of environmental cues on overweight and obesity. First, individuals with overweight can be compared directly with individuals with normal weight (e.g., Bongers et al., 2015; Castellanos et al., 2009; Prickett et al., 2015). This provides insight into fundamental processes that are altered between those who have become overweight and those who stayed lean. Although this approach demonstrates adaptations that are present after weight gain - and could therefore contribute to the maintenance of overweight and obesity - it does not allow conclusions on whether these factors were predisposing or if they developed alongside the weight gain. Other approaches are thus required to identify the (environmental) factors that contribute to the *development* of overweight and obesity.

One approach involves at-risk populations. A trait that has been associated with non-homeostatic eating and weight gain is restrained eating (Adams et al., 2019; Herman & Mack, 1975). Restrained eating, as measured by the restraint scale (RS; Herman & Polivy, 1980) is characterized by repeated attempts to control food intake through dietary restraint, which are interspersed with repeated bouts of overeating (Herman & Mack, 1975). These two phases follow a cycle in which the attempts at dietary restraint reflect a strategy to reduce the impact of previous phases of overeating (Snoek et al., 2008; van Strien et al., 2007). In the long term, the overeating phases are reflected in a higher body-mass index (BMI) and increased food cravings in individuals who attempt to restrain their food intake (i.e., restrained eaters [RE]) compared to those who do not (i.e., unrestrained eaters [URE]; Adams et al., 2019). Given that RE are thus at risk of developing overweight and obesity, identifying alterations in food cue processing in RE can provide indications of potential predisposing factors of weight gain.

A third possible approach to investigate factors contributing to overweight and obesity involves the comparison of individuals in fasted and satiated states. Similar to overweight and obesity (Wolz et al., 2015), fasting is associated with increased vigilance for food cues (Siep et al., 2009; Stice et al., 2013). It creates an altered motivational state that is associated with increased processing of food reward in the mesolimbic reward circuit (Ferrario et al., 2016). Activation in this circuit is also associated with non-homeostatic eating (Berthoud, 2006; Ferrario et al., 2016; Liu & Kanoski, 2018). Moreover, this circuit is altered in individuals with overweight and obesity (e.g., Castellanos et al., 2009; Kroemer et al., 2016). One study showed that, while normal weight individuals show increased attentional engagement with food cues when they are fasted, overweight and obese individuals have similarly increased attentional engagement with food cues regardless of homeostatic state (Castellanos et al., 2009). Therefore, adaptations taking place to promote food approach behavior when it is adaptive (i.e., in a fasted state) can provide a proxy for the processes that contribute to non-homeostatic eating when satiated in those with overweight and those prone to weight gain.

Considering these different avenues to better understand overeating, the current dissertation compares RE and URE with the aim of identifying cognitive adaptations that could contribute to the development overweight and obesity. Additionally, the current dissertation compares fasted and satiated participants to

investigate whether food cue processing is altered as a function of changes in homeostatic state as a proxy for altered processes in overweight and obesity.

Dual-Process Models of Weight Gain

The Impulsive System

Dual-process models (e.g., Kahneman, 2011; Strack & Deutsch, 2004) provide a comprehensive theory of the manifestation of overeating in these different populations. The Reflective-Impulsive Model (RIM; Strack & Deutsch, 2004) assumes that overeating occurs when the balance between two systems is disturbed. The first system, the *impulsive* system, reacts to actional input from the environment by activating relating concepts and corresponding behavioral schemata. When seeing a cupcake, for instance, previously learned associations, such as *buttery*, and *sweet*, are automatically activated, along with the appropriate behavioral schemata (e.g., approaching the cupcake, peeling away the cupcake liner, taking a large bite). In this example, if the impulsive system is too active, the activation of these related concepts is thought to induce craving, which contributes to overeating. Empirical evidence indeed provides support for increased impulsive processing in individuals with aberrant eating, as they demonstrate increased cognitive processing of the hedonic features of food (e.g., Stojek et al., 2018; Wolz et al., 2015), which is associated with overeating (Hardman et al., 2021; Stojek et al., 2018; Wolz et al., 2015).

One focus for research on the impulsive system has been automatic orientation towards salient food stimuli in individuals prone to overeating and fasted individuals (Strack & Deutsch, 2004). Typically, this has been studied by the measurement of attention allocation during the presentation of competing food and non-food stimuli (Wolz et al., 2015), with an increased attention towards food relative to non-food stimuli being denoted as an attentional bias (AB). In line with the RIM, studies indeed find an AB in populations prone to overeating. For instance, individuals with binge eating disorder (BED), who regularly eat objectively large amounts of food without compensatory measures (American Psychiatric Association, 2013), are quicker at recognizing food words compared to non-food words when they are slowly revealed (Schmitz et al., 2014). Similarly, adolescents with BED recognize food pictures in a matrix of non-food pictures quicker compared to weight and age

matched controls (Schmidt et al., 2016). A systematic review of AB in individuals with binge eating also found a robust food-oriented AB in behavioral measures (e.g., reaction times), as well as electrophysiology and eye-tracking (Stojek et al., 2018).

Contrarily, compared to URE and individuals with normal weight, RE and individuals with overweight and obesity do not consistently demonstrate a food-oriented AB in behavioral measures (Hagan et al., 2020; Hardman et al., 2021; Watson & Le Pelley, 2021), although electrophysiology and neural imaging suggest alterations in early attentional processing in individuals with obesity relative to individuals with normal weight (Hagan et al., 2020; Hendrikse et al., 2015). Additional environmental and state factors therefore likely contribute to alterations in attentional processing (Field et al., 2016). With regard to homeostasis, for instance, studies have shown that food-oriented AB is associated with hunger and craving (Hardman et al., 2021). This demonstrates that, when food carries a higher salience through an internal homeostatic or cognitive state, food cues may receive more attentional resources than non-food cues.

Thus, as suggested by the RIM, trait and state factors influence attentional processes towards food cues. Improving our understanding of the effect these factors have on food cue processing can help us better understand the environmental input that drives overeating.

The reflective system

In addition to the contributions of the impulsive system on aberrant eating, the RIM poses that there is a second system in place; the *reflective* system receives the processed information from the impulsive system and adds on abstract information (Strack & Deutsch, 2004). This includes personal goals that pertain to the represented object. Following the previous example, upon encountering a cupcake, the reflective system may activate personal dieting goals. If the reflective system notices that the activated behavioral schemata from the impulsive system are not in line with these goals, it can use cognitive control to modify behavior (Strack & Deutsch, 2004). This is in line with the view of cognitive control as a top-down process that is employed to interfere with ongoing responses (Friedman & Robbins, 2022). However, since this process inherently follows the activation of behavioral schemata in the impulsive system, interference is not always successful, especially if cognitive control is weakened. In these cases, the model predicts that food intake is

initiated despite pre-existing dieting goals, which then could result in overeating and subsequent weight gain.

Notably, cognitive control encompasses a range of executive functions (Diamond, 2013). One focus of research on control over food intake has been *inhibitory control*. Generally, inhibitory control is a cognitive tool used to regulate behavioral, cognitive and attentional processes that do not align with higher order goals (Diamond, 2013). This can be, for instance, in the form of inhibiting approach behavior towards appetizing food cues, suppressing cognitions that drive food intake, or by actively directing attention away from food cues. When the reflective system is (temporarily) weakened, a failure to inhibit food-related behaviors and cognitions may ensue, which could lead to overeating. Indeed, in line with the predictions of the RIM, research has shown that low indices of inhibitory control are associated with increased food intake (Byrne et al., 2021; Levitan et al., 2015).

Furthermore, the RIM predicts that inhibitory control should be weakened in individuals who regularly overeat (e.g., RE, individuals with obesity, individuals with BED) and individuals for whom food has relevance due to homeostatic state (e.g., fasted individuals). In accordance with this prediction, research has repeatedly demonstrated differences in inhibitory control between individuals with and without aberrant eating. For instance, hungry individuals have lowered inhibitory control compared to satiated individuals (He et al., 2019; Labonté et al., 2024; Loeber et al., 2013). Furthermore, in patients with bulimic-type eating disorders (i.e., eating disorders characterized by repeated binge eating episodes) one meta-analysis demonstrated that inhibitory control was lowered for generic stimuli and disease-specific stimuli (i.e., food and body shape; Wu et al., 2014). In patients with bulimia nervosa and BED, neurophysiological evidence indicates that lower behavioral indices of inhibitory control are associated with reduced activation in brain regions that regulate inhibitory control (Berner et al., 2023; Lavagnino et al., 2016; Skunde et al., 2016). Individuals with obesity similarly show lower inhibitory control in behavioral (e.g., Houben et al., 2014; Lavagnino et al., 2016; Nederkoorn et al., 2012) and neurophysiological measures (e.g., Alatorre-Cruz et al., 2021; Chen et al., 2018; Lavagnino et al., 2016). Behavioral inhibitory control deficits in adolescents were additionally associated with increased BMI and waist circumference at one year follow-up (Mayer et al., 2022), indicating that lowered inhibitory control could pose a risk-factor for weight gain. In line with this, weight-gain prone RE reliably demonstrate

decreased inhibitory control (Dong et al., 2014; Jansen et al., 2009; Nederkoorn et al., 2004; Schroeder et al., 2022), although evidence for the food-specificity of this effect is contradictory (Bartholdy, Dalton, et al., 2016; Houben et al., 2012; Watson & Le Pelley, 2021).

Thus, deficits in inhibitory control have been demonstrated in individuals with eating disorders, aberrant eating, obesity and in individuals in a food deprived state. In line with the RIM, this index of a weakened reflective system could allow for impulsive eating and subsequent weight gain. Similar to attentional processing, developing a better understanding of the conditions under which inhibitory control is weakened is therefore essential to understand how the (food) environment contributes to overeating.

Dual-process models: research gap

Taken together, research yields evidence for the relevance of the impulsive and reflective system with regard to the maintenance of aberrant eating. While the impulsive system drives behavior towards food, the reflective system compares whether these impulses align with abstract goals. From a theoretical perspective (Strack & Deutsch, 2004), a conflict occurs when the behavioral impulses from the impulsive system do not align with the goals of the reflective system. The behavioral outcome of this conflict depends on the balance between the effectiveness of inhibitory control and the extent to which the automatic motivational response is activated.

Strack and Deutsch (2004) suggest that overeating results from a dual impairment; if the activation in the impulsive system is too strong, and the activation in the reflective system is simultaneously weak, this should lead to increased appetitive behavior towards food cues. Conceptually, this discrepancy can be elicited by state factors, such as hunger, or by lasting changes to the impulsive and reflective system, such as in RE or individuals with overweight and obesity.

Notably, although studies have found that AB and inhibitory control deficits are associated with aberrant eating, few studies have examined whether these deficits are associated with the mental representation of food stimuli. This, however, is of pivotal importance as exposure to a wide range of food-related environmental cues is thought to contribute significantly to the increasing prevalence of overweight and obesity (Norman et al., 2016). Moreover, altered mental representations could help

understand why certain individuals are more prone to weight gain under these environmental circumstances (Haines et al., 2007).

Indeed, evidence of individually altered cue representation has been observed in other domains of abnormal psychology. In schizophrenia, for instance, patients with formal thought disorder demonstrate difficulties in representing abstract concepts (Barrera et al., 2005), while sensory hallucinations can be considered aberrant sensory experiences (Behrendt & Young, 2004). Additionally, the “thinking in pictures” theory in autism spectrum disorder postulates that it is easier for individuals with autism to process sensory than abstract representations (e.g., Bókkon et al., 2013; Kunda & Goel, 2011). For instance, one neuroimaging study used an embedded figure task to determine neural correlates of a visual processing task (Manjaly et al., 2007). In this task, participants had to indicate whether a simple figure was contained in a subpart of a more complex figure. Adolescents with autism spectrum disorders demonstrated stronger recruitment of posterior visual areas associated with (visual) sensory processing, whereas the adolescents in the control group demonstrated more parietal activation associated with global, abstract processing of the paradigm cues. As behavioral performance was the same across groups, the authors conclude that different types of representations were used to solve the same problem.

These observations are in line with theories of cognition that assume that mental representations can be altered based on current task requirements. For instance, construal level theory (Trope & Liberman, 2003) and theories on hierarchical control (Badre & Nee, 2018) pose that different degrees of abstraction are used to represent and operate on environmental information in a way that corresponds to current task demands. In our previous example, adolescents with autism spectrum disorder used more sensory representations to solve the problem at hand compared to the control group that used more abstract representations (Manjaly et al., 2007).

Extending theories of mental representation to food intake, the RIM also proposes that the impulsive and reflective systems operate on different types of information (Strack & Deutsch, 2004). The impulsive system relies on actionable objects (e.g., a pen, an apple) to activate relevant sensory concepts and behavioral schemata (e.g., writing, biting). Returning to our previous example of eating a cupcake, initiation of approach behavior towards a cupcake is activated alongside

implicit sensory expectations, such as that a cupcake will taste sugary, which, in turn, is accompanied by salivation.

The reflective system, on the other hand, relies on the activation of abstract goals and values that are associated with the object in question. In the example of the cupcake these are existing dieting- and health-goals. Since these two systems are thought to operate on different types of information, the way (high-calorie) food cues are represented may bias towards one way of processing over another. It is therefore plausible that mental representations that are preferentially sensory and *modal* – as opposed to abstract and *amodal* – in nature are associated with increased impulsive processing and decreased reflective processing. Returning to the predictions of the RIM, this would mirror the type of imbalance between impulsive and reflective processing that is theorized to contribute to aberrant eating. However, this influence of mental representations on food intake remains largely unexplored.

Mental Representations of Food

To understand how mental representations can affect food cue processing and food intake, the current dissertation makes use of a theoretical framework of modal and amodal cognition. Generally, modal representations consist of sensory information (e.g., integrated visual, olfactory, and gustatory information of a cupcake). Amodal representations consist of abstract information, such as features (e.g., a cupcake is round) and activation of related beliefs and concepts (e.g., a cupcake is unhealthy). Therefore, the current dissertation assumes that the *modal* representation of an object bears resemblance to the concepts that are processed in the impulsive system, while its *amodal* representation bears resemblance to the concepts activated in the reflective system.

Furthermore, the current dissertation assumes that the modality in which objects are presented correlates with different mental representations (see e.g., Paivio, 1978). Research has shown that the presentation of modal cues (e.g., pictures) or the focus on modal aspects of food primarily brings on sensory mental representations that are associated with impulsive processes (Nakamura et al., 2020; Pohl et al., 2017). The presentation of amodal cues (e.g., words), additionally activates abstract semantic networks that are more aligned with reflective processing (Kuchinke et al., 2005; Pohl et al., 2017; Schlochtermeyer et al., 2013). In line with the

RIM, we therefore expect modal cues to facilitate impulsive processing, while we expect amodal cues to facilitate reflective processing.

Related to the evidence in support of the RIM in the context of overeating as outlined above (sections *The Impulsive System* and *The Reflective System*), *impulsively processed* modal representations should therefore result in increased AB and lower inhibitory control compared to *reflectively processed* amodal cues. Moreover, in line with this prediction, it could be expected that individuals with food representations that emphasize modal features demonstrate more aberrant eating. However, it remains largely unexplored whether food cue representations vary depending on individual characteristics (e.g., restrained eating), and whether these representations subsequently influence aberrant eating.

To date, two studies have tested modality-specific effects on food cue processing in a general population. To do so, both studies used photorealistic pictures as modal stimuli and written information (food words, health information) as amodal stimuli. In the first study, AB was measured towards high- compared to low-calorie food for *words* and *pictures* in a dot probe task (Freijy et al., 2014). Participants were shown two task-irrelevant stimuli and were asked to react to a probe that subsequently replaced one of the pictures as quickly as possible. The AB towards food cues was operationalized as lowered reaction times when the probe was preceded by a high-calorie stimulus, and increased reaction times when the probe was preceded by a low-calorie stimulus. The study found a bias towards high-calorie food *pictures*, but away from high-calorie food *words*. This was, however, unrelated to RE, BMI and hunger in subsequent exploratory analyses.

A second study presented either two modal (pictures) or two amodal (health information sentences) stimuli simultaneously, from which participants had to choose which one they would rather eat (Kruse et al., 2024). In line with the view that amodal presentation aligns with the activation of health goals, participants chose the healthy option more frequently in the amodal (*verbal*) condition than in the modal (*picture*) condition. Moreover, when choosing unhealthy options, a larger conflict as evidenced by increased mid-frontal theta power in concurrently measured electroencephalography (EEG) could be observed in the modal compared to the amodal condition. Thus, this study yielded evidence for an increased conflict between the impulsive and reflective system during the processing of modal (*picture*) relative to amodal (*verbal*) stimuli. However, this study precludes us from concluding

whether mental representations are altered in aberrant eating. Therefore, further direct comparisons of modal and amodal cues are required that pinpoint whether these representations contribute to aberrant eating.

Mental representations of food: the impulsive system

Regarding impulsive processing, further indications for the relevance of mental representations in the realm of aberrant eating come from the result heterogeneity across studies. For example, in the context of attentional processing of food cues, there is a wide range of methods and cues that has been used to estimate food-directed AB (Nijs & Franken, 2012). Some paradigms, such as the modified Stroop task (Nijs et al., 2010), rely heavily on linguistic processing. In the modified Stroop task, participants need to read out the color of food words. If the food word meaning interferes with the color naming, the latency of naming the color of the text increases, which indicates an AB for food words (Dobson & Dozois, 2004). Tasks like the visual dot-probe task, on the other hand, typically employ task-irrelevant picture pairs that are replaced by a task-relevant probe to which the participant has to react (e.g., Castellanos et al., 2009; Freijy et al., 2014). If participants react more quickly to a probe placed over a food picture compared to a non-food picture, this indicates a food-directed AB. However, the processing of words and pictures takes different pathways, leading to reduced comparability between such fundamentally different paradigms (e.g., Paivio, 1978; Polivy & Herman, 2017).

Moreover, paradigms used to evaluate AB have tested different aspects of attention, which require a variety of cognitive demands from both bottom-up and top-down attentional processing. For instance, the visual dot-probe task measures *spatial* attention allocation, as it relies on bottom-up priming of spatial information of the (food) cue. Disengaging from the food cue may require top-down resources that target subsequent aspects of attention. Notably, paradigms that rely on similar spatial cuing are associated with smaller AB effects (Pool et al., 2016). In line with this, although exposure to food cues has been shown to increase food intake in RE (Polivy & Herman, 2017), the presence of a food related AB has been inconsistent across studies (Watson & Le Pelley, 2021). It has therefore been suggested that paradigms that target the *temporal* aspects of attention are better suited for detecting early bottom-up influenced AB, where the AB effect is more pronounced (Pool et al., 2016).

Temporal aspects of attention have typically been assessed by the Rapid Serial Visual Presentation (RSVP) paradigm. In this paradigm, identifying a first target stimulus in a sequence of rapid visual stimuli leads to an impairment in identifying a second target. This phenomenon refers to the *attentional blink* (Anderson, 2005; Most et al., 2005; Most et al., 2007; Raymond et al., 1995). Notably, the time frame for the attentional blink to occur can vary in dependence of the salience of the stimulus that elicits the attentional blink (Anderson, 2005; Most et al., 2005; Most et al., 2007).

In the RSVP, stimuli are presented in streams that consist of two stimuli of interest (a target and a distractor) and filler stimuli. Each stimulus has a presentation time of below 150 ms. In the stream, targets are preceded by distractors. Studies have shown that food cues can function as task-irrelevant distractors (i.e., without additional visual indicator) and can impair target identification if they precede the target by 200 – 500 ms (e.g., Ballestero-Arnau et al., 2021; Kirsten et al., 2019; Kirsten et al., 2023). In line with the rationale of the attentional blink, high salience of this distractor (i.e., food cues) should lead to reduced attentional resources and therefore reduced identification of the target stimulus (Most et al., 2005; Most et al., 2007). In other words, the RSVP measures the degree to which a stimulus can capture attention at the cost of subsequent information.

Based on the assumption from the RIM that aberrant eating is associated with increased impulsive processing, individuals with aberrant eating are expected to exhibit a larger attentional blink response to food cue distractors than individuals without aberrant eating behavior. Consistently, Neimeijer et al. (2013) found evidence of an AB for task-irrelevant food picture distractors in RE, but not in URE. However, to date the effect of stimulus modality on the salience of food as assessed by the RSVP has yet to be unexplored. Specifically, it is unclear whether amodal stimuli (i.e., food words) can elicit a larger attentional blink in RE than in URE. Therefore, the influence of food-cue modality on the early aspect of AB targeted by the RSVP should be investigated further.

Mental representations of food: the reflective system

Beyond the heterogeneity introduced in the AB literature due to various task demands, research on inhibitory control has similarly produced heterogeneous results. In part, a source of heterogeneity is the variation in stimulus types and stimulus

modality used across studies. Although no studies have systematically tested the effect of modality on inhibitory control, the synthesis of existing studies indicates a possible role of mental representations on inhibitory control in the context of aberrant eating.

To illustrate, studies that tested inhibitory control under fasted conditions have used a range of (control) stimuli, often with Go/No-Go tasks. In this task, participants typically react in response to one stimulus category (e.g., animals) appearing on the screen, while withholding the response for other categories (e.g., food). By varying the categories to which participants have to react and withhold responses, inhibitory control can be estimated based on reaction times and the errors made on both Go- and No-Go-trials (Donders, 1969). If food is used as a category, food-specific inhibitory control can be measured.

Using the Go/No-Go task to test food-specific inhibitory control to food *words*, for instance, Loeber et al. (2013) demonstrated that self-reported hunger negatively impacts inhibition for *amodal* (word) food distractors compared to neutral (word) distractors. Considering the RIM, this would speak in favor of increased impulsive and decreased reflective processing of amodal food cues under fasted conditions. Similar results have been found for food pictures; in one study, fasted participants made more commission errors (i.e., errors on No-Go-trials) when they had to consistently inhibit their reaction to food pictures (Howard et al., 2020). In line with these results, a functional Magnetic Resonance Imaging (fMRI) study replicated decreased inhibitory control for high-calorie food pictures in fasted individuals (He et al., 2019). This decreased performance was demonstrated through increased energy demands in the dorsolateral prefrontal cortex (dlPFC) in No-Go trials, indicating that inhibiting reactions to food images was more difficult when fasted. In context of the RIM, this thus speaks in favor of a weakened reflective system. Conversely, a recent study using functional Near-Infrared Spectroscopy (fNIRS) found no interaction between satiation and inhibitory control for food compared to valenced-matched non-food pictures (Labonté et al., 2024). Furthermore, a study using food and non-food pictures in a stop-signal task (SST; Logan, 1994) could also not replicate these results (Bartholdy, Cheng, et al., 2016). Despite general support for food-specific inhibitory deficits in a fasted state for both modal and amodal cues, further studies are thus required to directly compare food cue modalities and to validate previous study results.

As a second example, studies have taken two approaches to characterize inhibitory control deficits in RE. On the one hand, studies have used abstract, *amodal* cues (letters, 2D geometric shapes) to measure inhibitory control independent from food cues (e.g., Dong et al., 2014; Jansen et al., 2009; Nederkoorn et al., 2004). On the other, food-specificity of the effect has been tested using concrete, *modal* stimuli (i.e., food and non-food pictures; e.g., Ganor-Moscovitz et al., 2018; Houben & Jansen, 2014; Schroeder et al., 2022). To gain a continuous measure of inhibitory control, these studies regularly use the SST. In short, in the SST, participants perform a simple assignment in response to a stimulus, such as a button press (i.e., “go” response). On about 25% of trials a stop-signal (e.g., visual stimulus) follows the go signal in close temporal proximity. This set-up creates a “race” between the already initiated go-response and the inhibitory command initiated by the stop-signal. If inhibition has been initiated too late, the go-response is executed, whereas a timely initiated response leads to successful inhibition (Logan, 1994; Verbruggen et al., 2019). According to the *horse race model*, good inhibition is therefore characterized by a quick stopping response (Logan & Cowan, 1984); if the stop-signal is presented late into the ongoing go-response, but inhibition is still successful, this demonstrates good inhibitory capacity. To operationalize this, the stop-signal reaction time (SSRT) is defined as the time from stop-signal until the hypothetical go-response, which is calculated using the stop-signal delay (SSD; difference between stimulus and stop-signal onset) and the average reaction time on go-trials (Verbruggen et al., 2019). Lower values of the SSRT thus indicate higher inhibitory control.

With regard to the processing of amodal, non-food cues, one systematic review of studies using the SST found a reliable relationship between restrained eating and decreased inhibitory control (i.e., with letters and geometric shapes as cues; Bartholdy, Dalton, et al., 2016). Extending these findings, one neural imaging study using fMRI demonstrated increased attentional processing to go-cues as evidenced by increased activation in the orbitofrontal cortex (OFC) and other regions related to the motivational network (Dong et al., 2014). Furthermore, this study found that dlPFC activation following stop-cues was inversely correlated with the SSRT in RE, confirming that decreased inhibitory control processes contribute to lower inhibitory performance on the SST.

For amodal, non-food cues, the literature thus indicates that RE have lowered inhibitory control. In line with the RIM, we would expect food cues to elicit increased

impulsive and decrease reflective capabilities in this group. Therefore, we would expect especially concrete, modal food cues (e.g., food pictures) to elicit lower inhibitory control (i.e., longer SSRTs) compared to abstract cues. Indeed, there is support for this view; one study found indices of decreased inhibitory control specifically to food cues in individuals with overweight and obesity compared to normal weight controls (Houben et al., 2014). Further evidence of control over modal food cues comes from an EEG study, which indicated that RE required more cognitive resources to successfully inhibit their reaction to food cues compared to URE (Zhou et al., 2018). However, direct comparisons of abstract cues and modal food cues have not been made. Moreover, inhibitory control to abstract *food* cues remains unexplored. Therefore, a direct comparison of the effects of modal (e.g., picture) with amodal (e.g., word) food stimuli on inhibitory control is required to shed light on how food representations influence inhibitory control in aberrant eating.

Objectives and Expected Outcomes

In sum, dual-process models predict that increased processing of food stimuli by the impulsive system on the one hand and decreased inhibitory capacity in the reflective system on the other contribute to overeating and weight gain. Critically, the impulsive system operates on modal information, while the reflective system operates on amodal information. This allows for the general hypothesis that modal food cues, compared to amodal and non-food cues, elicit strong responses that express themselves in AB and weakened inhibitory control. Yet, there have been few direct comparisons of the influence of stimulus type on these processes. Therefore, the current dissertation aims to directly compare the effects of modal (picture) and amodal (word) food cues on (food-specific) AB and inhibitory control in fasted compared to satiated individuals and RE compared to URE. The specific aims of this work are threefold.

Study 1 focused on the influence of modality on mental representations in the impulsive system. Specifically, here we investigated the influence of food and non-food picture and word distractors on attentional processing of a subsequent target in an RSVP. The sample consisted of RE and URE, determined by the highest and lowest tertiles of restraint scores on the RS. Since RE are vulnerable to weight gain

and binge eating (Andrés & Saldaña, 2014; Kirkley et al., 1988), this set-up allows us to make inferences on whether altered mental representations could contribute to this vulnerability. It was expected that RE would correctly identify fewer targets than URE following food-pictures only. Performance was hypothesized to be similar for non-food picture, and (non-)food word distractors. To additionally map temporal aspects of attention, measurements took place with concurrent EEG. Specifically, the processing of salient stimuli (i.e., food-cues) has consistently been associated with two event related potentials (ERPs). First, the early posterior negativity (EPN) is a negative potential peaking around 200 – 300 ms which reflects stimulus salience (Junghöfer et al., 2001; Schupp et al., 2006). A previous study on anorexia nervosa demonstrated higher amplitudes in their EPN to food pictures, reflecting increased automatic attentional processing (Blechert et al., 2011). Second, the P300 is a centro-parietal positive potential peaking at around 300 to 450 ms after stimulus onset, which is enhanced for salient stimuli (Kanske et al., 2013) and reflects allocated attentional resources (Kranzloch et al., 2007). Food pictures can generally elicit an enhanced P300 (Carbine et al., 2018), and aberrant eating behavior may increase P300 amplitude (Blechert, Goltsche, et al., 2014; Hofmann et al., 2015; Nijs et al., 2009). In line with the behavioral predictions, it was thus expected that RE compared to URE demonstrated larger EPN and P300 following food-picture distractors. Again, the EPN and P300 were hypothesized to be similar for non-food picture, and (non-)food word distractors.

Study 2 focused on the relevance of mental representations within the reflective system. In this study, normal weight individuals in a fasted relative to satiated homeostatic state were tested as a mechanistic proxy for overeating. As previously stated, food deprivation instigates reward-processes that overlap with those activated in non-homeostatic eating in normal weight individuals (Ferrario et al., 2016). Determining altered cognitive processing in fasted compared to satiated individuals can thus provide insights in altered processing in non-homeostatic eating. Therefore, Study 2 tested the effect of food- and non-food cues of different modalities (pictures, words) on inhibitory control in an SST. Concretely, it was expected that fasted, but not satiated participants have lower inhibitory control (as indexed by longer SSRTs) specifically for modal (picture) food cues compared to non-food cues. Since amodal (word) food cues are more abstract and therefore hypothesized to be

preferentially processed by the reflective system, no differences between amodal food and non-food cues were expected.

Study 3 focused on the relevance of mental representations in food-related inhibitory control in a re-analysis of Study 2. Analog to Study 1, we targeted RE (compared to URE) to target a vulnerability for overweight and obesity and binge-eating disorder (Andrés & Saldaña, 2014; Kirkley et al., 1988). To this end, the original sample was divided in RE and URE according to their score on the RS. Participants scoring in the highest tertile were categorized as RE while those scoring in the lowest tertile were categorized as URE. It was expected that RE compared to URE had lowered inhibitory control (i.e., longer SSRTs) in the food-picture condition, but not in the non-food picture condition. Again, no differences in SSRT were expected in the amodal condition, regardless of stimulus type or group.

Combined, the current dissertation expands on previous research by exploring the importance of cue modality in two processes essential to regulation of food intake: attentional processing and inhibitory control. Hereby, it further delineates automatic and cognitive factors that predispose individuals to overeating. Finally, through direct comparisons of different modalities, this dissertation provides indications which food cues may especially contribute to the obesogenic environment and overeating.

Summary of methods and results

Study 1

Title: “Less distracted, more restrained: Electrophysiological attentional differences on the rapid serial visual presentation task in restrained eaters to Food Words and Pictures” (van den Hoek Ostende et al., 2026)

Methods

Participants. Participants were recruited in and around the University of Tübingen. All participants had to be between 18 and 69 years old, have a BMI > 17.5 and understand German at a native level. Exclusion criteria were vegan nutrition, (uncorrected) bad eyesight, color blindness, current pregnancy, lactation, medication that can influence reaction latencies, inability to consume a standardized lunch (e.g. due to food intolerances) and self-reported lifetime eating disorder.

An a-priori power analysis in Superpower (Lakens & Caldwell, 2021) using means and standard deviations from a food-specific RSVP with distractor-target trials used by Neimeijer et al. (2013) indicated that we required 120 participants for a power of $(1 - \beta) = .80$, if we use an $\alpha = .05$. To account for data loss, we aimed to additionally recruit 24 participants. Participants were divided in RE and URE by their RS scores. Participants within the upper tertile of RS scores on the screening questionnaire (range: 13–27) were put in the RE group, while those in the lower tertile (range: 0–8) were put in the URE group. A total of 144 participants completed the study (71 RE, 73 URE), with EEG data of sufficient quality available for 130 participants (62 RE, 68 URE). RE and URE did not differ in gender distribution ($\chi^2[2] = 0.46, p = .793$), hunger at the time of completing the experiment ($t[142] = 0.51, p = .610$) or age ($t[136] = 0.17, p = .866$; based on available data of 138 participants, RE: $n = 67$, URE: $n = 71$). However, in line with the literature (Adams et al., 2019), RE had a higher BMI compared to URE ($t[142] = 4.99, p < .001$).

Restraint Scale. The RS (Herman & Polivy, 1980) has 10 items with a possible total score ranging from 0–35. Five of these items assess weight fluctuations, while the other five measure cognitive attempts at restriction of food intake. The RS has good construct validity for normal-weight participants (Bohrer et al., 2015; van Strien

et al., 2007). In the current sample, we found a good internal consistency with Cronbach's alpha $\alpha = .88$.

Procedure. To participate in the study, prospective participants filled out an online screening questionnaire. If all criteria were met, and participants had a score in either the highest (RE) or lowest (URE) tertile of the RS (Herman & Polivy, 1980), participants were invited to the laboratory for the experiment. Participants refrained from consuming caloric beverages, food or caffeine in the three hours prior to the session. Participants were instructed not to consume alcohol 24 hours prior to participating and to sleep at least 6 hours in the night before participation. Women in their reproductive years were invited during their luteal phase (i.e., the week before menses), which was determined through the calendar method (Sohda et al., 2017).

At the beginning of the experimental session, participants gave informed consent and consumed a standardized light lunch (rice meal, 320 kcal) within 15 minutes. After lunch, participants were weighed, and had their height measured. Subsequently, they completed an unrelated experiment (ca. 20 minutes). Finally, the participants were prepared for the RSVP with concurrent EEG in a soundproofed room with dim lighting. Once the EEG set-up was prepared, participants filled out a series of visual analogue scales (VAS) to determine hunger levels. They then completed the RSVP, after which they repeated the VAS questions. Including EEG preparation, the RSVP took about an hour in total. Finally, participants were informed on the purposes of the experiment and remunerated 35€ or 3 course credits.

Material. The RSVP consisted of four blocks, each containing 72 trials. Each block was equally divided between trials containing exclusively modal stimuli (pictures) and trials containing exclusively amodal stimuli (words). Blocks were separated by 60 second breaks. A trial comprised a stream of stimuli, which were presented for 118 ms without inter stimulus interval. After a variable number of neutral filler stimuli (three, five or seven), the streams always included a distractor, which was either a food or a non-food stimulus (animal). The distractor was followed by another neutral filler stimulus, after which the target (an animal stimulus) was presented. The target was indicated through a blue frame. Four neutral stimuli followed the target at the end of every stream to maintain equal distance between the target and participants' answers (Neimeijer et al., 2013). After each stream,

participants were asked to type the target word (that described the image) they identified. Participants' answers were compared to correct answers, allowing for spelling mistakes. To ensure correct identification, all answers were additionally visually inspected in a blinded manner for group membership.

Our stimulus set for modal and amodal stimuli was constructed in a similar manner. Each consisted of three stimulus categories: 88 neutral filler stimuli, 36 food stimuli and 108 animal stimuli (36 distracters and 72 targets). Pictures were matched in valence and complexity, and words were matched for length and frequency (*Leipzig Corpora Collection*, German news corpus 2020). Pictures were 550 × 550 pixels, while words were presented in Arial with black letters. Font size was varied to match the width (550 pixels) of the images.

Data Processing. The EEG signal was recorded with with BrainVision Recorder 1.20 (Brain Products GmbH, Gliching, Germany) on an actiCHamp amplifier (Brain Products GmbH, Gliching, Germany) with 60 Ag/AgCl active electrodes (actiCAP slim electrodes), distributed in accordance with the 10-20 system. The Cz electrode was selected as online reference and the ground electrode was placed at AFz, using a sampling rate of 500 Hz and an online filter between 0.1 Hz and 100 Hz (Wolz et al., 2021). We placed two active electrodes on the outer canthi and one under the left eye to monitor for and later correct ocular artifacts (Gratton et al., 1983). We kept impedances below 20 k Ω .

We used BrainVision Analyzer 2.1 (Brain Products GmbH, Gliching, Germany) to process the acquired data. First, we re-sampled the data to 256 Hz and used the average recorded reference to re-reference the data. We used a low pass cut-off of 30 Hz to filter out lower frequencies. In a next step, we manually removed noise and movement artifacts. Eye movements were removed through an ocular correction independent component analysis. To ensure no artifacts remained, an automatic inspection of the data and removal of artifacts (maximal allowed voltage step 50 μ V/ms, maximal allowed difference of values in 200 ms intervals: 200 μ V, lowest allowed activity in 100 ms intervals: <0.5 μ V) was run. Data were segmented in segments starting 250 ms before distractor onset and until 1000 ms after distractor onset.

To determine the EPN and P300, each participant's individual signals were aligned to a 200 ms pre-stimulus onset baseline for each electrode and condition.

This yielded four average signals per electrode per person (food picture, food word, animal picture, animal word). We then took an average for each of these conditions over the cluster of electrodes used to determine the EPN and over the cluster of electrodes used to determine the P300. Visual inspection indicated that modal stimuli elicited an EPN at a medial occipital parietal cluster (PO4, PO3, POz, P3, P1, Pz, P2, P4, O1, O2, Oz; Blechert et al., 2011; Kirsten et al., 2023) while amodal stimuli elicited the EPN at bilateral parietal clusters (P5, P7, PO7, P6, P8, PO8; Fabi & Leuthold, 2018; Schupp et al., 2006; Scott et al., 2009). Therefore, we averaged the signal between 200 ms and 300 ms after onset over these modality-dependent clusters to determine the EPN. For the P300 we averaged data between 250 ms and 400 ms over central parietal electrodes (CP1, CP2, CPz, Cz, P1, P2, P3, P4, Pz). For both the EPN and P300, we removed systematic periodic effects of the RSVP by taking the difference between food and non-food images for each modality, giving us food specific differences per modality.

We analyzed the behavioral data with a generalized linear mixed model (GLMM) with random intercepts for participants (Bates et al., 2015). Likelihood-ratio tests (LRTs) were used to test the predictive value of Group (RE, URE), Modality (picture, word), Stimulus type (food, non-food), and all their interactions. For the EEG data, we used a 2 (Group: RE, URE) \times 2 (Modality: picture, word) mixed model analysis of variance (ANOVA) with the food-animal difference scores for EPN and P300 as outcome variable. The alpha level for all statistical analyses was set to $\alpha = .05$.

Results

RSVP performance. We did not find a three-way interaction between Group, Modality and Stimulus type. Rather, we found a two-way interaction between Group and Stimulus type ($\chi^2[1] = 8.41, p = .004$). Against our hypotheses, RE were more accurate in identifying targets after food compared to animal distractors ($t[140] = -2.43, p = .017$), while URE had similar accuracy for both distractor types ($t[144] = -1.97, p = .051$). We also found a significant Modality \times Stimulus Type interaction ($\chi^2[1] = 9.20, p = .002$). Participants provided more accurate responses for food items compared to animals in the picture condition ($t[286] = -3.18, p = .002$), whereas there was no significant difference in the word condition ($t[286] = -1.95, p = .052$).

Exploratory analyses indicated that this effect was significant in the RE group ($\chi^2[1] = 7.82, p = .005$), but not in the URE group ($\chi^2[1] = 2.68, p = .101$).

Electrophysiology. We found no significant main or interaction effects for the EPN (all F s < 3.61, p s > .060). However, we found a main effect of Modality for the P300, indicating larger differences between food and animal distractors for the picture condition compared to the word condition ($F[1,128] = 6.24, p = .014, \eta_p^2 = .046$).

Study 2

Title: “Modality matters: Fasted individuals inhibit food stimuli better than neutral stimuli for words, but not for pictures” (van den Hoek Ostende et al., 2024a)

Methods

Participants. We recruited participants through the online recruitment platform Prolific (www.prolific.co). Potential participants filled out a pre-study screening questionnaire, which checked in- and exclusion criteria. Individuals indicating that they had an exclusive vegan nutrition, bad (uncorrected) eyesight, were pregnant or lactating, or were unable to fast due to physical or mental health restrictions were excluded from participation. Furthermore, participants had to have a BMI between 18.5 and 25 kg/m², be between 18 years and 30 years old and speak English natively. At the end of the pre-screening questionnaire, participants that fulfilled all criteria were randomly assigned the fasting or satiated condition. Participants in the fasting condition were asked to fast for 16h overnight before completing the experimental part of the study. Participants in the satiated condition were asked to complete the experimental part of the study after eating lunch as usual. Groups did not differ in gender ($\chi^2[1] = 1.59, p = .207$), age ($t[141] = -1.05, p = .296$) or BMI ($t[141] = 0.97, p = .336$). Fasted and satiated individuals differed in self-reported hunger, with fasted individuals being more hungry than satiated individuals ($t[141] = 18.3, p < .001$).

Based on a pilot study we required 159 participants per group for a power of $(1 - \beta) = .90, \alpha = .05$, making the target sample size 318. Due to unexpectedly high drop-outs due to non-adherence to the fasting condition ($n = 122$) and task performance ($n = 102$), our final sample consisted of only $n = 67$ participants in the

fasting and $n = 76$ participants in the satiated condition, reducing our power to $(1 - \beta) = .55$.

Procedure. First, prospective participants filled out a screening questionnaire for the in- and exclusion criteria over SoSci Survey (Leiner, 2019). Those who fulfilled all criteria were randomized to either the fasted or satiated condition and given a personalized link to participate in the online experiment later that week.

The experimental session (ca. 50 min) comprised state VAS to determine hunger levels, questionnaires to characterize eating behavior and depressive symptoms, and finally an SST to determine inhibitory control. The SST included 16 practice trials, using a random subset of modal and amodal stimuli. Finally, participants indicated the last time they ate to reinforce exclusion based on eating/fasting adherence.

Stop-signal task. We programmed the SST in jsPsych (de Leeuw, 2015), basing it on the STOP-IT paradigm (Verbruggen et al., 2019). The SST comprised eight blocks of 128 each. Blocks contained either pictures (modal condition) or words (amodal condition) and were counterbalanced to account for cross-modal activation. The modality of the starting block was randomized. Within modality, 16 food and 16 non-food (animal) stimuli were shown to the participants. As in Study 1, pictures were complexity matched (Mayer, 2022), while words were matched in length and word frequency using the Corpus of Contemporary American English (Davies, 2010). Between blocks, participants were given 15 second breaks. During breaks, participants were given feedback on their performance in the previous block.

In each trial, a stimulus appeared to the left or to the right of a fixation cross. It was the task of the participants to indicate the location of the stimulus by pressing the “x” or “m” key, and to withhold their response if a stop-signal (in the form of a blue frame around the stimulus) was presented. The stop signal was presented in 25% of trials (Verbruggen et al., 2019). Stimuli were presented for 1250 ms or until the participant made a response. On stop-trials, the stop-signal appeared after the variable SSD, which was originally set to 200 ms. To ensure performance at around 50% as is required to compute the SSRT (Verbruggen et al., 2019), the SSD was decreased by 50 ms if participants failed to inhibit their response (i.e., making the task easier), while it was increased by 50 ms if participants correctly inhibited their

response (i.e., making the task more difficult). The SSD was set independently for each combination of modality and stimulus type (picture-food, picture-non-food, word-food, word-non-food).

Data processing and analysis. Our outcome variable, the SSRT, was calculated for each stimulus-modality combination using the integration method with replacement of response omission (Verbruggen et al., 2019). To test whether food cues are differently processed in dependence of modality and homeostatic state, we used a 2 (Group: fasted vs. satiated) \times 2 (Modality: picture vs. word) \times 2 (Stimulus type: food vs. non-food) ANOVA.

Results

Results: Our mixed ANOVA demonstrated a significant Group (fasted vs. satiated) \times Modality (picture vs. word) \times Stimulus type (food vs. non-food) interaction ($F[1,141] = 5.29, p = .023, \eta_p^2 = .036$). Follow-up 2 (Modality: picture vs. word) \times 2 (Stimulus type: food vs. non-food) repeated measures ANOVAs indicated that modality and stimulus type did not influence the SSRT of satiated individuals. For fasted individuals, however, there was an interaction of Modality and Stimulus Type ($F[1,66] = 8.20, p = .006, \eta_p^2 = .11$) and a main effect of Modality ($F[1,66] = 5.21, p = .026, \eta_p^2 = .07$). Subsequent t -tests revealed that the fasted group had better inhibitory control for non-food words than non-food pictures, as was evident in a lower SSRT ($t[66] = 10.25, p = .002$). There was no difference in SSRT in the food condition ($t[66] = 0.177, p = .675$), nor were there differences between stimulus types within the modal or amodal condition (all t s $< 3.00, p$ s $> .088$).

Study 3

Title: “Practice makes perfect: Restrained eaters' heightened control for food images” (van den Hoek Ostende et al., 2024b)

Methods

Participants. Study 3 was a reanalysis of Study 2. In this reanalysis we used the RS (Herman & Polivy, 1980) to divide participants in accordance with the grouping criteria of Study 1, i.e., in URE and RE by taking the lower and upper thirds of RS scores respectively. In the current sample, we found a good internal

consistency of the RS with Cronbach's alpha $\alpha = .80$. To split the sample, we included all participants that fasted for at least 12 hours or ate within the hour before starting the SST ($N = 203$). After division into groups, the sample consisted of $n = 81$ URE (RS score range: 0-8) and $n = 74$ RE (RS score range: 15-26). RE and URE were comparable in age ($t[153] = 1.33, p = .186$) and self-reported hunger level ($t[153] = -0.64, p = .526$). However, the gender distribution in both groups differed ($\chi^2[1] = 6.09, p = .016$). Specifically, the RE group comprised of proportionately more females than the URE group.

Data processing and analysis. The SSRT for each condition was calculated according to the integration method with replacement of response omission (Verbruggen et al., 2019). To determine effects on inhibitory control, we used a 2 (Group: RE vs. URE) \times 2 (Modality: picture vs. word) \times 2 (Stimulus type: food vs. non-food) mixed model ANOVA. Since admittance to the final sample depended on fasting instruction adherence, which is not of importance to the current analysis, we repeated the analysis with the full sample that fulfilled all SST requirements, but not the (loosened) fasting instructions.

Results

We found a significant Group \times Modality \times Stimulus type interaction ($F[1,153] = 4.95, p = .028, \eta_p^2 = .031$). Follow-up analyses showed that in RE there was an interaction between Modality and Stimulus type ($F[1,73] = 4.43, p = .039, \eta_p^2 = .057$) in the absence of main effects. Follow-up analyses did not indicate any significant differences between conditions (all t s $< 2.10, p$ s $> .15$). In line with our hypotheses, there were no interaction or main effects of Modality and Stimulus type in the URE group (all F s $< 1.43, p$ s $> .24$).

Furthermore, follow-up 2 (Group) \times 2 (Stimulus type) mixed ANOVAs conducted for each modality indicated an interaction between Group and Stimulus type for pictures ($F[1,153] = 4.55, p = .034, \eta_p^2 = .029$), but not for words (all F s $< 0.60, p$ s $> .44$). Again, follow-up t -tests did not reveal differences between individual conditions (all t s $< 2.85, p$ s $> .10$). Results remained the same when the analyses controlled for group assignment or gender distribution.

Including all participants with valid SST data (RE: $n = 94$, URE: $n = 97$) yielded similar results with regard to the three-way interaction (Group \times Modality \times Stimulus

type interaction: $F[1,189] = 4.43$, $p = .037$, $\eta_p^2 = .023$) and the two-way interaction for Modality and Stimulus type within RE ($F[1,93] = 4.53$, $p = .036$, $\eta_p^2 = .046$). The two-way interaction within the picture modality could not be replicated in the extended sample.

Discussion

Summary

The rising prevalence of overweight and obesity negatively impacts the overall health of affected individuals (Hruby et al., 2016) and puts a financial burden on healthcare systems (Effertz et al., 2016; Grover et al., 2015). The RIM (Strack & Deutsch, 2004) postulates that the development of overweight and obesity is associated with a dual impairment. On the one hand, the *impulsive* system, which operates on environmental input by activating appropriate behavioral schemata, may respond more strongly to food cues in individuals prone to non-homeostatic eating. This should, for example, be evident in an AB toward food cues (Hagan et al., 2020; Polivy & Herman, 2017; Stojek et al., 2018). On the other hand, the RIM assumes that a second system, the *reflective* system, is weakened. This system monitors if the actions that are activated by the impulsive system are compatible with existing higher order goals, for example dieting goals. Incompatible actions can subsequently be inhibited using cognitive control. A weakened reflective system should therefore be evident in reduced inhibitory control toward food cues (Bartholdy, Dalton, et al., 2016; Lavagnino et al., 2016).

According to the RIM, the two systems activate different types of representations that align with their operation goals. The impulsive system operates on sensory objects in the environment, activating related behavioral schemata (e.g., peeling away cupcake liner), whereas the reflective system activates higher-order goals related to the object (e.g., dieting goals). The mental representations of food therefore range from concrete, sensorimotor or “modal” in the impulsive system to abstract, symbolic or “amodal” in the reflective system. Theories in other areas of psychology make a similar distinction (Binder & Desai, 2011; Dove, 2009; Kiefer & Pulvermüller, 2012; Zwaan, 2014) and assume that these representations differentially affect cognitive processing (e.g., Kaup et al., 2024). Nevertheless, few studies have investigated how mental representations of food cues influence impulsive and reflective processing. Therefore, the current dissertation aimed to compare the effects of modal (picture) and amodal (word) food cues on reflective and impulsive processing in aberrant eating.

Notably, for the presented aim we surmised that the modality in which stimuli are presented largely corresponds to the respective representational modality. That

is, we assume that modal food stimuli (e.g., photorealistic images) correspond to modal representations (e.g., activation of sensory experiences such as *sweet*). Amodal food stimuli on the other hand (e.g., food words) correspond more closely to amodal representations (e.g., a cupcake is round and calorie dense). Based on this assumption, we hypothesized that modal food cues activate the impulsive system in individuals to whom food cues are particularly salient. Specifically, this pertains to both individuals in a fasted homeostatic state (i.e., hungry participants) and individuals with an aberrant eating behavior such as in RE. In accordance with the RIM, these conditions should lead to increased attentional processes and decreased inhibitory control to modal food stimuli. We did not expect food-specific effects on attentional or inhibitory control processes for amodal food in comparison to amodal non-food cues, as we theorized that amodal food cues activate abstract food-related goals (e.g., dietary goals) which could allow for increased reflective processing. Therefore, similar inhibitory control as to non-food cues was expected. In addition, we did not expect differences for modal compared to amodal non-food stimuli.

We addressed these hypotheses in three studies. In Study 1, we aimed to investigate how food and non-food picture and word distractors affect attentional processing of RE compared to URE. To answer this question, participants completed an RSVP with concurrent EEG. Contrary to our hypotheses, we found that RE had *better* (instead of the assumed decreased) target identification accuracy for targets preceded by food compared to non-food distractors. URE, on the other hand, had similar accuracy for targets preceded by food and non-food distractors. Note that exploratory analyses indicated that this effect was driven by modal food stimuli. These results thus suggest that food stimuli, especially when presented modally, elicited a *smaller* attentional blink and were therefore *less* salient than animal stimuli to RE than URE (Anderson, 2005; Most et al., 2007).

Paradoxically, at the electrophysiological level, we found a significant higher food-specific P300 in the picture compared to the word condition. In general, the P300 reflects attention allocation to salient stimuli (Olofsson et al., 2008; Polich & Criado, 2006). In line with our hypotheses, this finding suggest that modal food cues were *more* attention grabbing than amodal food cues relative to modal and amodal non-food cues, respectively. Although generally distractor P300 correlates negatively with identification accuracy (McArthur et al., 1999), a previous study using food distractors did not find the same correlation (Kirsten et al., 2023). Similarly, our study

did not find evidence for a correlation between task performance and P300. The electrophysiological findings thus demonstrate that, compared to the amodal condition, the modal condition elicited greater attention allocation to food cues than to non-food cues. Taken together, Study 1 suggests that, although in line with our expectations modal food cues generally elicit a greater attentional orientation than amodal food cues, RE may inhibit this activation more effectively. Indeed, the ability to inhibit distractors may be a predictor of target identification accuracy (Dux & Marois, 2008) and could therefore offer a potential explanation why RE had relatively higher accuracy rates after (modal) food distractors than URE *despite* increased attentional allocation towards these cues.

In Study 2, our aim was to investigate the effect of homeostatic regulation on modality- and food cue-dependent inhibitory control by manipulating levels of hunger. In the fasted group, participants were asked to abstain from food intake for 16 hours, while the satiated group was instructed to have lunch as regular before completing the experiment. To measure inhibitory control, we used an SST with task-irrelevant food and non-food pictures as well as food and non-food words. We found that fasted individuals had better inhibitory control for amodal non-food compared to modal non-food stimuli, whereas their inhibitory capacity for modal and amodal food cues was comparable. Note that satiated individuals demonstrated the same level of inhibitory control across stimulus type. Thus, against our hypotheses, the findings of Study 2 indicate that under food deprivation cues that are not state relevant (i.e., animals) allow for better inhibitory control in amodal than modal conditions, whereas inhibitory control is similar for state relevant (i.e., food) cues across modalities.

Finally, in Study 3 we performed a reanalysis of the data from Study 2 to investigate whether RE exhibit a modality-specific inhibitory control deficit for food compared to non-food cues. Participants were assigned to RE and URE groups using the criteria from Study 1. We found that food and non-food cues differentially affected RE based on modality. Contrary to our hypotheses, modal food cues were more easily inhibited compared to modal non-food cues, while this relationship was reversed for amodal cues. As expected, there was no influence of modality or stimulus type on inhibitory control in URE. These findings were independent of assignment to the hungry or satiated group.

Taken together, the studies presented here suggest that amodal food cues are salient to individuals prone to aberrant eating behavior such as RE. Specifically, in RE, i.e., individuals who cognitively counteract physiological hunger signals (and are thus considered non-homeostatic eaters), amodal food cues are less effectively inhibited than modal food cues. Contrarily, in healthy fasted individuals (i.e., individuals who follow homeostatic signals), inhibitory processing for modal and amodal food cues are similar, whereas processing of non-food cues differs depending on modality. Thus, the results indicate altered food cue processing based on modality.

The findings partly contrast our original hypotheses, which stated that we expected amodal food cues to be easier to inhibit and to elicit less attentional processing. Although electrophysiological findings from Study 1 support increased attentional processing of modal compared to amodal food cues, we observed a reduced inhibitory control over amodal food cues in fasted individuals and RE, as well as evidence of better inhibitory control in RE than in URE. Therefore, an extension of the theoretical framework used to derive our hypotheses is necessary to improve our understanding of how mental representations of food cues influence fasted individuals and RE.

Processing Amodal Food Cues: Embodiment

One avenue to synthesize the results of the current dissertation with the RIM (Strack & Deutsch, 2004) is by incorporating ideas from the embodiment framework (Glenberg, 2010) in our theoretical assumptions of how amodal food cues are processed.

Based on the RIM, we originally assumed that impulsive and reflective systems operate on distinct representation types: concrete, sensorimotor, *modal* representations and abstract, symbolic or *amodal* representations. Moreover, we assumed that these representations largely correspond to the modality in which stimuli are presented and that they differentially affect cognitive processing. Regarding amodal food cues, we therefore posed that these cues would activate abstract food-related goals (e.g., dietary goals) which should allow for better inhibitory control. Contrary to this prediction, we found that food items are associated with lower inhibitory control than non-food items in both fasted individuals (Study 2) and RE (Study 3).

An embodied view of cognition (e.g., Glenberg, 2010) offers a potential explanation of why amodal food cues did not allow for better cognitive control compared to modal and non-food conditions. Pertaining to the current studies, the embodied view of cognition would assume that abstract cues (e.g., the word CUPCAKE) are given meaning through the activation of sensory and motor systems that are activated when interacting with the actual object (e.g., activation in the gustatory cortex, behavioral schemata associated with eating). Although it is debated whether this framework can account for processing of abstract concepts with no physical counterpart in the real world (e.g., Dove, 2016), neurophysiological evidence suggests that words describing concrete objects elicit similar activation to the objects themselves (Kiefer & Pulvermüller, 2012). For instance, González et al. (2006) displayed odor-related words (e.g., CINNAMON) and non-odor-related words to participants in an fMRI setting. They found that odor-related words activated the olfactory cortex, whereas the non-odor related words did not. Moreover, another study used fMRI to directly compare how viewing pictures of valenced objects and the words naming those objects influenced affective processing (Schlochtermeyer et al., 2013). They found that emotional information processing was similar for valenced pictures and words, supporting the view that words elicit similar processing to the objects they represent.

In light of the current dissertation, our amodal food cues could similarly have predominantly activated gustatory and hedonic features. In terms of the RIM, this would correspond to increased impulsive processing. Under these conditions, the RIM would predict that amodal food cues should activate the impulsive system more strongly and therefore be more difficult to inhibit than amodal non-food cues in individuals with RE and fasted individuals. Consistent with this view, we found relatively lower inhibitory control for amodal food cues than amodal non-food cues in fasted individuals (Study 2) and RE (Study 3). Further in support of this view, Papiés et al. (2017) demonstrated that RE, but not URE, activate hedonic concepts when reading food-related sentences. Another study demonstrated that being subjected to a list of written food cues can increase food cravings (Oakes & Slotterback, 2000). Moreover, Loeber et al. (2013) demonstrated that hunger was associated with higher SSRTs (i.e., lower inhibitory control) to food words in an SST, mirroring the direction of our findings on food compared to non-food words.

Adopting the RIM and an embodied framework of cognition, the current findings and existing literature therefore support the view that, in fasted individuals and RE, amodal food cues are associated with lower inhibitory control than non-food cues. To strengthen this theory, future studies are required to establish how amodal food cues influence craving and food intake. Moreover, studies may focus on how food representations can be altered to prospectively reduce reactivity to environmental food cues, as this could aid in the development of strategies to reduce overeating in a food-cue-rich environment.

Valence as a Determinant of Inhibitory Control

Although embodiment theory could explain the relative lower indices of inhibitory control to amodal food cues, it does not offer a framework on why non-food words were more easily inhibited than non-food pictures (Study 2 and 3), whereas this pattern was different for food words and pictures.

One possibility is that the current findings were mediated by stimulus valence. Generally, (high-calorie) food stimuli are positively valenced (Blechert, Meule, et al., 2014). Thus, in order to isolate the food-specific contribution to altered inhibitory control, control stimuli should be matched on valence (Labonté & Nielsen, 2023). This is especially important as cue valence was shown to affect inhibitory control. As such, in a study by Verbruggen and De Houwer (2007) participants completed an SST with positive, negative and neutral stimuli. They found that, relative to neutral stimuli, those of positive or negative valence were associated with longer SSRTs on the SST. Notably, this effect was largely modulated by arousal. The current dissertation used a pre-study survey to select food and non-food stimuli of similar valence and arousal. However, hunger was not manipulated ahead of survey completion, and there was no measure of dietary restraint to determine whether stimuli were valued differently in individuals with low and high restrained eating. Moreover, we did not obtain valence ratings directly from our participants in the current studies. Therefore, fasted individuals and RE may have had a different affective response to the presented food- and non-food stimuli across the current studies. This could, in turn, have contributed to the three-way interactions found in Study 2 and Study 3, where control groups (i.e., satiated individuals and URE) had similar SSRTs in all conditions, whereas we found modality- and food-specific differences in SSRTs in fasted individuals and RE.

The mediation of inhibitory control through valence is also compatible with an aspect of the RIM called *motivational orientation*, which poses that affect and arousal are at their core intertwined with impulsive processing (Strack & Deutsch, 2004). If stimuli are associated with increased positive valence and arousal, the RIM hypothesizes that this more strongly activates impulsive processes and that this biases stimulus approach behavior. In terms of the SST, such increased impulsive processing and approach tendency would indeed result in *longer* SSRTs as such impulses would be more difficult to inhibit. Applied to the current findings, we observed better inhibitory control for amodal than modal non-food cues in the fasted condition of Study 2. Possibly, amodal non-food words carried a lower valence in the fasted condition, while state-relevant amodal food words maintained their high valence. In line with this interpretation, Loeber et al. (2013) found that self-reported hunger negatively impacted inhibitory control for amodal (i.e., word) food compared to non-food stimuli in a Go/No-Go task in which valence was not actively matched. Moreover, in a study in which control stimuli were not matched on valence, fasted participants made more commission errors to food than non-food pictures (Howard et al., 2020).

Further support for the outlined explanation comes from another study that used valence-matched control stimuli in a Go/No-Go task with concurrent fNIRS study (Labonté et al., 2024). In their study, they ensured stimulus compatibility through participants' valence and arousal ratings. Controlling for stimulus valence and arousal in this manner, they found no interaction between satiation and inhibitory control for food pictures. Thus, future studies should focus on valence and arousal to determine whether modality- and food-specific differences on the SST in fasted individuals and RE relates to stimulus valence. To this end, subjective valence ratings should be obtained at the experimental session (Labonté et al., 2024), while the use of block-design could enable the use of skin conductance to measure arousal levels when inhibiting different types of stimuli (Benikos et al., 2013).

Processing Modal Food Cues in RE: Cognitive Control

Although embodiment and stimulus valence provide a potential explanation of the relation between amodal food and non-food stimuli, these theories fail to address the evidence we found for enhanced inhibitory control towards modal food stimuli in RE in Study 1 and Study 3. In Study 1, we found a higher target identification

accuracy for targets preceded by modal food distractors than amodal food distractors. Generally, this finding is at odds with Neimeijer et al. (2013), who found lower target identification accuracy for RE when targets were preceded by modal food distractors than when preceded by modal non-food distractors.

In part, the enhanced target detection after food cues is attributable to the task design, as the study used the same category for non-food distractors and targets, thereby increasing the relevance of the non-food distractors. This increased saliency could have increased the attentional blink and thereby have reduced the accuracy in target identification after non-food distractors. In addition to the category overlap between non-food distractors and targets, Study 1 consistently used a lag of 2 (i.e., one distractor image between distractor and target), which made the positioning of the target predictable for participants. In combination with target and distractor alignment, this may have made especially food stimuli a signal for the upcoming target.

Against this, even though the mentioned design choices may explain why food distractors were unexpectedly associated with increased target recognition accuracy, they do not explain the larger difference in accuracy between *modal* food and non-food distractors relative to the smaller difference between *amodal* food and non-food distractors. Moreover, our analyses indicate that this difference was driven by RE, who – relative to URE – were generally more accurate at identifying targets after food distractors compared to non-food distractors. In other words, despite the limitations posed by the design, our data indicated that RE were less distracted by food stimuli than URE, and that modal food cues were less distracting than amodal food cues when they are interpreted relative to non-food cues. This observation thus seems to oppose the original hypothesis that, relative to amodal cues, modal food cues are more salient to RE than URE.

Our electrophysiological data, on the other hand, demonstrated an increased P300 for modal food distractors compared to non-food distractors. This reflects increased food-specific motivated attention to pictures relative to words, indicating that modal food distractors were more salient than amodal (food and non-food) distractors across groups (Polich & Kok, 1995; Wolz et al., 2015). Paradoxically, this is generally in line with our original hypothesis that modal stimuli are primarily processed by the impulsive system and therefore evoke more attentional resources.

To sum up, while our EEG findings indicate heightened attentional processing of food pictures, our behavioral data suggest lowered attentional food cue processing. The question then becomes how these two contrasting results can be unified within our theoretical framework. Note that RE exhibited increased cognitive control over (modal) food cues. In an earlier RSVP study, RSVP performance and attentional blink were strongly influenced by participants' ability to inhibit a distractor (Dux & Marois, 2008). In a similar vein, a study on posttraumatic stress disorder (PTSD) found that threatening stimuli elicited a smaller attentional blink compared to neutral stimuli in individuals with PTSD, but not in control groups (Amir et al., 2009). This supports the notion that personally relevant stimuli can be associated with the inhibition of distractors on the RSVP. The same is applicable to our study, in which RE inhibited modal food stimuli more effectively than URE *despite* increased salience. Furthermore, this interpretation also corresponds to the findings of Study 3. In Study 3, RE inhibited modal food stimuli better than amodal food stimuli.

The increased inhibitory control in RE for modal food stimuli as evidenced in Study 1 and 3 is in line with the counteractive control theory. This theory poses that active dietary schemata can temporarily decrease food intake in RE (Fishbach et al., 2010; Polivy & Herman, 2017). Accordingly, although RE are prone to weight gain (Adams et al., 2019), they are also sensitive to diet primes, which can at least temporarily curb their food intake (Polivy & Herman, 2017). When diet goals are activated in RE, this may then lead to increased inhibitory control. Indeed, literature on inhibitory control trainings supports the view that cognitive control could be transient in RE. In these trainings, participants must withhold responses to high-calorie food cues in paradigms that resemble the Go/No-Go task. Previous studies have demonstrated that RE that withheld their response to high-calorie food in such trainings reduce food intake more strongly than URE (Houben & Jansen, 2011; Lawrence et al., 2015; Veling et al., 2011). However, the achieved inhibitory control over food intake may decrease again over time (Adams et al., 2021).

Within the framework of the counteractive control theory, diet goals may have been activated during our studies in the RE groups, which temporarily increased inhibitory control specifically to modal food cues (i.e., pictures). Further in support of this theory, food pictures may be associated with neural activation in regions that are involved in the processing of higher order information of food (i.e., healthiness estimates) and inhibitory control. One study, for instance, showed that food pictures,

especially of processed foods (i.e., foods which are typically high-calorie and considered unhealthy) elicit activation in frontal cortical regions critical to cognitive control, e.g. the dlPFC (Avery et al., 2025; Rösch et al., 2020). Recruitment of these regions can help reduce subsequent food intake (Carbine et al., 2018).

Empirical evidence for increased food cue suppression in individuals vulnerable to overeating comes from a study by Kumar et al. (2016), who demonstrated that early bottom-up suppression of food cues was more pronounced with increasing BMI. Furthermore, Werle et al. (2024) found indications of early food cue suppression in an overweight and obese sample, but not in a normal weight control sample. Since RE is associated with increased BMI (Adams et al., 2019), these studies provide a first indication that inhibitory control to food cues may also be associated with RE. Moreover, if automatic control over threatening food cues indeed occurs in RE, we would expect this effect to extend to other food modalities that are associated with food availability, such as olfaction. Early evidence for this comes from a recent study that used food odors to prime individuals with and without dietary restraint (Berebbi et al., 2025). After being primed with food cues, inhibitory control increased for RE, whereas it decreased for the URE. Taken together, research indicates that inhibitory control over modal food stimuli fluctuates in RE, and that if study circumstances induced restriction, this may have led to short term increases in inhibitory control.

Returning to the RIM, we previously hypothesized that valence could facilitate impulsive processing, and therefore decrease inhibitory control for salient stimuli. Here, we find electrophysiological evidence that food pictures were especially salient to RE, whereas behavioral indices still demonstrated increased inhibitory control for these food pictures. Based on the counteractive control theory we can deduct that in RE, the impulsive system can take up a motivational orientation that facilitates avoidance of (modal) food. Indeed, Strack and Deutsch (2004) suggest that the impulsive system can be put in a motivational orientation that facilitates avoidance or approach behavior. The current findings suggest that this motivational orientation is applied specifically to modal food cues. This again implies that amodal food stimuli are not controlled as strongly and therefore elicit relatively less inhibitory control as found in Study 3.

Of course, future studies are required to test this theory, as well as explore the conditions under which increased inhibitory control is used for early suppression. For

example, to test this hypothesis, measures of valence (e.g., congruent stimulus ratings) as well as congruent measures of inhibitory control, for example via fNIRS (Labonté et al., 2024) can be used. In line with this interpretation of the data, we would expect valence to be similar for food pictures and food words, whereas indices of inhibitory control such as activation in the dlPFC should be increased specifically for food pictures.

Limitations

There are several general limitations to the current work that need to be considered when interpreting its findings. First, all studies included both male and female participants. Generally, physiological determinants of eating behavior are believed to differ between males and females (Asarian & Geary, 2013). At the cognitive level males and females also demonstrate different patterns of inhibitory control over high-calorie food stimuli (Mühlberg et al., 2016). Regarding RE, dietary restraint is additionally more pronounced in females (e.g., Klem et al., 1990; Legget et al., 2023; Smith et al., 2020). There are also indications that dietary restraint is differentially associated with other eating behavior traits, such as emotional eating based on gender (Smith et al., 2020). Moreover, dietary restraint was shown to be associated with different homeostatic regulation processes in females and males (Jastreboff et al., 2014). Although the current studies either controlled for gender differences, or had balanced samples, future studies should take into consideration that there may be differences in modality-based inhibitory control and attentional processing that the current studies were not equipped to examine.

Second, for Study 1 and Study 3 we used extreme tertiles to divide our sample into RE and URE. The current work may therefore have inflated effect sizes (Preacher, 2015). Moreover, when interpreting the work, it should be noted that we can only apply the effect to individuals with extreme scores and cannot make any inferences on individuals with middle scores. Therefore, it cannot be concluded that improvements in inhibitory control for briefly presented modal food stimuli linearly increase with increased dietary restraint.

Third, for our experiments we used pictures as modal cues and written words as amodal cues. If we conceptualize modality as a spectrum (Kaup et al., 2024), beyond the ways assessed in the present studies, there are several ways in which food can be (re)presented. We would thus assume that different degrees of concrete,

sensory representations to abstract symbolic representations are between and beyond the cues we used for the current studies. An example of a stimulus presentation that lays between the photorealistic images and written words we used in the current studies, could for instance be a schematic drawing of a food item. As such, the current studies cannot make inferences about how RE and fasting interacts with a spectrum of cue modalities. Moreover, the two types of modalities chosen here had distinct visual properties; words were black letters, while the pictures had colors and intricate details that may elicit a stronger emotional response (Schlochtermeyer et al., 2013). As we did not use control stimuli with similar visual properties, some of the effects may be due to or may have been obscured by differences in visual properties. In this vein, we also cannot exclude the possibility that the use of words and images in the same paradigm may have led to changes in how each modality individually was processed. In the online SST paradigm of Study 2 and 3, this possibility was indicated by order effects (i.e., if a modal or amodal block was shown first) on the SSRT, even though a one-to-one pairing of pictures to words was not possible in this design. A better understanding of these crossmodal interactions is required, for instance, to understand whether using designs where modal and amodal cues are mixed (e.g., Study 1) lead to different representations of modal and amodal cues compared to block designs (e.g., Study 2, 3). Future studies should therefore not only vary the degrees of concreteness and abstractness of the stimuli, but that also consider how these stimuli interact with each other.

Additionally, with regard to Study 2 and Study 3 the use of an online design introduced more noise to the data (Gagné & Franzen, 2023). To reduce the impact of environmental cues, participants were instructed to complete the task in a distraction-free environment without food or drink. However, the use of an online design prevented us from standardizing food intake in the satiated condition, and it should be expected that the (food) environment in which the participants completed the study was highly variable (even though this variability applies to both conditions and groups). Furthermore, noise was likely introduced through the use of various technical equipment (Gagné & Franzen, 2023). This underlines that, moving forward, on-site laboratory studies are required with standardized satiation and fasting conditions to validate the current results.

Finally, the current findings were obtained using an SST and an RSVP that used (non-)food stimuli in a manner that was not task relevant. In the SST,

participants were asked to judge the position in which the stimulus was presented, while in the RSVP food cues were only used as distractors. Since we did not ask participants to freely recall or identify the (food) cues encountered in the task, it is unclear how deeply the stimuli were processed. This has several possible implications for the current interpretation of the data and the direction of future studies in this field. First, depth of processing may influence inhibitory control (Best et al., 2016). Particularly, if a task demands more processing of the stimulus, features that may influence inhibitory control (e.g., sensory aspects of food) will be more prominent and could lead to larger fluctuations in inhibitory control. Applied to the current studies, encouraging deeper food cue processing, for example by making stimulus type (i.e., food vs. non-food) task relevant, could emphasize differences in modality and thereby enhance modality differences. In other words, we may find larger effect sizes for the effects observed in the present studies. On the other hand, the lower processing demands induced by our task-irrelevant set-up may have facilitated inhibitory control processes especially in RE. In one study using fMRI, Pohl et al. (2017) demonstrated that task demands influence the neural networks that are recruited when processing stimuli; when participants attended to amodal features, higher order representations were activated than when participants attended to modal features. As participants in Study 2 and Study 3 were not required to actively attend to the stimuli, but rather judge spatial placement, it is possible that higher order representations were activated also in the modal condition, which may have allowed for better cognitive control. Future studies should manipulate task demands to focus on different aspects (i.e., modal, amodal) of food in order to better understand how stimulus representation, rather than presentation, influences cognitive control in aberrant eaters.

Conclusion and Outlook

The current dissertation aimed to directly compare the effects of modal (picture) and amodal (word) food cues on (food-specific) AB and inhibitory control in food deprived compared to satiated individuals (Study 2) and RE compared to URE (Study 1 and 3).

Overall, we found evidence of effects of modality on inhibitory control and attentional processes that were dependent on state (i.e., fasting) and trait (i.e., dietary restraint) eating behavior. Critically, however, our findings ran against the

initial hypotheses we derived from the RIM (Strack & Deutsch, 2004) and the conceptualization of modality as variance in cognitive representations, which can be employed depending on the cognitive faculties that are activated (Kaup et al., 2024).

There are two main hypotheses that we derived from our interpretation of the findings in our three studies. First, differences in modality-based control over food and non-food cues in fasted participants could be due to changes in valence and arousal for amodal, but not modal cues, as valence and arousal influence inhibitory control on the SST (Verbruggen & De Houwer, 2007). Although changes in valence may also play a role in the inhibitory capacity of RE, the enhanced inhibitory control for modal stimuli, as evidenced by Study 1 and 3, requires an additional explanation. Hence our second interpretation is that RE have enhanced cognitive control over threatening (i.e., more modal) food cues. To better understand the influence of modality on food cue processing in individuals that are prone to overeating, future studies should focus on testing these hypotheses.

Regarding valence and arousal, future studies should use a combination of measures to run concurrently with the study (Kaneko et al., 2018; Labonté & Nielsen, 2023). Subjective measures of stimulus valence could constitute ratings of valence and arousal that are measured in both fasted and satiated states before or after completing the experimental paradigm. To measure valence concurrently, electrodermal activity (EDA) can be used, as this measure seems to be sensitive to stimulus valence, but not food/non-food content (Kuoppa et al., 2016). Based on the current work, we would expect stimulus valence for food and non-food stimuli to be comparable across all stimulus categories for satiated individuals and URE (i.e., individuals without trait or state increased processing of food cues). For fasted individuals and RE, on the other hand, we would expect a lower valence for our amodal control stimuli, when compared to modal control as well as modal and amodal food stimuli. Furthermore, we expect valence estimates to be associated with subsequent inhibitory control in fasted individuals, with higher valence corresponding to lower inhibitory control. Since we expect RE to additionally cognitively regulate modal food stimuli, we expect that valence is not associated with modal food cues (e.g., photorealistic pictures or food odors). Should our hypothesis be supported, this would indicate that inhibitory trainings that work through valence alteration are especially promising (Yang et al., 2022), and should include amodal in addition to modal stimuli to devalue a larger range of food cues.

To test the theory of enhanced inhibitory control and avoidance for modal food cues in RE, future studies are required that include neural measures of inhibitory control in addition to behavioral measures such as the SSRT. For instance, fNIRS has previously been used to measure hemodynamic activity in the dlPFC as well as the inferior frontal gyrus as neural correlates of inhibitory control in obesity and BED (Berner et al., 2023; Labonté et al., 2024; Rösch et al., 2020). In line with the current interpretation of our results, we would expect RE to demonstrate increased activity in these areas for modal food stimuli compared to URE. As we found indications of decreased inhibitory control for amodal food stimuli, we would expect lower activation in RE compared to URE for amodal food stimuli in those areas.

In addition to fNIRS as a hemodynamic measure, EEG could provide an additional electrophysiological measure of food avoidance. Werle et al. (2024), for instance, found increased avoidance of food stimuli in individuals with overweight and obesity in a Go/No-Go paradigm with concurrent EEG. By presenting distractors and targets simultaneously, they could extract the N2pc, a lateralized potential that serves as an indicator of the spatial attention allocation (Eimer, 1996). Since distractors and targets were presented simultaneously, the N2pc also serves as a measure of early suppression of (food) distractors. Thus, their finding of a weakened N2pc for individuals with overweight and obesity could also be interpreted as stronger control over food than non-food stimuli. In line with these findings, we would expect modal food distractors to elicit a weaker N2pc compared to control distractors in RE compared to URE. For amodal food distractors, on the other hand, we would expect stronger N2pc for food than non-food distractors.

In all, hemodynamic and electrophysiological evidence of early control over (modal) food stimuli would strengthen the suppression of threatening food cues in RE. Notwithstanding, RE is associated with long term weight gain (Adams et al., 2019) and therefore the conditions under which suppression in RE and overweight and obesity is successful (e.g., stimulus modality), are issues that will subsequently require further attention (Werle et al., 2024).

Another important issue for future research is the extension of our findings to other modalities. As previously noted, our current results used two distinct cue types that were both captured by the visual modality. However, other cue presentation formats, such as olfaction or thinking about food for a prolonged time, can also induce food cravings (e.g., Berebbi et al., 2025; Fedoroff et al., 1997; Jansen et al.,

2003; Larsen et al., 2012). Indeed, olfaction and gustation are crucial to food intake (Rolls, 2011). As previously stated, extending our hypothesis of increased control over threatening food cues in RE to olfactory stimuli, we would expect to see increased inhibitory control to (high-calorie) food cues compared to neutral food cues. In line with this prediction, Berebbi et al. (2025) demonstrated better inhibitory control in dieters after being exposed to an olfactory food cue. Direct comparisons between olfactory and more abstract cues are thus required to generalize our theory to other sensory modalities and help generalize our findings to modality as a spectrum rather than a dichotomy (Kaup et al., 2024).

Additionally, combining different sensory inputs and different modalities may also influence mental representations (Berndt et al., 2020), perception of food and food intake (Biswas et al., 2021). As the food environment is complex, combining stimuli of different modalities is an avenue for further research to better understand how joined food cues may influence inhibitory control.

Concluding, the current dissertation aimed to investigate how modality may affect food-related attentional and inhibitory processes and to provide initial insights in how the variety of foods in the environment can contribute to the rise of overweight and obesity. Generally, we find that amodal food cues are similarly difficult, or more difficult to control compared to modal cues. Potentially, control processes are in place for more threatening sensory stimuli, but not for less threatening abstract cues, even though they also elicit higher arousal and food craving. This uncontrolled processing may then contribute to overeating also in presence of abstract cues. Future studies are required to test this hypothesis, as well as extending these findings to the larger spectrum of modality.

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Appendices

Appendix A: Study 1

van den Hoek Ostende, M. M., Gawrilow, C., Kaup, B., & Svaldi, J. (2026). Less distracted, more restrained: Attentional differences on the Rapid Serial Visual Presentation task in restrained eaters to food words and pictures. *Appetite*, 217, 108356 <https://doi.org/10.1016/j.appet.2025.108356>

Appendix B: Study 2

van den Hoek Ostende, M. M., Schwarz, U., Gawrilow, C., Kaup, B., & Svaldi, J. (2024a). Modality Matters: Fasted Individuals Inhibit Food Stimuli Better Than Neutral Stimuli for Words, but Not for Pictures. *Nutrients*, 16(14), e2190. <https://doi.org/10.3390/nu16142190>

Appendix C: Study 3

van den Hoek Ostende, M. M., Schwarz, U., Gawrilow, C., Kaup, B., & Svaldi, J. (2024b). Practice makes perfect: Restrained eaters' heightened control for food images. *European Eating Disorders Review*, 32(1), 90-98. <https://doi.org/10.1002/erv.3023>

Appendix A

Study 1:

van den Hoek Ostende, M. M., Gawrilow, C., Kaup, B., & Svaldi, J. (2026). Less distracted, more restrained: Attentional differences on the Rapid Serial Visual Presentation task in restrained eaters to food words and pictures. *Appetite*, 217, 108356 <https://doi.org/10.1016/j.appet.2025.108356>



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Less distracted, more restrained: Attentional differences on the rapid serial visual presentation task in restrained eaters to food words and pictures

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ABSTRACT

Restrained eaters (RE) are individuals that regularly show disinhibited food intake despite attempts of cognitive dietary restraint. This disinhibition is often attributed to an abundance of food cues in the environment that repeatedly draw attention, although the literature remains ambiguous. One source of ambiguity is the influence of different food cue modalities (pictures, words) on attentional processes. The current study therefore investigates the effect different modalities have on attentional bias to food cues in RE ($n = 70$) compared to unrestrained eaters (URE; $n = 74$). After a standardized lunch, participants completed a Rapid Serial Visual Presentation task with concurrent electroencephalography. Trials consisted of streams of pictures or words, with task-irrelevant food and animal distractors at lag 2 before an animal target appeared. Model comparisons indicated a significant Group \times Distractor Type interaction. Specifically, RE were more accurate at identifying targets that were preceded by food compared to animal stimuli than URE. Exploratory analyses indicated that this was especially due to food pictures. This finding was not accompanied by changes in event related potentials. Furthermore, we found a significant Modality \times Distractor Type interaction. In the picture, but not in the word condition, participants correctly identified targets preceded by a food distractor more often than when preceded by an animal distractor. This finding was accompanied by an increased P300 after food cues. In all, we showed that RE more effectively ignore food cues, especially in the image condition. This contributes to a body of research that demonstrates increased inhibitory control over food cues in RE. Future studies have to determine under which conditions inhibition of food cues is successful in RE.

1. Introduction

Rates of obesity and overweight have increased over the past decades and continue to rise (Wang et al., 2020). For the individual, creating a caloric deficit through caloric restriction seems a simple method to remedy unwanted weight gain. Indeed, when moderate calorie-restricting diets are implemented consistently, they can help curb weight-gain and bouts of overeating (Schaumberg et al., 2016). However, adherence to these diets is often hampered by physiological and cognitive factors (Schaumberg et al., 2016), leaving many individuals with the intention to restrain their food intake, without effectively cutting back their energy intake (Herman & Polivy, 1980). Such restrained eating is characterized by *cognitive* restraint over food intake with repeated lapses in dietary control, which – contrary to weight loss – is associated with long term weight gain and loss of control

over eating (Adams et al., 2019; Andrés & Saldaña, 2014; Kirkley et al., 1988). Research has shown that especially rigid restraint (i.e., attempts to cut unhealthy foods from the diet completely), opposed to flexible restraint, is associated with poorer dieting outcomes (Westenhoefer et al., 2013). In line with dual-process models (Strack & Deutsch, 2004), this results from an interaction of strengthened impulsive processing of food cues, and weakened reflective control over food-oriented behavior. Specifically, strengthened impulsive processing is thought to result from an attentional bias (AB) towards (high caloric) foods in these restrained eaters (RE; Polivy & Herman, 2017). Indeed, individuals with rigid restraint demonstrate AB towards food, whereas flexible restrainers do not (Westenhoefer et al., 2013). It is therefore important to understand how RE process different food-related cues, especially in environments where these are abundant.

Emotionally or motivationally salient cues can elicit ABs, especially

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when they are acutely relevant (Pool et al., 2016). Accordingly, hungry individuals show increased food processing compared to satiated individuals (Hardman et al., 2021). Some studies have shown that this increased attention towards food under homeostatic deprivation is predominantly observed in individuals with normal weight, whereas individuals with overweight and obesity demonstrate comparable levels of attentional allocation irrespective of their hunger level (Castellanos et al., 2009; Nijs et al., 2010). With regard to RE however, the results of food-related AB studies have been inconsistent, and, when combined in a meta-analysis, no evidence of an AB was found (Watson & Le Pelley, 2021). However, more recent studies demonstrate that AB for food in RE depends on stimulus material and the facets of attention being studied (Dondzilo et al., 2022; Moore et al., 2022; Watson et al., 2021).

Notably, most previous paradigms focused on behavioral measures of *spatial* attention. These included reaction time towards food stimuli compared to simultaneously presented non-food stimuli, as well as the time taken to identify a food stimulus among non-food stimuli. Both are associated with smaller attentional biases, potentially because the size of AB toward salient stimuli is larger in the early stages of bottom-up processing and weakened when top-down control is required, for instance, for button presses (Pool et al., 2016). Conversely, paradigms that measure the *temporal* component of attention, which relies more strongly on bottom-up processing, should be associated with larger ABs (Pool et al., 2016). Therefore, paradigms measuring this temporal component may be better suited to capture AB in RE.

The temporal component of attention to a (food) cue is reflected in the amount of time a certain cue (e.g., food) occupies attentional resources. In this time window, it is not possible to actively attend to subsequent cues, leading to a transient impairment in visual recollection of the second cue (Anderson, 2005; Raymond et al., 1995). If the attentional blink is longer (i.e., the time in which other cues are not recollected is longer), this is an indication of an AB for the stimulus that induced it. The attentional blink can be induced by introducing two targets, or by the presence of emotionally salient cues in close temporal proximity to a subsequent target. With regards to the latter, this occurs even when the emotional stimuli are not task-relevant, a phenomenon that is referred to as *emotion-induced blindness* (Anderson, 2005; Most et al., 2005, 2007). The Rapid Serial Visual Presentation (RSVP) task makes use of the attentional blink and emotional blindness by presenting a stream of cues in quick succession. In this stream, there are two stimuli of interest. These can either both be targets that are visually marked, or a target that is preceded by a task-irrelevant salient stimulus. The accuracy of identifying the last target in the stream is used to determine the allocation of attentional resources to the preceding stimulus (Raymond et al., 1995).

The RSVP task has been used previously to demonstrate attentional biases for phobic and threatening stimuli (e.g., Amir et al., 2009; Trippe et al., 2007). With regard to AB to food cues, previous studies have demonstrated that food cues also induce the attentional blink (e.g., Ballesterio-Arnau et al., 2021; Kirsten et al., 2023; Schmitz et al., 2015). Two studies have previously measured AB in dieters through the RSVP. Specifically, Neimeijer et al. (2013) found that, in comparison to neutral distractors, task-irrelevant food cue distractors resulted in a more pronounced attentional blink for subsequent targets, albeit exclusively in RE. In contrast, the results of Kirsten et al. (2019) indicated that food cues elicited a more pronounced attentional blink compared to neutral cues, irrespective of group membership. Contrary to the former study, the latter study employed *task-relevant* food cues in a design that compared controls with successful dieters rather than RE. However, as described previously, successful restraint seems to be a distinct construct from cognitive restraint with regard to body mass index (BMI) and food craving (Adams et al., 2019) limiting the comparability of these results.

Efforts to gain a better understanding of these processes may be supported by electroencephalography (EEG), which offers a high temporal resolution and is therefore a suitable method to investigate attentional processes. Previous studies have demonstrated that several

event-related potentials (ERPs) are associated with the processing of salient stimuli in the RSVP. Among these, the P300, a positive ERP peaking at around 300 ms after stimulus onset, reflects attentional resources allocated to processing target stimuli (Kranzloch et al., 2007) and is enhanced for emotionally valenced compared to neutral pictures (Kanske et al., 2013). Notably, this also translates into increased attention for individually salient stimuli. In individuals with spider phobia, for instance, speeded detection of spider pictures in an RSVP was accompanied by a larger P300 (Trippe et al., 2007). Similarly, food cues – which are generally salient – also elicit an enhanced P300 (Carbine et al., 2018), which is even increased in individuals with aberrant eating behaviors (Blechert et al., 2014; Hofmann et al., 2015; Nijs et al., 2009). In addition to the P300, the early posterior negativity (EPN; 200ms–300 ms after stimulus onset) is also an ERP that is associated with stimulus salience in the RSVP. Specifically, it reflects emotional arousal through enhanced amplitudes following valenced stimuli (Schupp et al., 2006), even when cues are presented in rapid succession (Junghöfer et al., 2001).

One stimulus dimension that has not received much attention in current research on food-related processing is stimulus modality. The food environment consists of a large range of stimuli that differ in degree of abstractness. For instance, pictures of food in commercials provide a more sensory (i.e., modal) experience than food words on a menu, which we here consider to be amodal. Already Paivio (1978) distinguished between different types of mental codes (perceptual vs. verbal) and assumed that cognitive processes differed depending on the format of representation utilized in encoding the respective stimuli. Nowadays most domains of psychology implicitly distinguish between more concrete, sensorimotor or modal representations on the one hand, and more abstract, symbolic or amodal representations on the other hand (Binder & Desai, 2011; Dove, 2009; Kiefer & Pulvermüller, 2012; Zwaan, 2014), with the assumption that the two types of representations fulfill different functions for cognition and thus gain the upper hand in a context- and task-dependent manner (e.g., Kaup et al., 2024). Although representational modality (modal vs. amodal) must be distinguished from stimulus modality (e.g., pictures vs. words), the two are likely associated (Kuchinke et al., 2005; Nakamura et al., 2020; Schlottermeier et al., 2013). Both words and pictures may give rise to modal or amodal representations. However, pictures are more readily represented in a modal fashion and words more readily represented in an amodal fashion, and thus the standard representational formats may differ between the two stimulus types. We therefore consider it highly likely that stimulus modality will differentially affect stimulus processing not only in dependence of group membership (i.e., hedonic vs. homeostatically-driven food intake), but also stimulus type (salient vs. non-salient stimuli).

To illustrate, consider a picture of fries and the word *fries*. Strack and Deutsch (2004) assume that actionable items, as they are often depicted in pictures, evoke automatic behavioral schemata that are associated with the object. A picture of fries therefore invokes motor plans associated with their consumption. On the contrary, the word “fries” does not possess properties that are immediately actionable, so more abstract constructs are activated. In this paper we are interested in potential differences in these relationships between RE and unrestrained eaters (URE). Possibly, food pictures constitute a particularly strong trigger of impulsive processes for individuals for whom these stimuli are highly salient (e.g., individuals with overweight or RE). In line with this consideration, Herman and Polivy (2008) theorize that *sensory* (modal) food cues differ from normative (amodal) ones, in that normative cues equally influence both RE and URE, whereas sensory cues exclusively affect RE. Indeed, one study found that RE compared to URE inhibited modal food pictures more successfully than amodal food words (van den Hoek Ostende et al., 2024b), although this could not be induced by manipulating homeostatic state (van den Hoek Ostende et al., 2024a). Similarly, Freijy et al. (2014) found that high-calorie pictures and words elicited biases in opposite directions. Specifically, in this study

high-calorie *pictures* attracted *more*, whereas high-calorie *words* attracted *less* attention in a dot-probe paradigm with low-calorie control stimuli. This converges with the interpretation of [van den Hoek Ostende et al. \(2024b\)](#) that high-calorie food pictures may be more threatening and may therefore recruit higher inhibitory control networks compared to high-calorie food words. Empirical support for this assumption comes from a study by [Kruse et al. \(2024\)](#), in which food pictures elicited more conflict when choosing a low-calorie food over a high-calorie food compared to when the high-calorie food was chosen over a low-calorie food. This type of conflict was absent in the condition where amodal information (i.e., health information) was provided on food cues. These results suggest that cue processing may depend on cue *modality*. Therefore, the present study aimed to assess differences in attentional processing of both modal (picture) and amodal (word) cues.

Taken together, the current study aims to investigate potential differences in attentional processing of modal and amodal food cues through measuring behavioral performance on the RSVP and concurrent ERPs. To this end, we selected a target population that scores in the upper third (RE) or lowest third (URE) of the Restraint Scale ([Herman & Polivy, 1980](#)), with the idea to model an analog sample to individuals with high loss of control over eating ([Andrés & Saldaña, 2014](#); [Kirkley et al., 1988](#)). We hypothesize that the modality of food cues matters especially for RE. Thus, we expect to find a difference between modal and amodal food cues (pictures vs. words) in our task for RE but not for URE. We hypothesize that food pictures elicit increased early attentional processing in RE. Thus, we expect RE to correctly identify fewer targets following food picture distractors compared to word and neutral picture distractors. Correspondingly, we expect RE to have larger EPN and P300 amplitudes in response to pictorial food distractors compared to verbal food distractors and animal picture distractors. By contrast, in URE we do not expect differences in identification rates or ERP amplitudes in dependence of distractor type or modality.

2. Methods

This study's hypotheses, planned sample, variables and paradigms were preregistered, and can be found on Open Science Framework ([osf.io/4j3mn](#)). All data is available upon request to the corresponding author.

2.1. Participants

We recruited participants through mailing lists and flyers distributed in and around the local university. To be included in the study, participants completed an online screening questionnaire that outlined our inclusion and exclusion criteria. Participants had to be between 18 and 69 years old, have a BMI >17.5 and have an excellent command of German. Conversely, participants were excluded for vegan nutrition, current pregnancy or lactation, (not corrected) bad eyesight, medication that influences reaction times, color blindness, inability to consume the standardized lunch, or self-reported lifetime eating disorder.

We calculated sample size through an a priori power analysis in Superpower ([Lakens & Caldwell, 2021](#)). We derived means and standard deviations for identification of modal stimuli from the distractor-target trials used by [Neimeijer et al. \(2013\)](#), which provided us with estimates for non-food and food stimuli in both RE and URE. In line with our hypotheses, we estimated the amodal stimuli (words) to have similar values as non-food modal (picture) stimuli. Given these values, for a power of $(1 - \beta) = 0.80$ and $\alpha = .05$ for the expected interaction, we aimed at a sample size of 120 participants (i.e., 60 RE, 60 URE). To account for dropouts, we recruited 12 additional participants per group. In total, 369 participants completed the study screening. We invited participants in the upper and lower thirds of scores to participate, of which 144 completed the study (71 RE, 73 URE). EEG data with sufficient trials per trial type per person was available for 130 participants (62 RE, 68 URE).

All participants obtained course credit or received €35 for their participation. The institutional review board of the local university approved this study (project number 945/2020BO2), which was conducted in accordance with the ethical code of the World Medical Association (Declaration of Helsinki).

2.2. Design and procedure

Prospective participants completed an online screening in SoSci Survey ([Leiner, 2019](#)) comprising all inclusion criteria and the Restraint Scale ([Herman & Polivy, 1980](#)). Those who were eligible for participation and whose score fell in the highest or lowest thirds of restraint scores were invited to come in for the laboratory part of the study. Experimental appointments always started at 12:00. At the day of the laboratory session, participants needed to refrain from consuming caffeine, food, or caloric beverages in the 3 h prior to their appointment. Furthermore, they had to have abstained from alcohol consumption for 24 h prior to participation and had to have slept at least 6 h the night before. Since food salience may be affected by the menstrual cycle (e.g., [Buffenstein et al., 1995](#)), all participants (besides those in menopause) were invited in the luteal phase (i.e., the week before their expected menses) as determined through the calendar method ([Sohda et al., 2017](#)). Additionally, participants were asked to disclose their medication intake in the past week. Upon arrival, participants gave informed consent and confirmed that they met all requirements for participation that day. If so, they were given a standardized small lunch (rice meal with tomato sauce, about 300 calories) to eat within 15 min. Following lunch, the participants were weighed, and their height was measured. This was followed by the completion of an unrelated, reaction time-based classification experiment in which participants had to classify stimuli as food or as toys (approximately 20 min). Notably, the stimulus set was distinct from the main experiment.

For the RSVP, participants were relocated to a soundproofed room with dim lighting conditions, where the electrodes were affixed, and the RSVP was completed. Additionally, participants completed a brief array of state questions and visual analogue scales (VAS) to assess sweet, savory and general food craving as well as hunger levels before and after the RSVP as well as before and after the unrelated task ([Supplemental Fig. S1](#)). Following the completion of the experimental measurements, participants were provided with a link to the questionnaires, which they were instructed to complete at home.

2.3. Rapid serial visual presentation

The present study aligns with the RSVP approach proposed [Neimeijer et al. \(2013\)](#). It consisted of four blocks of 72 trials each. Each trial consisted of a stream of stimuli that succeeded each other without interstimulus interval. Critically, each trial contained one distractor and one target ([Fig. 1](#)). Trials started with three, five or seven (neutral) filler stimuli, ahead of a food or animal distractor. This variability in stream length ensured participants could not learn the timing of the target. For every trial, a filler stimulus followed the distractor stimulus, which was then succeeded by the target stimulus. This target stimulus was marked by a blue frame. The trials were concluded with the presentation of four additional filler stimuli, which served to maintain the consistency of the information presented after the target throughout the trials ([Neimeijer et al., 2013](#)).

Participants were instructed to type what word or picture appeared in the blue box at the end of each trial. Participants' answers were compared to the correct answer (verbal targets) or correct answer options (pictorial targets). To accommodate for potential spelling errors in participants' responses, a minimum of 75 % matching was required for a response to be considered correct. For pictures, we allowed multiple correct answers if images could be interpreted as ambiguous. To select appropriate stimuli and responses for the current study, we conducted a separate, only survey of potential stimuli. Participants in this survey

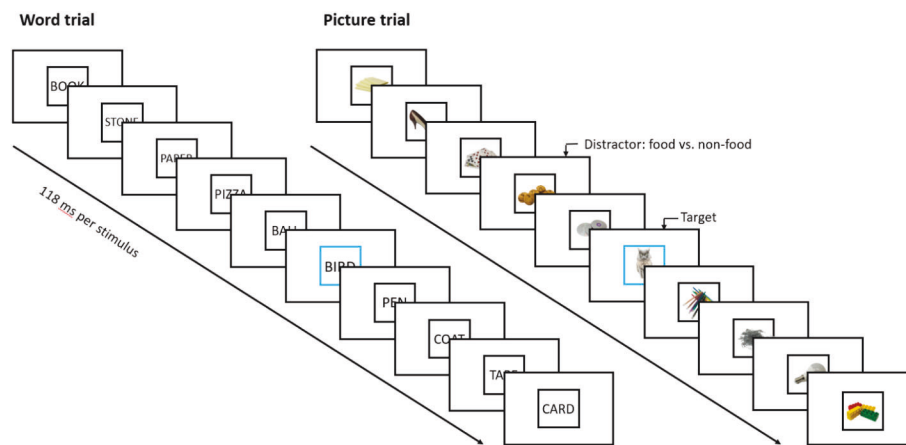


Fig. 1. Rapid Serial Visual Presentation task. Example of a word and a picture stream with three fillers preceding a distractor. Distractors were either foods or animals. Targets were presented at lag 2 from the distractor. Each stream contained 4 filler stimuli after the target.

were asked to rate all stimuli on valence and arousal, and food stimuli additionally on tastiness. Participants also wrote down what they would call the picture stimuli. These answers were used to make the list of correct answers on the RSVP. Notably, the classification of correct versus incorrect answers was conducted in a blinded manner for group membership. All stimuli were presented 118 ms. The timing of responses from participants was not assessed.

Within each block, half of the trials comprised amodal (word) stimuli, while the other half comprised modal (picture) stimuli. To reduce cross-modal activation between amodal and modal stimuli in the same block, distractor and target stimuli were split into two sets with distinct items. Sets alternated over the blocks, and the starting set was counterbalanced between participants. Within each block, stimuli were randomized over trials but remained within their own category (words and pictures, respectively). Participants took 60 s breaks between blocks. The RSVP was programmed in Presentation. The monitor measured 518 by 324 mm with a resolution of 1920 by 1200 pixels.

Our stimulus set consisted of 88 pictures of office supplies (filler stimuli), 36 palatable, high-caloric food stimuli (distractors), and 108 animal stimuli (36 of which functioned as distractors and 72 of which functioned as targets). Pictorial stimuli were matched in regard to valence ratings on the pre-study survey and complexity with the ‘imagefluency’ package in R (Mayer, 2022). Similarly, the verbal material consisted of 88 words related to office supplies, 36 words pertaining to food, and 108 words denoting animals. The latter material was divided into 36 distractors and 72 targets. The verbal food and animal distractors were matched for length and frequency, as indexed by the *Leipzig Corpora Collection* (German news corpus based on material from 2020). The food stimuli set comprised sweet and savory items. All stimuli measured 550 by 550 pixels. Words were presented in Arial with black letters, and in a varying font size, so that the word met the width of the stimulus box.

2.4. Questionnaires

2.4.1. Restraint Scale

We used the Restraint Scale (RS) to measure restrained eating (Herman & Polivy, 1980). The RS comprises 10 items, with a total score ranging from 0 to 35. Each item assesses either weight fluctuations or diet attempts. In the current study, the RE group consisted of individuals who expressed interest in participating in the study and whose RS score at the online screening fell within the upper third of the total distribution (13–27). The URE group consisted of individuals whose RS score fell within the lowest third (0–8). For normal-weight participants, the RS has good construct validity, while it has lower internal consistency and score overestimation for individuals with overweight and obesity

(Bohrer et al., 2015; van Strien et al., 2007). The internal consistency in the current sample was high, $\alpha = .88$.

2.4.2. Further questionnaires

To additionally characterize our sample on measures of psychopathology, eating behavior and inhibition, participants filled in several questionnaires after participating in the study. To assess overall eating disorder pathology, we used the Eating Disorder Examination Questionnaire (EDE-Q; Fairburn & Beglin, 1994), a 28-item self-report measure with each item rated on a 7-point Likert-scale. The German version has good psychometric properties (Hilbert et al., 2007). Here, we found excellent internal consistency, $\alpha = .97$. Furthermore, the Dutch Eating Behavior Questionnaire (DEBQ; Grunert, 1989; van Strien et al., 1986) was employed to assess emotional eating, external eating and restraint eating to cover three aspects related to overeating. Each of these subscales consist of 10 items that are answered on a 5-point Likert scale, and has good (external eating, $\alpha = .89$) to excellent (restraint, emotional eating $\alpha > .90$) reliability (Nagl et al., 2016). Additionally, we assessed several general characteristics that could influence task performance. Specifically, we measured depressive symptoms with the German version of the Beck Depression Inventory-II (BDI-II; Beck et al., 1988; Hautzinger et al., 2006), self-control with the brief self-control scale (Bertrams & Dickhäuser, 2009; Tangney et al., 2004), impulsivity with the UPPS Impulsive Behavior Scale (Schmidt et al., 2008; Whiteside & Lynam, 2001) and general motivation with the behavioral inhibition system (BIS) and behavioral approach system (BAS) scales (Carver & White, 1994; Strobel et al., 2001).

2.5. Data processing

We recorded EEG with BrainVision Recorder 1.20 (Brain Products GmbH, Gliching, Germany) on an actiChamp amplifier (Brain Products GmbH, Gliching, Germany). We used 60 Ag/AgCl active electrodes (actiCAP slim electrodes), distributed in line with the 10–20 system. Impedances were kept below 20 k Ω . We used the Cz electrode as online reference with a sampling rate of 500 Hz and an online filter between 0.1 Hz and 100 Hz (Wolz et al., 2015, 2021). The ground electrode was placed at AFz. Four of the active electrodes were placed above and below the left eye as well as on both outer canthi to monitor eye movement for later ocular artifacts correction (Gratton et al., 1983). Data were analyzed using BrainVision Analyzer 2.1 (Brain Products GmbH, Gliching, Germany). First, we reduced the sampling rate to 256 Hz and re-referenced the data to the average recorded reference. Data was filtered with a high pass cut-off of 0.1 Hz, a low pass cut-off of 30 Hz. Further noise and movement artifacts were manually removed, while we corrected eye movements through an ocular correction independent

component analysis and used an automatic inspection method to remove remaining artifacts afterwards (maximal allowed voltage step 50 $\mu\text{V}/\text{ms}$, maximal allowed difference of values in 200 ms intervals: 200 μV , lowest allowed activity in 100 ms intervals: $<0.5 \mu\text{V}$). After artifact rejection, segmentation of data into segments starting 250 ms before picture stimulus onset and until 1000 ms after picture stimulus onset was conducted. 130 participants had enough segments (minimum of 20 segments per category) to calculate ERPs.

For the ERP analysis, we aligned the signal to a 200 ms pre-stimulus baseline and averaged the signal separately for every participant and separately for each electrode and each condition (food picture, food word, animal picture, animal word). We subsequently averaged the signal over the electrodes used to determine the EPN and the electrodes used to determine the P300 over their respective electrode clusters for each participant. For the EPN, previous studies using food stimuli used a medial occipital-parietal cluster (Blechert et al., 2011; Kirsten et al., 2023), whereas other studies focused on lateralized parietal activation (e.g., Fabi & Leuthold, 2018; Schupp et al., 2006; Scott et al., 2009). We therefore used visual inspection of topographic maps to determine how the EPN was localized. This revealed different topographies for pictures and words. To represent the EPN, we therefore calculated the EPN for pictures as the average over medial occipital parietal electrodes (PO4, PO3, POz, P3, P1, Pz, P2, P4, O1, O2, Oz), and the EPN for words as the average over lateral parietal electrodes (P5, P7, PO7, P6, P8, PO8; e.g., Blechert et al., 2011; Fabi & Leuthold, 2018; Schupp et al., 2006; Scott et al., 2009). For both modalities, we calculated the average from 200 ms to 300 ms post stimulus onset. For determining the P300, we averaged over central parietal electrodes from 250 ms to 400 ms (CP1, CP2, CPz, Cz, P1, P2, P3, P4, Pz).

2.6. Data processing and analysis

To determine the effects of Group, Modality and Distractor Type on the RSVP accuracy, we employed generalized linear mixed models (GLMMs) with random intercepts for participants using the lme4-package (Bates et al., 2015) in R (R Core Team, 2024). Specifically, we used likelihood-ratio tests (LRTs) to test the predictive value of Group, Distractor Type, Modality, and their interactions on correct identification of the target stimulus. Notably, our design included animal stimuli both as distractors and target stimuli, while food stimuli acted exclusively as distractors. Thus, animal stimuli were more task-relevant compared to food stimuli, which could lead to greater accuracy for targets preceded by food distractors than targets preceded by non-food distractors. Therefore, to ensure that any significant effects do not merely result from facilitated learning of the association between distractor and targets over time, we additionally tested each significant model against a model with paradigm block as additional interacting factor.

Similar to Kirsten et al. (2023), the fillers of the RSVP elicited systematic periodic effects observable in our time series (Supplemental Figs. S2 and S3). Therefore, to eliminate this noise, we calculated the individual differences between food and non-food ERPs. This allowed us to subsequently compare the food specific arousal effect for modalities, and how modality interacts with group. To this end, we subjected these differences to a 2 (Group: RE, URE) \times 2 (Modality: Picture, Word) mixed Analysis of Variance (ANOVA), with the EPN and P300 as dependent variables. To determine the effect of Distractor Type, we used 2 (Group: RE, URE) \times 2 (Distractor Type: food, non-food) mixed ANOVA within each modality as follow-up analysis.

3. Results

3.1. Descriptives

RE and URE did not differ regarding sex, hunger, and age (Table 1). In line with previous studies, RE had increased eating pathology (Stice

Table 1

Group characteristics. ^a Age data was available for N = 138 participants (RE: n = 67, URE: n = 71) ^b Questionnaire data was available for N = 114 participants (RE: n = 57, URE n = 57), BMI = Body Mass Index, BDI-II = Beck's Depression Inventory-II, EDE-Q = Eating Disorder Examination Questionnaire.

N	RE Mean	URE Mean	Statistics	p-value
	(SD)	(SD)		
	71	73		
Gender (n female)	51	56	$\chi^2(2) = 0.46$	0.793
(n non-binary)	1	1		
Age ^a	25.9 (9.6)	25.6 (9.4)	$t(136) = 0.17$	0.866
Hunger	28.1 (24.4)	26.1 (23.0)	$t(142) = 0.51$	0.610
BMI	25.0 (4.4)	21.9 (3.1)	$t(142) = 4.99$	<0.001
EDE-Q total ^b	2.31 (1.3)	0.44 (0.6)	$t(112) = 10.2$	<0.001
EDE-Q restraint ^b	2.25 (1.4)	0.31 (0.6)	$t(112) = 9.49$	<0.001
EDE-Q eating concern ^b	1.44 (1.3)	0.22 (0.5)	$t(112) = 6.79$	<0.001
EDE-Q shape concern ^b	2.91 (1.5)	0.75 (0.8)	$t(112) = 9.36$	<0.001
EDE-Q weight concern ^b	2.64 (1.5)	0.49 (0.7)	$t(112) = 9.56$	<0.001
BDI-II ^b	12.6 (7.8)	6.3 (7.4)	$t(112) = 4.41$	<0.001

et al., 2010), depressive symptoms (Ringham et al., 2008) and BMI (Adams et al., 2019).

3.2. RSVP performance

Full model comparisons are described in Table 2. Comparisons indicated a significant main effect of Distractor Type ($\chi^2[1] = 62.54, p < .001$). Since this could point at learning effects of the relationship between distractor and target (see 2.6), we therefore checked whether our significant effects were better explained by learning effects over time. Moreover, we refrain from interpreting this main effect.

To determine the effects of Group, Modality, Distractor Type and their respective interactions on target identification accuracy, we used model comparisons through LRTs. Against our hypotheses, we did not find a Group \times Modality \times Distractor Type interaction (Fig. 3; $\chi^2[1] = 0.971, p = .325$). Instead, LRTs indicated that the Modality \times Distractor Type interaction significantly improved model fit ($\chi^2[1] = 9.20, p = .002$; Fig. 3): the difference between food and animal distractors was larger for pictures than for words. However, follow-up *t*-tests indicated that for the picture condition – again against our predictions – participants provided significantly more accurate responses after food distractors compared to after animal distractors ($t[286] = -3.18, p = .002$). In the word condition, there was no significant difference in the number of accurate responses provided after food and animal distractors ($t[286] = -1.95, p = .052$). Post-hoc exploratory analyses demonstrated that this effect was driven by differences in the RE group ($\chi^2[1] = 7.82, p = .005$), as the interaction was not significant for URE ($\chi^2[1] = 2.68, p = .101$). To ensure that the interaction did not result from facilitated learning given the unequal distribution of animal vs. food distractor-target combinations (see 2.6), we tested for a 3-way interaction between Block, Modality and Distractor Type. Model comparisons of the model with the 3-way interaction, all 2-way interactions and main effects against the model with all 2-way interactions and main effects were not significant ($\chi^2[1] = 0.54, p = .463$).

LRTs further indicated a significant Group \times Distractor Type interaction ($\chi^2[1] = 8.41, p = .004$). The difference between food and animal distractors was larger for RE than for URE. Follow-up *t*-tests conducted separately for Group indicated that RE had significantly higher accuracy for targets preceded by food relative to animal distractors ($t[140] =$

Table 2
Model equations with corresponding AIC, BIC and LRTs.

Model	Equation	tested parameter	χ^2	df	p	AIC	BIC
GLMM1.0	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + v_{oi} + v_{oj}$					29150	29176
GLMM1.1	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + \text{group}_i \times \beta_1 + v_{oi} + v_{oj}$	β_1	2.24	1	0.134	29150	29184
GLMM1.2	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + \text{dist}_j \times \beta_2 + v_{oi} + v_{oj}$	β_2	62.54	1	<0.001	29090	29124
GLMM1.3	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + \text{mod}_j \times \beta_3 + v_{oi} + v_{oj}$	β_3	13.13	1	<0.001	29139	29174
GLMM2.0	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + \text{group}_i \times \beta_1 + \text{dist}_j \times \beta_2 + \text{mod}_j \times \beta_3 + v_{oi} + v_{oj}$					29070	29122
GLMM2.1	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + \text{group}_i \times \beta_1 + \text{dist}_j \times \beta_2 + \text{mod}_j \times \beta_3 + \text{group}_i \times \text{dist}_j \times \beta_4 + v_{oi} + v_{oj}$	β_4	8.41	1	0.004	29064	29124
GLMM2.2	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + \text{group}_i \times \beta_1 + \text{dist}_j \times \beta_2 + \text{mod}_j \times \beta_3 + \text{group}_i \times \text{mod}_j \times \beta_5 + v_{oi} + v_{oj}$	β_5	2.11	1	0.146	29070	29131
GLMM2.3	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + \text{group}_i \times \beta_1 + \text{dist}_j \times \beta_2 + \text{mod}_j \times \beta_3 + \text{dist}_j \times \text{mod}_j \times \beta_6 + v_{oi} + v_{oj}$	β_6	9.20	1	0.002	29063	29124
GLMM3.0	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + \text{group}_i \times \beta_1 + \text{dist}_j \times \beta_2 + \text{mod}_j \times \beta_3 + \text{group}_i \times \text{dist}_j \times \beta_4 + \text{group}_i \times \text{mod}_j \times \beta_5 + \text{dist}_j \times \text{mod}_j \times \beta_6 + v_{oi} + v_{oj}$					29070	29122
GLMM3.1	$\text{logit}(PR(\text{correct}_{ij})) = \beta_0 + \text{group}_i \times \beta_1 + \text{dist}_j \times \beta_2 + \text{mod}_j \times \beta_3 + \text{group}_i \times \text{dist}_j \times \beta_4 + \text{group}_i \times \text{mod}_j \times \beta_5 + \text{dist}_j \times \text{mod}_j \times \beta_6 + \text{group}_i \times \text{dist}_j \times \text{mod}_j \times \beta_7 + v_{oi} + v_{oj}$	β_7	0.97	1	0.324	29058	29144

Notes. $PR(\text{correct}_{ij})$ = probability of an accurate response of person i for stimulus j ; β_0 = mean logit of the probability of a correct answer for a participant of the restrained eating group, and an animal picture; β_1 = estimate for the main effect of group (RE, URE) of participant i ; β_2 = estimate for the main effect of the distractor type (animal, food) of stimulus j ; β_3 = estimate for the main effect of the modality (picture, word) of stimulus j ; β_4 = estimate for interaction effect of group and distractor type; β_5 = estimate for interaction effect of group and modality; β_6 = estimate for interaction effect of distractor type and modality; β_7 = estimate for interaction effect of group, distractor type and modality; v_{oi} = random intercept of person i ; v_{ok} = random intercept of stimulus j ; AIC = Akaike information criterion; BIC = Bayesian information criterion; selected models in bold.

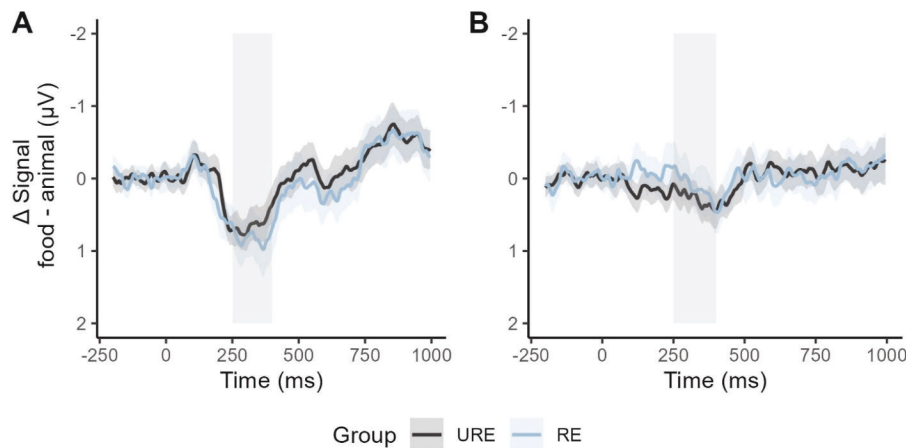


Fig. 2. P300 for modal and amodal stimuli in dependence of group. **A)** the difference between food and animal distractors for activity in central parietal electrodes (CP1, CP2, CPz, Cz, P1, P2, P3, P4, Pz) for picture trials. **B)** Difference in activity for word trials. Food specific effects are indicated by differences from zero. Area used to determine P300 is displayed in grey. Shading indicates 95 % confidence interval. There are no differences between restrained eaters (RE) and unrestrained eaters (URE).

$-2.43, p = .017$), while URE did not ($t[144] = -1.97, p = .051$). To again ensure that this interaction did not result from facilitated learning of the association between distractor and targets, we tested for a 3-way interaction between Block, Group and Distractor Type. Model comparisons indicated no significant improvement in fit ($\chi^2[1] = 0.67, p = .415$).

Finally, there was a main effect of Modality ($\chi^2[1] = 13.13, p < .001$), which indicated that participants were more likely to accurately identify words than pictures. There was no main effect from Group ($\chi^2[1] = 2.44, p = .134$) or interaction effect of Group \times Modality ($\chi^2[1] = 2.11, p = .146$). Results did not change if only the subsample used for the ERP analysis was used for the behavioral analysis. The final preferred model that contained all main effects and significant 2-way interactions had excellent split half reliability with correction after the Spearman-Brown prophecy formula, $r_{SB} = 0.92$ (Cicchetti, 1994).

3.3. ERP results

We used a mixed ANOVA to test whether the difference in amplitudes between food and non-food differed over modalities and group. We found no significant main effects for Group ($F[1,128] = 0.097, p = .757$), Modality ($F[1,128] = 3.61, p = .060$) or their interaction (F

$[1,128] = 0.074, p = .786$) on the EPN (Fig. S3).

For the P300, there was a main effect of Modality ($F[1,128] = 6.24, p = .014, \eta_p^2 = 0.046$; Fig. 2), indicating greater differences between the amplitudes of food and non-food stimuli in the picture compared to the word condition. Follow-up tests indicated that, in the picture condition, food distractors elicited a more positive P300 compared to animal pictures ($t[129] = 40.7, p < .001$). Although the P300 difference between verbal food and animal distractors also reached significance ($t[129] = 4.16, p < .001$), the interaction indicates that this difference is smaller compared to the P300 difference of the images. Pearson correlation indicated no correlation between P300 and task performance ($r = -0.05, p = .273$). Neither the effect of Group ($F[1,128] = 0.35, p = .558$) nor the interaction effect of Group \times Modality was significant ($F[1,128] = 2.10, p = .150$).

Because our inclusion criteria of a BMI larger than 17.5 kg/m^2 allowed for individuals with underweight to partake in the study (World Health Organization, 2000), we repeated all analyses excluding the $n = 5$ participants reporting a BMI below 18.5 kg/m^2 . This did not change the reported results.

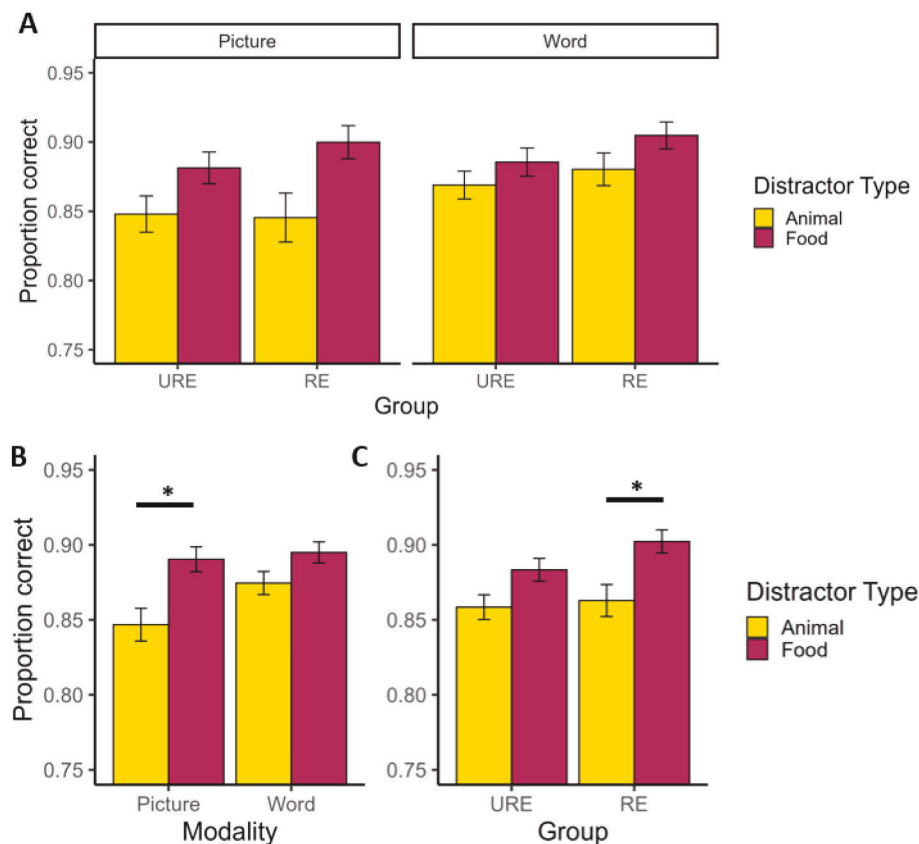


Fig. 3. Accuracy of target identification. **A)** Accuracy of target identification on a rapid serial visual presentation (RSVP) task. **B)** Participants are more accurate at identifying targets after food compared to animal distractors in the picture, but not in the word condition. Bars represent the combined data of both groups. **C)** Restrained eaters (RE) but not unrestrained eaters (URE) were more accurate in identifying targets that followed a food distractor compared to an animal distractor. Error bars reflect the standard errors. For readability, all bar graphs start at 0.75.

4. Discussion

RE attempt to compensate periods of disinhibited eating by exerting cognitive control over their food intake (Herman & Mack, 1975). Despite these attempts, restrained eating is associated with weight gain and increased food cravings (Adams et al., 2019). To date, results on AB in RE have been inconsistent (Watson & Le Pelley, 2021). Notably, though, most studies have focused on the spatial aspects of attention, whereas the temporal component of AB has largely been neglected (Neumeijer et al., 2013; Wolz et al., 2015). In addition to the temporal dynamics and in line with the reflective-impulsive model (Strack & Deutsch, 2004), the modality of the stimuli employed across the different studies may account for the observed heterogeneity. In the present study, we therefore investigated the temporal dynamic of attention and its dependence on stimulus modality in RE and URE, using an RSVP paradigm with food distractors while concurrently measuring EEG. At the behavioral level, we found an enhanced accuracy for targets that were preceded by a food distractor in RE compared to URE. Furthermore, we found an interaction of modality and stimulus type. Thereby, participants were especially more accurate at identifying food targets relative to non-food targets in the picture condition, which was also reflected in a higher P300 for food in the picture compared to the word condition.

We originally hypothesized that compared to amodal (verbal) food cues, modal (pictorial) food cues would decrease target detection specifically in RE (Neumeijer et al., 2013). Contrary to this hypothesis, accuracy was increased more after food distractors compared to after animal distractors in the picture compared to the word condition. A comparable increase in orientation towards neutral targets after high-calorie food pictures was observed by Frejby et al. (2014). In their

dot-probe task, participants demonstrated a speeded recognition of probes that followed a high-calorie compared to a low-calorie picture. Conversely, for food words they observed that low-calorie foods attracted more attention than high-calorie foods.

In addition to these findings at the behavioral level, we found evidence that food distractors relative to non-food distractors elicited a larger P300 in the picture condition than in the word condition. However, other than predicted, this tendency was not specific to RE. Pictures generally elicit stronger affective responses (Hinojosa et al., 2009), which coincides with a larger difference in P300 for food vs. animal distractors in the pictorial than the verbal condition in the present study. Generally, the P300 reflects attentional processing (Polich & Criado, 2006), especially of affective salient stimuli (Olofsson et al., 2008). In the RSVP, for instance, relative to control participants, P300 was enhanced for spider target-images in individuals with spider phobia (Trippe et al., 2007) and for words denoting dieting behavior in women with body dissatisfaction (Gao et al., 2011). Generally, an enhanced P300 is accompanied by an increase in performance on target detection (Mathis et al., 2012; Trippe et al., 2007). In line with this, individuals with binge eating disorder are more engaged with food compared to neutral stimuli (Schmitz et al., 2015). In the current task, however, we used task-irrelevant food distractors rather than food targets. The principle behind the attentional blink suggests that increased attentional processing at this stage should coincide with subsequent lower target detection. Although pre-target elicited P300 generally correlates negatively with target detection (McArthur et al., 1999), we did not find a significant correlation between P300 and task performance. Of note, this coincides with the findings by Kirsten et al. (2023), who found no correlation between the attentional blink for modal food cues and ERPs. Future studies are thus required to determine the exact processes behind

food-related emotional blindness. Nevertheless, the current findings underline the influence of stimulus modality on food cue processing (Freijy et al., 2014; van den Hoek Ostende et al., 2024b; van den Hoek Ostende et al., 2022). Deepening our insight into modality-dependent processing of food cues is paramount to a better understanding on how contextual factors trigger and maintain non-homeostatic eating. This is essential to understand how the food environment contributes to increasing rates of overweight and obesity. Note that, however, the etiology of overweight and obesity is multifactorial, and is associated with different cognitive and neurophysiological markers (e.g., Aviram-Friedman et al., 2020; Masood & Moorthy, 2023). Given the high EDE-Q scores of the current sample, the current results pertain particularly to individuals prone to overeating due to eating disorder pathology. This is essential to keep in mind when designing interventions that aim to reduce food-related AB to increase control over food intake (e.g., Kakoschke et al., 2014; Werle et al., 2024; Zhang et al., 2018). For instance, should future studies indicate that cue processing based on food modality is associated with food intake, trainings may be improved by using a variety of stimuli that are tailored towards the differences between modal and amodal aspects of food.

Additionally, we found stimulus-type specific differences in target identification accuracy between RE and URE. Specifically, our findings indicated that RE compared to URE demonstrated a larger difference in accuracy between identifying targets that followed food distractors compared to targets that followed non-food distractors. Conversely, target identification accuracy for food and non-food distractors was comparable in URE. This behavioral finding contrasts studies that have demonstrated an emotion-induced attentional blink for food images (e.g., Ballesterio-Arnau et al., 2021; Kirsten et al., 2019; Kirsten et al., 2023), and is more in line with studies demonstrating increased top-down control of RE over food stimuli (Watson et al., 2021). It is particularly at odds with the study by Neimeijer et al. (2013), which found lower target identification accuracy in RE specifically for food distractors. Crucially, the current study differs from previous research in its use of a single category for both non-food distractor and target stimuli. In other studies, a selection of distressing and non-valence-matched stimuli were employed (Neimeijer et al., 2013) or category-unspecific neutral stimuli (Kirsten et al., 2019). Whereas the non-food distractors were from the same category as the targets, the food distractors always preceded the target with a reliable lag. The current results seem to implicate that under these conditions, RE are better at using this contingency than URE. This interpretation is further strengthened by the incentive sensitization theory. Accordingly, dopaminergic pathways are triggered by rewarding (food) cues, leading to increased attention for these cues – a relationship that is reinforced by the ensuing increase in approach behavior (Berridge, 2009; Robinson & Berridge, 1993). Evidence for the AB postulated by this theory in individuals prone to overeating has been found in a range of studies (e.g., Dondzilo et al., 2022; Stojek et al., 2018; Sutton et al., 2022). Accordingly, a similar sensitization may have made participants with RE more susceptible to learning the contingency between distractor and target.

Moreover, the improved accuracy at recognizing targets following food cues is in line with previous research that demonstrated enhanced suppression of food cues in RE when inhibitory contingencies with food cues are high. For instance, various studies on inhibitory control trainings with RE demonstrate that RE, but not URE, reduce their food intake after repeatedly inhibiting their response to food cues (Houben & Jansen, 2011; Lawrence et al., 2015; Veling et al., 2011), despite attentional biases to food cues being evident at baseline (Veling et al., 2011). Additionally, it is plausible that differences in task performance reflect differences in inhibitory control. A study by Dux and Marois (2008) indicated that humans' ability to inhibit distractors in the RSVP stream is a key determinant of individual differences in performance and attentional blink magnitude. In this vein, one RSVP study on post-traumatic stress disorder (PTSD) found evidence that individuals with PTSD were more accurate at identifying neutral targets that were

preceded by a disorder-specific threatening stimulus compared to neutral stimuli (Amir et al., 2009), which can be interpreted as quicker control over individually salient stimuli. Relating this to the current study, our data thus support the alternative view that modal food cues are more threatening and thus recruit higher inhibitory control networks compared to verbal food cues and non-food cues. Indeed, a recent study found increased control specifically for modal food stimuli in RE compared to URE (van den Hoek Ostende et al., 2024b). In the current study, RE (but not URE) similarly demonstrated a larger difference in accuracy between food and non-food distractors in the modal than in the amodal condition. As this was an exploratory analysis, however, a follow-up study powered for this effect should be conducted to validate this finding.

Furthermore, the satiation established by the small lunch prior to the experiment may have further enhanced RE's diet-specific schema activation. In line with an increased AB under food deprivation (Hardman et al., 2021), previous studies have shown that the attentional blink after food distractors is smallest when participants are sated, and increases under food deprivation (Davidson et al., 2018; Piech et al., 2010), although one study that did not manipulate hunger levels did not find an effect of hunger on target detection (Kirsten et al., 2019). Another factor that could have made the control of food stimuli more salient to RE was the weighing and measuring during the experimental appointment (Polivy & Herman, 2017). In sum, the use of distractors in our design precludes the possibility to determine whether the relatively increased attentional blink for animals is solely due to their task-relevance or additionally determined by a decrease in food-relevance due to satiety or study conditions. Future studies should therefore use a large variety of targets to decrease their predictability (Kirsten et al., 2019). Additionally, the relevance of the food-distractors should be manipulated through brief food deprivation (Hardman et al., 2021) and the use of food stimuli that are tailored to idiosyncratic cravings (Giuliani et al., 2013).

The present study needs to be interpreted under consideration of several limitations. First, it is important to acknowledge that in our version of the RSVP the distractors consistently preceded the target with two lags. This may have facilitated contingency learning between distractor and target and may thus have improved accuracy over time. However, against this possibility our additional analyses including block as a factor did not change the result pattern. Therefore, although absolute accuracy should be interpreted with caution, we can interpret the current findings by taking into consideration the *relative* differences between food and non-food distractors. Second, relative to food distractors, animal distractors were of higher task relevance because they were used both as distractor and target category. This design choice precludes interpretation of the overall higher accuracy for targets following food vs. animal stimuli. Still, we found interactions between stimulus type and modality that would not be expected under the assumption that food words and pictures are processed similarly. In the same vein, we found an interaction between stimulus type and group that would not be expected under the assumption that RE and URE process food cues similarly in the current design. Notably, though, given this design limitation, these effects were only interpreted with the relative differences in accuracy after food and non-food distractors. Third, our participants had RS scores in the extreme lower- and upper-third of all participants that completed the selection questionnaire. The effect sizes in the current study may therefore be inflated and not applicable to individuals with middle RS scores (Preacher, 2015). Fourth, in contrast with most RSVP studies, participants were required to identify the target by typing it, rather than by selecting the correct stimulus out of a selection of candidate targets. This may have altered the importance of exact target detection and may have therefore increased the incentive to ignore the distractor stimuli. However, an attempt at increasing motivation for target detection through monetary reward did not lead to enhanced performance (Most et al., 2007). Fifth, picture and word processing differ from one another in complexity and

the neural substrates used to decode that specific modality (Schlochtermeyer et al., 2013). Although these stimulus processing differences are likely comparable across groups, we cannot rule out the possibility that the modality effect found in the present study interacted with alterations in modality-specific processing in RE. For example, some studies have shown that individuals with (sub-clinical) eating disorders demonstrate food-specific impairments in working memory relative to healthy individuals (e.g., Fenton & Ecker, 2015; Svaldi et al., 2014). Therefore, further studies need to more directly test whether the task performance differences found result from such an interaction, for example through concurrent measurements of modality-specific working memory. Sixth, the low spatial specificity of EEG, which for instance became apparent when localizing the EPN, the ERP results allow only a limited interpretation of the contributing regions and processes. Finally, the current study included both female and male participants, although the emotional interference effect for food distractors is larger in females than in males (Kirsten et al., 2019). Although our groups were comparable in their sex composition, the inclusion of males could have diminished the effect sizes. This should be taken into consideration for follow-up studies.

To conclude, the current study aimed to investigate whether a food- and modality-specific AB exists for RE. Although we find evidence for enhanced identification accuracy of targets after food distractors in RE, this effect was not dependent on stimulus modality. Instead, we found that modality and distractor type interacted independent of group, and that food stimuli enhanced target identification in the picture, but not in the word condition. These general differences in the processing of food cues of various modalities could explain general heterogeneity in the AB literature. Moreover, it indicates that future mechanistic studies and trainings aimed at improving food regulation should consider food-cue modality.

CRedit authorship contribution statement

Mechteld M. van den Hoek Ostende: Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Formal analysis, Data curation. **Caterina Gawrilow:** Writing – review & editing, Funding acquisition. **Barbara Kaup:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Jennifer Svaldi:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Ethics statement

The institutional review board of the University Hospital of the University of Tübingen approved this study (project number 945/2020BO2), which was conducted in accordance with the ethical code of the World Medical Association (Declaration of Helsinki). All participants gave informed consent prior to data collection.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.appet.2025.108356>.

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Appendix B

Study 2:

van den Hoek Ostende, M. M., Schwarz, U., Gawrilow, C., Kaup, B., & Svaldi, J. (2024a). Modality Matters: Fasted Individuals Inhibit Food Stimuli Better Than Neutral Stimuli for Words, but Not for Pictures. *Nutrients*, *16*(14), e2190.

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Article

Modality Matters: Fasted Individuals Inhibit Food Stimuli Better Than Neutral Stimuli for Words, but Not for Pictures

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Abstract: The current study aimed to evaluate the effect different modalities (pictures and words) of food stimuli have on inhibitory control under different homeostatic states. To this end, the homeostatic state was altered by asking participants to fast for 16 h ($n = 67$) or eat lunch as usual ($n = 76$) before completing an online stop-signal task with modal (pictures) and amodal (words) food and valenced-matched non-food stimuli. The inclusion of non-food stimuli allowed us to test the food specificity of the effect. We found a significant Group \times Modality \times Stimulus Type interaction ($F(1,141) = 5.29, p = 0.023, \eta_p^2 = 0.036$): fasted individuals had similar inhibitory capacity for modal and amodal food stimuli but better inhibitory capacity for non-food words compared to images, while there were no inhibitory differences in dependence on either modality or stimulus type in satiated individuals. Thus, we were able to show that inhibitory capacities to modal compared to amodal stimuli depend on participants' current state of fasting. Future studies should focus on how this lowered inhibitory capacity influences food intake, as well as the role of stimulus valence in cognitive processing, to clarify potential implications for dieting and weight loss training.

Keywords: homeostasis; satiation; cognitive control



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1. Introduction

The social infrastructure of Western societies contributes to the overconsumption of food of little nutritional value and fosters overweight and obesity [1]. In this diverse environment, food cues take many different forms. At a distance, abstract cues such as signs and menus can be observed, whereas sensory cues become more salient in higher proximity to food when we can experience their smell, sight, and, potentially, taste. Repeatedly resisting cravings induced by food cues becomes more difficult in the fasting state when these cues become more salient [2]. Indeed, exposure to food cues when fasting can increase food approach behavior; those with lower impulse control will select more products when fasting than when satiated [3]. Thus, reducing food intake to counteract overeating and weight gain may exacerbate impaired control over food intake by inducing hunger, ironically promoting uncontrolled eating and hindering individuals in their attempts to lose weight. A thorough understanding of the altered food processing in the fasting state is therefore paramount to combat the physical and mental consequences of overeating.

According to the reflective-impulsive model [4], non-homeostatic eating (i.e., eating in the absence of hunger) can be ascribed to a dual cognitive impairment. On the one hand, excessive impulsive processing capitalizes on food cues in our environment, exaggerating the attentional and motivational resources assigned to food consumption. On the other hand, exhausted resources of the reflective system result in lowered cognitive control, which hinders efforts to inhibit consumption. Notably, these tendencies are enhanced under relevant motivational states, such as hunger [4,5]. Furthermore, hunger is linked to enhanced anticipatory and consummatory reward responses [6,7]. Thus, hunger is associated with

altered cognitive and physiological processes that are adaptive for homeostatic (i.e., hunger-driven) eating. However, these same processes can contribute to non-homeostatic eating, which puts people at risk for overweight and obesity [8,9]. Altered food cue processing during hunger may, therefore, be analogous to altered processes in individuals that are prone to non-homeostatic eating. Thus, developing a better understanding of the cognitive changes that promote homeostatic eating also provides insight into relevant pathways for non-homeostatic eating. As decreased inhibitory control is also associated with increased food intake [10,11], the relationship between inhibitory control and food deprivation may be a particularly promising avenue for understanding cognitive adaptations under fasting conditions that promote food intake.

Still, the relationship between aberrant inhibitory control and food deprivation remains ambiguous. Hunger, as an internal state, may influence inhibitory control with regard to state relevant cues, such as food cues (Jones et al., 2018) [12]. In studies using go/no-go tasks as a measure of inhibitory control, researchers found evidence of decreased inhibitory capacity to food stimuli within hungry participants, either when paired with non-food stimuli [13] or when high- and low-caloric stimuli were compared [14]. Likewise, Bartholdy et al. [15] found that fasted individuals engaged in steeper delay discounting, another marker of lowered inhibitory control, which quantifies the preference for small immediate rewards over large future rewards. Paradoxically, within the same study, they additionally found that fasting improved participants' inhibitory control on a stop-signal task [16,17]. This result needs to be interpreted with caution, however, since too few trials were included in the paradigm for a reliable estimate of inhibitory control [18]. Thus, there are indications for reduced inhibitory capacity in fasted individuals, but the issue warrants further research.

At present, it is unknown which food cue modalities elicit the need for inhibitory control. Several studies have shown that exposure to food cues in various modalities can lead to increased caloric intake [19–21] and that motivational responses are enhanced under food deprivation [6,22]. This suggests a general need for inhibitory control when encountering food cues. Specifically, olfactory [19–21], visual, and cognitive [19] food cues have been shown to influence food intake, hunger, or food craving [22]. However, as of yet, researchers in this domain have not focused on the difference between different stimulus modalities, such as words vs. pictures, which might give rise to different types of representations and, therefore, differentially affect inhibitory control (see e.g., [23], dual-coding theory). Pictures of objects share more of the relevant sensory properties with the objects they depict and may thus activate more modal representations compared to words referring to these objects, which might be associated with more amodal representations (for a discussion, see [24]). Indeed, as part of their theory, Strack and Deutsch [4] posit that the two postulated systems operate on different representations. Whereas the impulsive system operates through behavioral schemata activated by associated input from the environment, the reflective system processes semantic and episodic information to arrive at behavioral intentions. Therefore, stimuli with different degrees of sensory properties may be preferentially processed by different systems. Specifically, modal (sensory) stimuli have an immediate relevance for behavioral schemata pertaining to eating. This type of information processing is associated with impulsive processing. Indeed, this is in line with other areas of research [25]. For example, it has been shown that pictorial negations ease the execution of the corresponding behavior [26] and more strongly activate affective processes [27]. The latter is particularly interesting, as increased arousal to food cues may contribute to overeating [28,29]. Amodal (abstract) stimuli, on the other hand, do not have immediate implications for behavior and may rather speak to the evaluative semantic processes of the reflective system. If true, in a fasted state, in which behavioral schemata pertaining to food intake are highly relevant, we would expect modal stimuli to directly activate the impulsive system, bringing on the abovementioned impaired inhibitory control. Amodal stimuli, on the other hand, should not have as large an impact since they only influence impulsive tendencies indirectly over the reflective system. In contrast to

these considerations, a recent review that took into account stimulus modality (pictures vs. words) observed an effect of stimulus type for alcohol but not for food stimuli [12]. However, this review was based on studies using a range of paradigms for testing inhibitory control, making their results less comparable. Moreover, none of these paradigms directly compared various modalities for food stimuli.

Given the importance of this factor for the impulsive-reflective model (see above), the current study aims to examine multiple food cue modalities in a single paradigm in order to obtain a more precise estimate of their effects. Because we conceptualize modality on a spectrum from sensory to abstract [25] and the sensory input should remain consistent, we used (non)-food pictures as modal stimuli and (non)-food words as amodal stimuli. As valence could influence SST performance [30,31], we included valenced-matched control stimuli (animals) to determine whether the effects would be food-specific. Notably, hunger modulates food processing but not the processing of high-valence pictures [32]. The aim of this study was to evaluate the effect of food cues in different modalities (pictures and words) on inhibitory control under different homeostatic states (fasting and satiated). Observed differences in inhibitory control specific to food cues in either modality would underscore the need for a better understanding of how different food cues influence food intake. To this end, we conducted a pre-registered online study during the COVID-19 pandemic. Fasted and satiated participants completed a stop-signal task (SST [16,17]) as an inhibitory control task with modal (images) and amodal (words) food and non-food cues. In line with previous research [13,14], we expected longer SSRTs (thus reduced inhibitory control) for fasted compared to satiated participants for modal food stimuli, while we did not expect to find this difference for modal non-food stimuli. We expected no significant differences in the SSRTs between food and non-food amodal stimuli. We also did not expect the fasted and satiated groups to have different SSRTs for amodal stimuli.

2. Materials and Methods

This study's hypotheses, planned sample, variables, and paradigms were preregistered and can be found on the Open Science Framework (<https://osf.io/vk7he> (accessed on 3 June 2024), with data and analysis available at <https://osf.io/472kr/> (accessed on 3 June 2024). This study ran from mid-April until the end of May 2022.

2.1. Participants

Participants were recruited using Prolific (www.prolific.co (accessed on 3 June 2024)). Inclusion and exclusion criteria were enforced through a pre-study screening questionnaire. Exclusion criteria were current pregnancy or lactation, bad eyesight, and color blindness. Additionally, participants were excluded if they were unable to fast due to expected/potential physical (e.g., diabetes mellitus) or mental (e.g., eating disorders) negative effects or if they were unwilling to do so for other reasons. Vegan nutrition was a further exclusion criterion due to the use of a stimulus set that included non-vegan products (e.g., cheese). As hunger modulates the processing of food cues in normal weight but not overweight participants [9,13], included participants needed to have a body mass index (BMI) between 18.5 and 25 kg/m². Participants also had to be between 18 years and 30 years old and speak English as their first language. Participants were compensated a total of £10.25 for completing this study. Partial credit was given to participants who only completed the pre-selection questionnaire.

The sample size was calculated using a priori power analysis through Superpower [33]. Means and standard deviations for modal and amodal food stimuli were taken from a pilot study. With a power of $(1 - \beta) = 0.90$, $\alpha = 0.05$, we required 159 participants per group, totaling 318 participants. Given a dropout rate of 15% due to SST performance incompatible with the horse-race model [18], we aimed to recruit 366 individuals (i.e., 183 fasted and 183 satiated). A total of 367 participants completed the full study, out of which 164 were discarded: 31 participants did not fill out one or more of the questionnaires, 71 demonstrated behavior on the SST that was incompatible with the horse-race model [18],

and out of the remaining participants, 122 did not fulfill the fasted or satiated criteria (see 2.1.1). We thank an anonymous reviewer for suggesting the use of stringent inclusion criteria, leaving a total sample of 143 participants (67 fasted and 76 satiated). This reduced our power to only $(1 - \beta) = 0.55$ for the expected effect size.

2.2. Design and Procedure

This study required participation in two parts, both completed fully online and on separate days. In the first step (10 min), participants completed a screening of inclusion and exclusion criteria via the SoSci Survey [34]. At the end, they were instructed to choose a day in the upcoming week in which they could either fast overnight or eat their meals as usual, depending on random assignment. On this day, they needed to complete the second part of this study through a personalized link either before (fasted condition) or after (satiation condition) lunch.

On this second day (approximately 50 min, depending on variation in reaction times in the SST and questionnaire completion times), participants indicated their hunger levels among filler state questions on a 0–100 scale visual analogue scale (VAS), after which they completed the questionnaires and the SST. This included 16 practice trials in which participants could familiarize themselves with the task. Practice trials included a random subset of stimuli from both modal (picture) and amodal (word) categories. Finally, participants indicated when they last consumed calories under the assurance that this would not influence their compensation.

2.3. Stop-Signal Task

Participants indicated the location of continuously presented words or pictures by key press [35]. In some trials, a stop signal followed the presentation of the stimulus. Participants were instructed to inhibit their response upon seeing this stop signal. The task ran with two separate sets of picture and word stimuli so that the pictures of the first set were described using the words of the second set and vice versa. Participants were randomly assigned a stimulus set at the beginning of the SST. Overall, we had 32 pictures of high-caloric food and 32 non-food pictures (animals). Pictures were complexity-matched within their set using the ‘imagefluency’ package in R [36]. For the amodal stimuli, we selected 32 corresponding English food words and 32 non-food (animal) words. Words were matched per set in length and frequency using the Corpus of Contemporary American English [37]. This corpus represents word frequencies in American media such as film, print, and webpages. Pictures were pre-rated and taken from our internal database.

Besides 16 practice trials, participants completed a total of eight blocks of 128 trials each, totaling 1024 trials. In 25% of trials, the stop signal was shown. The stop-signal presentation was balanced over blocks and over stimulus types. All trials started with a fixation cross, which was displayed for 250 ms. Afterwards, a food picture or word was presented to either the left or right of the fixation cross. Participants were instructed to indicate whether the stimulus appeared left or right of a fixation cross with the right and left arrow keys as quickly and accurately as they could (Figure 1). Stimuli remained on the screen for up to 1250 ms or until a response key was pressed. The modality of the stimulus and its content were irrelevant to the task. On stop trials, a stop signal in the form of a blue box appeared around the stimulus with a variable delay after stimulus onset. This stop-signal delay (SSD) was originally set to 200 ms and increased or decreased depending on the individual participant’s performance. If participants correctly inhibited their response, the SSD was increased by 50 ms, making stopping on subsequent trials more difficult. If, on the other hand, participants incorrectly pressed a key, the SSD was decreased by 50 ms. The goal of this tracking algorithm was that the participant could inhibit around 50% of all stop trials, which is required for a reliable calculation of the Stop-Signal Reaction Time (SSRT [18]), our imputed measure of inhibitory control. SSDs tracked for all combinations of modality and stimulus type (picture–food, picture–non-food, word–food, and word–non-food) to later estimate independent SSRTs.

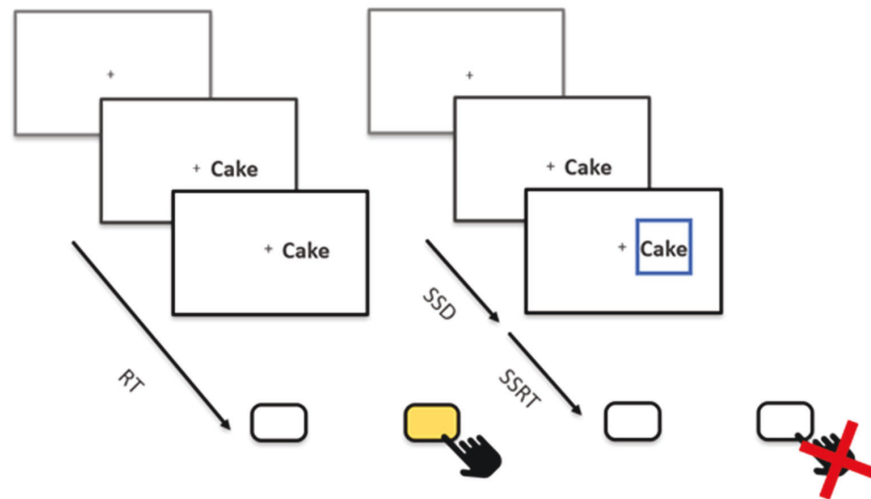


Figure 1. A Schematic Overview of the Stop-Signal Task. The fixation cross was presented for 250 ms, followed by the stimulus presentation until participants responded or for a maximum of 1250 ms. No feedback was given between trials; instead, participants received feedback on their performance during the 7 breaks between blocks. Each break lasted 15 s. The initial SSD was set to 200 ms, which was shortened (missed) and lengthened (stopped) by 50 ms after each stop trial. RT = Reaction Time, SSD = Stop-Signal Delay, SSRT = Stop-Signal Reaction Time.

To ensure limited interactions between pictures and words, each block exclusively contained trials of one of these modalities. Blocks alternated between modalities, and the starting block was counterbalanced. Between each block, participants took 60-s breaks, during which they received feedback on their performance; they were presented with their (overall) mean reaction time, the number of go-trial omissions, and the percentage of successfully inhibited stop-trials, together with a reminder that go-trial omissions should be 0 and that around 50% of stop-trials should be successfully inhibited [18]. Participants were instructed not to wait for the stop signal. The SST was programmed with jsPsych [38] and an adaptation of the STOP-IT paradigm [18]. Previous versions of the SST demonstrated poor to good test–retest reliability [39–41], while models indicate higher reliability of SSRT estimates for the integration method used here [18].

2.4. Questionnaires

To assess participants' eating disorder pathology, participants completed the Eating Disorder Examination Questionnaire (EDE-Q [42]), which consists of 28 items that are answered on a 7-point Likert scale. To assess the severity of depressive symptoms, participants completed the Beck Depression Inventory-II (BDI-II [43]), a self-report measure that consists of 21 items rated on 0–3 Likert scales. Both the EDE-Q [44] and the BDI-II [45] have good psychometric properties. In the present study, Cronbach's α was $\alpha = 0.94$ for the EDE-Q and $\alpha = 0.92$ for the BDI-II. Additionally, participants completed the Restraint Scale (RS [46]). The RS was added for exploratory purposes since restraint eating is our grouping variable for a related project. The scale has 10 items, which reflect weight fluctuations and diet attempts. Cronbach's alpha for the RS in the present sample was $\alpha = 0.81$.

2.5. Data Analysis

All data were analyzed in R [47] using the tidyverse package [48]. We pre-processed and calculated modality-specific SSRTs using the integration method with the replacement of response omissions [18]. This method allows for a reliable estimate of the SSRT since it accounts for omitted go trials and incorporates every individual's stopping probability [18]. We subjected reaction times and SSRT estimates to a 2 (Group: fasted vs. satiated) \times 2 (Modality: picture vs. word) \times 2 (Stimulus type: food vs. non-food) mixed-model analysis

of variance (ANOVA). Effect sizes are reported as partial eta-squared (η_p^2) and are defined as small ($\eta_p^2 = 0.01$), medium ($\eta_p^2 = 0.06$), and large ($\eta_p^2 = 0.14$) [49].

3. Results

3.1. Group Characteristics

Fasted and satiated groups did not differ significantly in terms of sex distribution, age, body mass index (BMI), BDI-II score, or EDE-Q (sub)scores. Crucially, groups significantly differed in their self-reported hunger, with the fasted group reporting higher hunger levels than the satiated group (Table 1).

Table 1. Group characteristics. BMI = body mass index, BDI-II = Beck's Depression Inventory-II, EDE-Q = Eating Disorder Examination Questionnaire, RS = Restraint Scale.

	Fasted Mean (SD)	Satiated Mean (SD)	Statistics	p-Value
<i>n</i>	67	76		
Sex (n women)	43	55	$\chi^2(1) = 1.59$	0.21
Age	24.3 (3.9)	24.9 (3.4)	$t(141) = -1.05$	0.30
Hunger	72.1 (23.3)	16.3 (16.3)	$t(141) = 18.3$	<0.001
BMI	21.9 (1.7)	21.6 (1.9)	$t(141) = 0.97$	0.34
RS	11.9 (6.2)	11.6 (5.9)	$t(141) = 0.25$	0.81
EDE-Q total	1.4 (1.2)	1.3 (1.2)	$t(141) = 0.42$	0.68
BDI-II	13.9 (11.1)	14.9 (11.4)	$t(141) = -0.51$	0.61

3.2. Stop-Signal Reaction Time

We observed a significant interaction of Group \times Modality \times Stimulus Type of small to medium effect size ($F(1,141) = 5.29$, $p = 0.023$, $\eta_p^2 = 0.036$; Figure 2) in the absence of main effects ($F_s < 1.75$, $p_s > 0.19$). Post-hoc 2 (Modality: picture vs. word) \times 2 (Stimulus type: food vs. non-food) repeated measures ANOVAs conducted separately for each group revealed a significant interaction of Modality \times Stimulus Type with a medium to large effect size ($F(1,66) = 8.20$, $p = 0.006$, $\eta_p^2 = 0.11$) and a main effect of Modality of medium effect size ($F(1,66) = 5.21$, $p = 0.026$, $\eta_p^2 = 0.07$) in the fasted group. As expected, there were no significant differences in the SSRT in the satiated group (all $F_s < 1.44$, $p_s > 0.23$). Against our expectations, follow-up t -tests revealed that fasted participants had a lower SSRT for words compared to pictures in the non-food condition ($t(66) = 10.25$, $p = 0.002$), indicating better inhibitory control for words (Figure 2). In the food condition, there were no SSRT differences between words and pictures ($t(66) = 0.177$, $p = 0.675$). There were no differences between stimulus types within the picture or word modality (all $t_s < 3.00$, $p_s > 0.088$).

3.3. Reaction Time

We found a significant main effect of Modality on reaction time ($F(1,141) = 17.64$, $p < 0.001$) so that participants reacted faster to words than to images. We further found a main effect of Stimulus Type ($F(1,141) = 24.73$, $p < 0.001$), with participants reacting quicker to non-food compared to food stimuli. There was also a significant interaction of Group \times Stimulus Type ($F(1,141) = 4.25$, $p = 0.039$), with satiated participants reacting quicker than fasted participants in the non-food condition but not in the food condition. There were no other significant main effects or interactions (all $F_s < 3.36$, $p_s > 0.070$). Average reaction times, as well as other SST parameters, can be found in the Supplementary Materials (Table S1).

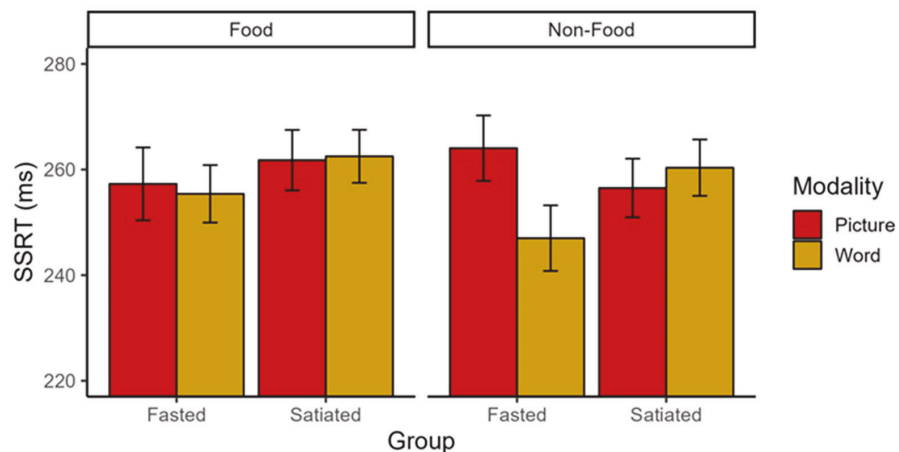


Figure 2. SSRT for Group, Modality, and Stimulus type. Individuals who are fasted have better inhibitory capacity for non-food words compared to pictures, whereas individuals who are satiated do not show this tendency. The figure reflects mean and standard errors. SSRT = Stop-Signal Reaction Time.

4. Discussion

The reflective-impulsive model [4] is often used to explain the decreased inhibition for salient food cues observed in heightened motivational states, such as hunger or aberrant eating behavior. However, the influence of different types of mental representations on these processes has been largely neglected. Here, to better understand how inhibitory control interacts with regular homeostatic appetite regulation, we used sensory, modal (picture), abstract, amodal (word) food, and non-food stimuli in a common inhibition paradigm to test their impact on fasted and satiated individuals. We assumed that pictures would be associated with more modal representations while words would be associated with more amodal representations of the respective content. Crucially, we found an interaction that points to an inhibitory advantage specifically for amodal over modal non-food stimuli in fasted individuals, which could not be observed in satiated individuals. Therefore, our results indicate a hitherto unrecognized interaction between mental representations and homeostasis in inhibitory control.

Still, the direction of these processes did not align with our expectations. Originally, we postulated that modal food stimuli would primarily activate the impulsive system, which should correspond to inhibitory difficulties for food after fasting when it is highly relevant. Conversely, we expected that amodal stimuli would activate the reflective system, thus omitting the activation of approach tendencies and the associated reduced inhibitory capacity in both fasted and satiated states. However, in line with Bartholdy, Cheng, Schmidt, Campbell, and O'Daly [15], we did not find any differences between groups or modalities in the food condition. Rather, we found an inhibitory advantage for amodal over modal stimuli for non-food stimuli in fasted individuals. As such, potentially amodal stimuli only weaken inhibitory control if they are state-relevant (i.e., food stimuli in the current study), whereas state-irrelevant amodal stimuli are associated with better inhibition. Because decreased inhibitory control is associated with increased food intake [10,11], understanding which stimuli elicit decreased inhibitory control may help us target specific stimuli when designing training programs to increase inhibitory control. Indeed, training programs that repeatedly require the inhibition of tempting food stimuli can reduce subsequent food intake [50,51], and understanding which stimuli are particularly threatening under conditions of satiety and hunger may help us to improve these training programs.

Paradoxically, however, we found no differences in inhibitory control in satiated individuals. This may be due to the nature of the non-food stimuli. These were valence-matched rather than neutral to eliminate valence as a possible explanatory variable of our results. However, this positive valence may have differentially affected inhibitory processes.

In alcohol-dependent individuals, for instance, word valence influenced stopping processes independent of cue exposure [30]. In a healthy sample, valenced pictures have also affected stopping efficiency [31]. As the food stimuli did not carry an additional motivational relevance for the satiated group, the food stimuli may have elicited different inhibitory processes in satiated individuals, potentially explaining why we only find modality and stimulus-dependent differences in the fasted group. Our reaction time data may even indicate that food had a lower valence in the satiated group. In the present study, satiated individuals displayed faster reaction times only to non-food stimuli compared to fasted participants. Assuming that faster reaction times indicate increased attentional allocation and stimulus relevance [52], it is possible that non-food stimuli had a higher valence in the satiated group. Thus, the interaction between Group and Stimulus Type in the present study may reflect an unexpected discrepancy in valence in satiated individuals. This discrepancy may be due to the fact that the ratings used for stimulus selection were obtained from participants in different states of satiety, and food stimuli have less relevance when satiated. To further investigate how valence influences performance in both reaction time and SSRT, future studies should, therefore, use stimulus types with varying degrees of valence and include concurrent stimulus valence ratings. It should also be noted that, due to our significantly reduced power, our null results must be interpreted with caution, as smaller effects may be masked. Despite this limitation, we can observe that even if small true effects are present in the data, they are not consistent with our hypotheses: in all conditions except for non-food pictures, the fasted group had descriptively better inhibitory control than the satiated group, whereas we expected the fasted group to have worse inhibitory control in the modal food condition. Therefore, the current data seem to support a rejection of the original hypotheses.

Nevertheless, the current results provide a first indication that stimulus modality cannot be assumed to be trivial regarding inhibitory control. This extends previous research, which also found that modality can affect performance in a dot-probe task, albeit as a function of caloric value rather than the homeostatic state [53]. Thus, the choice of stimulus modality in food processing studies may be a source of heterogeneity in the existing literature. Moreover, stimulus modality can be considered a potential factor of interest in abnormal eating due to its interaction with the homeostatic state. In fact, one study has shown that hunger interacts with reduced inhibitory control to induce higher caloric intake [3]. Others have found that hunger differentially affects inhibitory control and reward sensitivity in individuals with overweight [54] and unsuccessful dieters [55]. Future studies should, therefore, consider trait-like eating behavior and weight factors when further investigating the interaction between stimulus modality and homeostasis. Furthermore, although addressing more amodal stimuli already expands the range of relevant stimuli, previous studies have shown that other sensory stimuli, such as olfactory food cues [19–21], and abstract stimuli, such as cognitive food cues [19], also induce hunger and craving. If we conceptualize modality as a spectrum [25], with food pictures and smells on the modal side and words and cognitions on the amodal side of the spectrum, we might expect inhibitory control over olfactory stimuli to mimic food pictures, whereas cognitive stimuli might mimic our results related to food words. In addition, the combination of multiple sensory inputs may influence our perception and intake of food [56], but their effects on inhibitory control remain unexplored. Finally, in accordance with reduced inhibitory control in individuals with overweight [57] or unsuccessful dieters [58], training programs have been developed to improve food-related inhibition in these groups [59]. However, these training programs have mostly targeted pictures (e.g., [60,61]), whereas our results suggest that words similarly elicit inhibitory control. Thus, future inhibition training programs may benefit from incorporating a variety of stimuli and contexts that better reflect the diversity of sensory and abstract experiences in our food environment.

This study has several limitations. First, due to unexpectedly high dropout rates, our sample size was smaller than required to achieve the intended statistical power. Notably, though, this limited power specifically decreased our ability to find the assumed three-way

interaction. Since the identified three-way interaction differed from our initial assumptions and the descriptive direction of the effects in the data contradicts our initial hypothesis, we still have grounds to reject this initial hypothesis. Therefore, replication of this unexpected effect in a laboratory setting is crucial for consolidating these findings. Furthermore, because previous laboratory SST experiments have shown lower attrition rates (e.g., [57,62]), such studies are needed to control for any selection bias introduced by administering the stop-signal task online rather than in the laboratory. Second, our stimuli were irrelevant to the task. To categorize the images, participants only had to indicate the location of the stimulus appearance. Also, as we did not ask participants to freely recall or identify the stimuli presented, we do not know the extent to which participants processed pictorial and verbal stimuli. As such, the depth of processing may have influenced the effect of the stimuli on cognitive control [62]. In particular, since such processing would enhance modality differences, the presence of an interaction between stimulus modality and homeostasis in a task that did not require stimulus processing highlights its potential relevance. Third, as mentioned above, based on pilot pre-ratings of the stimuli used, our animal stimuli were positive in valence rather than neutral, which may have influenced both attentional [63] and inhibitory processing [31]. Therefore, image valence should be assessed concurrently to test for valence as a possible moderator. Fourth, the word and picture stimuli had distinct visual properties; where the pictures had a range of colors, the words consisted of simple black and white letters, which were exclusively in English. It is, therefore, possible that the effects we find are based on these different visual properties rather than the processing of their meaning or using different languages or writing systems. Hence, future studies should control for these differences by manipulating meaning in addition to valence, e.g., by employing illegible scripts. Similarly, order effects on the SSRT could indicate that the representations of pictures and words influence each other, even when a one-to-one pairing is not possible and stimuli are divided into pictures and words based on subcategories (sweet and savory). Further research is therefore needed to better understand how these representations affect inhibition individually and how they interact when used together. Fifth, it is likely that our study suffered from selection bias. Although dropout rates were similar for fasted and satiated individuals, participants were explicitly asked whether they were theoretically willing to be assigned to either group. Those who indicated they would not accept their randomized assignment were not invited for further participation. Hence, the current study does not represent participants who are theoretically unwilling to fast. Furthermore, because hunger affects food processing differently in individuals who are overweight [9], we included only individuals with normal weight in the current sample. Therefore, our results are limited to altered processing under different homeostatic states in a population that has relatively stable homeostatic control over its food intake. Because the processes that influence homeostatic and nonhomeostatic eating overlap at several nodes in the brain's feeding and reward systems [8], the current findings can only be used to hypothesize that modality may differentially affect the processing of food cues in populations characterized by nonhomeostatic eating. Sixth, it is important to acknowledge that the current experiment only sheds light on inhibitory control as measured via the SST. Paradigms such as the go/no-go task measure other aspects of inhibitory control [64], so further research is needed to fully understand the impact of modality on this overarching construct. Finally, because the studies were conducted entirely online due to the COVID-19 pandemic, we had no control over actual food intake, the device used to complete the SST, or other confounding factors such as sleep, medication use, stress, and emotional state. Although we instructed participants to complete the task in a distraction-free location, the (food) environments in which participants completed the paradigm were also likely to be highly variable. This variability also prevented us from using more objective measures of eating behavior, which we attempted to overcome by asking participants to report their last meal. However, self-reported food intake is thought to be inaccurate with respect to caloric intake [65]. As we attempted to systematically manipulate hunger, variation in reported intake may have influenced participant inclusion and exclusion criteria for participants,

thereby exacerbating our selection bias. We must, therefore, expect increased noise in our data, highlighting the importance of controlled laboratory studies to replicate these findings, especially when controlling for hunger levels.

5. Conclusions

In summary, we found evidence that homeostatic state, stimulus type, and stimulus modality interact in their influence on inhibitory control over positively valenced stimuli. Specifically, whereas fasted individuals have better cognitive control for words compared to pictures, no such differences are found in satiated individuals. A deeper understanding of these processes may help us to better understand how the homeostatic state interacts with the food environment to drive eating behavior, which, in turn, has implications for weight regulation through restrictive dieting. Further research is needed to better understand the mechanisms underlying this relationship, particularly with regard to affective processing and its implications for populations who struggle to control food intake.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/nu16142190/s1>, Table S1: Stop-signal task characteristics.

Author Contributions: Conceptualization, J.S., B.K. and M.M.v.d.H.O.; methodology, J.S. and M.M.v.d.H.O.; software, M.M.v.d.H.O. and U.S.; validation, J.S. and M.M.v.d.H.O.; formal analysis, M.M.v.d.H.O. and J.S.; investigation, M.M.v.d.H.O.; resources, J.S.; data curation, M.M.v.d.H.O.; writing—original draft preparation, M.M.v.d.H.O.; writing—review and editing, J.S., U.S., B.K. and C.G.; visualization, M.M.v.d.H.O.; supervision, J.S.; project administration, J.S.; funding acquisition, J.S. and C.G. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The institutional review board of the local university approved this study (project number 945/2020BO2), which was conducted in accordance with the ethical code of the World Medical Association (Declaration of Helsinki).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: This study's hypotheses, planned sample, variables, and paradigms were preregistered and can be found on Open Science Framework (<https://osf.io/vk7he> (accessed on 3 June 2024)), with data and analysis available at <https://osf.io/472kr/> (accessed on 3 June 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

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Appendix C

Study 3

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RESEARCH ARTICLE

Practice makes perfect: Restrained eaters' heightened control for food images

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Abstract

Objective: Restrained eaters (RE) show behaviourally unregulated food intake, which is often explained by a deficit in inhibitory control. Despite evidence for general inhibitory deficits in RE, it remains unclear how the variety of (food) cues in our environment can influence cognitive control.

Method: In this re-analysis, we explored the inhibitory capacity of RE and unrestrained eaters (URE) on a stop-signal task with modal (pictures) and amodal (word) food and non-food stimuli.

Results: Although we did not find the expected inhibitory deficits in RE compared to URE, we found a significant Group \times Modality \times Stimulus Type interaction. This indicated that RE have relatively good inhibitory control for food, compared to non-food modal cues, and that this relationship is reversed for amodal cues.

Conclusions: Hence, we showed differential processing of information based on food-specificity and presentation format in RE. The format of food cues is thus an important new avenue to understand how the food environment impedes those struggling with regulating their eating behaviour.

KEYWORDS

cognitive control, dual processes, modality, restrained eating, stop-signal task

Highlights

- Restrained eaters, but not unrestrained eaters, differentially inhibit abstract and sensory cues.
- The nature of this relationship is contingent on the cues representing food or non-food objects.
- Inhibition is relatively good for sensory food cues (pictures) compared to abstract food cues (words).

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1 | INTRODUCTION

High-caloric foods have become exceedingly available, putting a strain on many individuals, as they need to regulate cravings induced by the omnipresence of food (Strack & Deutsch, 2004). This burden falls on some more than others. On the one hand, we see steadily increasing rates of overweight and obesity (Ng et al., 2014), and that dieting is associated with long-term weight gain rather than weight loss (Lowe, 2015). On the other hand, many individuals living in the same (food) environment maintain normative weight without restricting their food intake.

Restrained eating may play into this dichotomy. Individuals with high restrained eating (i.e., restrained eaters [RE]) attempt to limit food intake through cognitive control, while regular disinhibited-eating episodes undermine these attempts (Herman & Mack, 1975). In RE, food cues can exacerbate dietary inhibition (Polivy & Herman, 2017; Shimizu & Wansink, 2011) and disproportionately elicit attention (Hollitt et al., 2010; Meule et al., 2011, 2012). Moreover, RE tend to have a higher body mass index (BMI) and experience more cravings than their unrestrained counterparts (Adams et al., 2019). Indeed, in normal-weight individuals, restraint likely reflects a strategy to cope with weight gain and overeating, albeit an unsuccessful one (Snoek et al., 2008; van Strien et al., 2007). Gaining a deeper understanding of how RE process food information differently from unrestrained eaters (URE) is therefore imperative to discern the mechanisms that contribute to the development of overweight, as well as the mechanisms associated with failed weight loss.

Because deregulation of food intake is one of the defining characteristics of restrained eating, research has taken a particular interest in the relationship between inhibitory control and restrained eating (Herman & Mack, 1975). Response inhibition is of particular interest, as this executive function serves to override automatic responses to cues from the environment (Diamond, 2013). In light of dual process models (Strack & Deutsch, 2004), inhibitory control is part of the reflective system, which has the overarching goal to align behaviour with complex cognitive goals. By contrast, the impulsive system activates behavioural schemata based on input from the environment. If these tendencies oppose the goals of the reflective system, response inhibition can be used to regulate behaviour. For instance, when food cues may initiate approach behaviour that goes against RE's goal of losing weight (Seibt et al., 2007; Veenstra & de Jong, 2010), inhibitory control may need to be employed to regulate these impulses. If inhibitory capacity is low, inhibitory control should fail disproportionately often, resulting in

failed dieting attempts or even weight gain. As such, RE are hypothesised to have decreased inhibitory control (Bartholdy et al., 2016). With regard to response inhibition, this is often measured by a stop-signal task (SST), which measures how well participants can inhibit already initiated responses (Verbruggen et al., 2019), as opposed to, for example, Go/No-go tasks, which measure inhibition before initiation (e.g., Meule et al., 2011). Indeed, studies focusing on general response inhibition as measured by the SST have found evidence for this view (Dong et al., 2014; Jansen et al., 2009; Nederkoorn et al., 2004). However, tests of food-specificity of this effect have shown mixed results. While some research corroborates general inhibitory deficits (Schroeder et al., 2022), others found neither food-specific nor general inhibitory deficits (Houben et al., 2012). In contrast to restrained eating, as defined by Herman and Mack (1975), when measures of *successful* restriction of food intake are used, inhibitory advantages for food items have even been identified alongside deficits for general cues (Ganor-Moscovitz et al., 2018). Thus, although some support for the inhibitory deficits in RE exists, the current literature is contradictory (Bartholdy et al., 2016; Watson & Le Pelley, 2021), an issue that is exacerbated by varied methods to operationalise response inhibition (Diamond, 2013; Logan & Cowan, 1984), and as such warrants further research, especially with regard to the food (un)specificity of these effects.

The modality in which relevant (food) cues are provided may also contribute to heterogeneity in previous studies. Specifically, stimuli of different modalities, such as words versus pictures, may give rise to different mental representations (see e.g., Paivio, 1978, dual-coding theory). With regard to the above-mentioned dual-process models (Strack & Deutsch, 2004), modal sensory cues (e.g., images) are processed mainly by the impulsive system, as sensory experience with objects informs us which behavioural schemata are appropriate to interact with them. Such an interaction is not possible with amodal, or abstract cues (e.g., words). Rather, these are more readily processed by the reflective system, in which they are thought to activate goals and concepts to which they relate. If different modalities of (food) cues activate different systems, certain cues may more readily elicit response inhibition than others. Specifically, we expect less inhibition for modal cues since they more strongly activate the impulsive system encompassing automatic approach tendencies, especially for RE, as they have heightened approach tendencies upon seeing food cues (Veenstra & de Jong, 2010). Despite a recent meta-analysis which found no effects of modality on inhibitory capacity in individuals with overweight (Jones et al., 2018), studies that directly compared the effects of

different modalities are largely absent. Hence, in the present study, we use food and non-food cues of two distinct modalities in a single design, allowing us to test the food-specificity of inhibitory control deficits while considering the influence of (food) cue modality.

The current study is a re-analysis of data from fasted and satiated individuals (van den Hoek Ostende et al., 2022) who completed an SST (Logan, 1994; Logan & Cowan, 1984) with food and non-food cues in different modalities (pictures vs. words; van den Hoek Ostende et al., 2022). Within the modal condition, we expected RE to have lowered inhibitory control for food, but not for non-food pictures compared to URE. We did not expect any differences between food and non-food words. Furthermore, we expected RE, but not URE, to have lowered inhibitory control for food pictures compared to food words, with no differences expected between non-food pictures and words.

2 | METHOD

2.1 | Participants

In this re-analysis, we used the data from a previous study on hunger and satiety (van den Hoek Ostende et al., 2022). All participants were recruited over Prolific (www.prolific.co). On the platform, the study was only shown to registered users worldwide between 18 and 30 years of age who were fluent in English. Other participation criteria were screened in a pre-screening questionnaire. At this stage, we excluded participants with vegan nutrition, who were currently pregnant or lactating, or who had bad, uncorrected eyesight or colour blindness. Participants could only participate if they were (physically and mentally) able to fast for 16 h and were theoretically willing to do so. Furthermore, we only included participants with a BMI between 18.5 and 25.0 kg/m². We compensated participants with £10.25 for the completion of the total study. Partial credit was given to participants who only completed parts of the screening or main task.

For our analysis, we divided the original sample ($N = 203$) into RE and URE groups by taking the upper- and lower-thirds of Restraint Scale scores, resulting in 74 RE, and 81 URE participants in the final analysis sample. The participants in the final sample were mostly from the United Kingdom ($n = 94$) and the United States ($n = 37$) with further participants coming from other countries (e.g., South Africa [$n = 7$], Canada [$n = 5$]). The institutional review board of the local university approved this study (project number 945/2020BO2), which was conducted in accordance with the ethical code of the World Medical Association (Declaration of Helsinki).

2.2 | Design and procedure

Participants completed the screening questionnaire (5 min) and main experiment (50 min) on two separate occasions over SoSci Survey (Leiner, 2019). At the end of the screening, participants were instructed to complete the main experiment at lunchtime on a day of their choice. Half of the participants completed the main experiment after fasting for 16 h, while the other half completed the main experiment while satiated. During the main experiment, participants answered several state questions (e.g., hunger, thirst) on 0–100 visual analogue scales. They subsequently filled out questionnaires and completed the SST. This included 16 practice trials, in which participants practiced both ‘go’ and ‘stop’ reactions on a random subset of stimuli. During this phase, participants got immediate feedback on their performance.

2.3 | Stop-signal task

Participants were instructed to indicate the location of a continuously appearing stimulus through button-press (Svaldi et al., 2014). A stop-signal followed the stimulus presentation in a subset of trials and indicated that participants needed to inhibit their response. Stop-signals were equally balanced over stimulus modality and type. Overall, stimuli comprised 32 pictures of high-caloric food, 32 pictures of animals (non-food controls), and their corresponding nouns in English (black ink, font Arial). These were divided into two sets so that each set consisted of half the pictures and the remaining half of words that did *not* correspond to these pictures. Each participant was randomly assigned a set. Within each set, we matched food and non-food pictures regarding complexity and food and non-food words regarding length and frequency according to the Corpus of Contemporary American English (Davies, 2010).

After finishing 16 practice trials, participants completed 1024 trials divided into eight blocks of 128 trials each, interspersed with 15 s breaks, during which participants received feedback on their performance. Each block was assigned a single modality so that it contained either only (food and non-food) pictures or only (food and non-food) words. Block modality alternated throughout the experiment, with the modality of the first block being randomly assigned. The feedback at the end of each block included the participant's mean reaction time, the number of go-trial omissions, and the percentage of successfully inhibited stop-trials. We also reminded participants that, ideally, their go-trial omissions should be at 0, and their stop-probability around 0.50.

At the beginning of each trial, a fixation cross was shown in the centre of the screen for 250 ms, after which a stimulus was presented to its left or to its right. Participants had to indicate the side of the stimulus as quickly and accurately as possible, without waiting for the stop sign, with the 'x' and "m" keys on the keyboard. Stimuli disappeared when participants indicated its location, or when 1250 ms passed. In 25% of trials, a stop-signal appeared, with signals being balanced over modality and stimulus types. The stop-signal was a blue box that appeared around the stimulus after the stop-signal delay (SSD). This variable delay was initially set to 200 ms and was adapted throughout the experiment; upon each correct inhibition, the SSD was increased by 50 ms, and upon each missed stop-trial (participant pressed a key), the SSD was decreased by 50 ms. This made the task more or less difficult, with the goal of reaching an SSD at which the participant can inhibit around 50% of all stop trials. The SSD was adapted separately for each modality and stimulus type. These values, combined with the stop-probabilities and participants reaction times on go-trials, were later used to compute the stop-signal reaction time (SSRT) with the integration method with replacement of response omission (Verbruggen et al., 2019), so that higher values on the SSRT indicated lower inhibitory control, and vice versa. The SST was an adaptation of the STOP-IT task from Verbruggen et al. (2019) and programmed in jsPsych (de Leeuw, 2015).

2.4 | Questionnaires

2.4.1 | Restraint scale

We measured restrained eating with the Restraint Scale (RS; Herman & Polivy, 1980). This scale has 10 items with a total score range of 0–35. The restraint scale reflects two factors: weight fluctuations and diet attempts. Here, we defined RE as those scoring in the upper third of scores (14 and higher) whereas we defined URE as those scoring in the lowest third of scores (up to 8). We chose these criteria to remain consistent with an ongoing pre-registered study the modality effect on attentional bias in RE. Previous studies demonstrated good construct validity for normal-weight participants, with lower internal consistency and score overestimation in overweight and obesity (Bohrer et al., 2015; van Strien et al., 2007). Additionally, the construct does not fully generalise beyond western societies (Dolan & Ford, 1991; Heatherton et al., 1988; Meule, 2016) and confounds may exist with related constructs such as impulsivity (Jansen et al., 2009), hedonic overeating (Ouwens et al., 2003) and unsuccessful dieting (Houben et al., 2012). The internal consistency in the current sample was good, $\alpha = 0.80$.

2.4.2 | Further questionnaires

In the original study (van den Hoek Ostende et al., 2022), we also used the Eating Disorder Examination Questionnaire (EDE-Q; Fairburn & Beglin, 1994) to assess eating disorder pathology. The self-report measure consists of 28 items that are answered on a 7-point Likert-scale. The EDE-Q has good psychometric properties (Peterson et al., 2007), and in the current study, internal consistency was excellent, $\alpha = 0.93$. Additionally, we assessed the severity of depressive symptoms with Beck Depression Inventory-II (BDI-II; Beck et al., 1988). This questionnaire consists of 21 items, which were rated with scores from 0 (not at all applicable) to 3 (fully applicable), which previous research assigned good psychometric properties (Segal et al., 2008). Internal consistency in the present study was excellent, $\alpha = 0.92$.

2.5 | Data analysis

We used the integration method with replacement of response omission (Verbruggen et al., 2019) to determine four SSRT values for each condition (picture-food, picture-non-food, word-food, word-non-food). We subsequently analysed SSRTs using 2 (Group: RE vs. URE) \times 2 (Modality: picture vs. word) \times 2 (Stimulus type: food vs. non-food) mixed model analysis of variance (ANOVA).

3 | RESULTS

3.1 | Descriptives

As expected (Stice et al., 2010), participants with high restraint also had higher overall eating pathology (Table 1). In line with the literature, we also found more severe depressive symptoms in RE than URE (Ringham et al., 2008), and, despite normative weight being an inclusion criterion, we observed a higher BMI in RE, which typically correlates with RS scores (Adams et al., 2019). Furthermore, gender was distributed differently in RE than URE, with the RE group having a larger proportion of female participants. This is in line with generally higher restraint scores in women (Klem et al., 1990). Participants did not significantly differ in age (Table 1).

Participants completed the study anywhere between 0 and 20 h postprandial; half the participants were randomly appointed to an overnight fast, and half to eat as regular. Although we re-assigned groups by top and bottom thirds of RS scores, a Chi-Square Test of Independence demonstrated no relationship between restrained stated and originally appointed condition ($\chi^2 [1, N = 155] = 0.30$,

$p = 0.63$). Moreover, participants did not differ significantly in experienced hunger (Table 1).

3.2 | Stop-signal reaction time

We observed a significant three-way interaction of Group \times Modality \times Stimulus type ($F [1153] = 4.95$, $p = 0.028$, $\eta_p^2 = 0.031$; Figure 1). We found no other significant main or interaction effects (all $F_s < 0.87$, $p_s > 0.35$). Notably, the three-way interaction remained significant when additionally controlling for the skewed gender distribution between RE and URE and incorporating metabolic state as an additional factor did not change the outcome of the present analysis (Supplementary Analysis 1).

Post-hoc 2 (Modality: picture vs. word) \times 2 (Stimulus type: food vs. non-food) repeated measures ANOVAs conducted separately for the two groups of participants revealed a significant Modality \times Stimulus type interaction in RE ($F [1,73] = 4.43$, $p = 0.039$, $\eta_p^2 = 0.057$), in the absence of main effects (Figure 1). As expected, within URE, no significant effects were found (all $F_s < 1.43$, $p_s > 0.24$). Against our expectations, however, follow-up t -tests within RE conducted separately for modality and stimulus type did not reveal any significant differences (all $t_s < 2.10$, $p_s > 0.15$). Furthermore, a post-hoc 2 (Group: RE vs. URE) \times 2 (Stimulus type: food vs. non-food) mixed ANOVA conducted separately for the two modality types revealed a significant group \times stimulus type interaction in pictures ($F [1153] = 4.55$, $p = 0.034$,

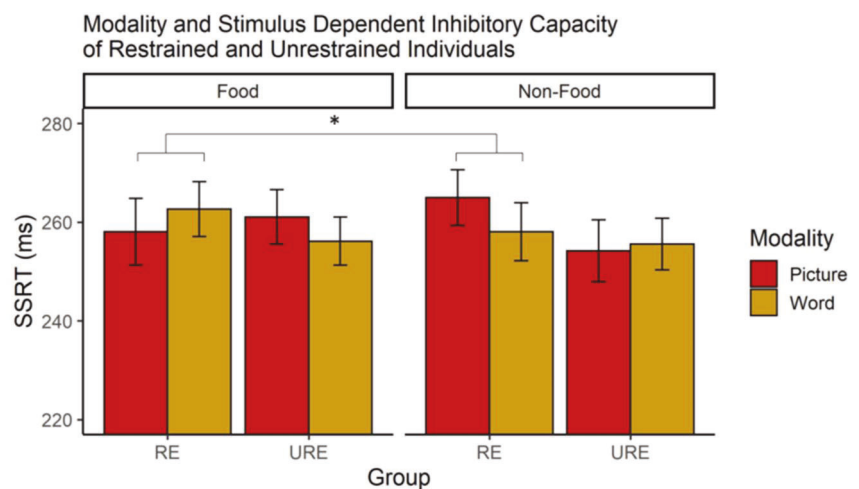
TABLE 1 Group characteristics.

	RE Mean (SD)	URE Mean (SD)	Statistics	<i>p</i> -value
<i>n</i>	74	81		
Gender (<i>n</i> female)	51	40	$\chi^2 (1) = 6.09$	0.016
Age	24.6 (3.4)	23.9 (3.7)	$t (153) = 1.33$	0.186
Hunger	42.6 (36.0)	46.3 (36.1)	$t (153) = -0.64$	0.526
BMI	22.4 (1.8)	21.3 (1.7)	$t (153) = 4.12$	<0.001
RS	17.9 (3.3)	6.0 (2.1)	$t (153) = 27.54$	<0.001
EDE-Q total	2.2 (1.0)	0.50 (0.4)	$t (153) = 13.88$	<0.001
EDE-Q restraint	2.2 (1.5)	0.40 (0.6)	$t (153) = 10.03$	<0.001
EDE-Q eating concern	1.3 (1.1)	0.17 (0.2)	$t (153) = 9.04$	<0.001
EDE-Q weight concern	2.4 (1.3)	0.55 (0.5)	$t (153) = 12.34$	<0.001
EDE-Q shape concern	3.0 (1.3)	0.90 (0.7)	$t (153) = 12.59$	<0.001
BDI-II	18.1 (11.3)	9.5 (9.1)	$t (153) = 5.28$	<0.001

Note: Bold value represents the amount of participants per group.

Abbreviations: BDI-II, Beck's Depression Inventory-II; BMI, Body Mass Index; EDE-Q, Eating Disorder Examination Questionnaire, RE, Restrained Eater; RS, Restraint Scale; URE, Unrestrained Eater.

FIGURE 1 Modality and Stimulus dependent Inhibitory Capacity of Restrained and Unrestrained individuals. The interaction of modality and stimulus type is associated with differential inhibitory control in restrained, but not in unrestrained eaters. Figure reflects means and standard errors. RE, Restrained Eaters; SSRT, Stop-Signal Reaction Time; URE, Unrestrained Eaters.



$\eta_p^2 = 0.029$) in the absence of main effects. Within the word modality, no significant effects were found (all $F_s < 0.60$, $p_s > 0.44$). Follow-up t -tests within the picture modality conducted separately for group and stimulus type did not reveal any significant differences (all $t_s < 2.85$, $p_s > 0.10$). Post-hoc ANOVAs dividing the data by stimulus type (food vs. non-food) did not yield any significant results (all $F_s < 2.56$, $p_s > 0.11$). All means and standard deviations can be found in Table S1.

Admittance of participants to the final sample of the original study depended on instruction adherence. Since we found that neither group assignment, nor reported hunger differed between RE and URE, and that group assignment did not influence our results, we repeated the 2 (Group: RE vs. URE) \times 2 (Modality: picture vs. word) \times 2 (Stimulus type: food vs. non-food) ANCOVA with all valid data sets, independent of instruction adherence (Supplementary Analysis 2). Our analyses yielded the same results.

4 | DISCUSSION

Restrained eating describes the degree to which individuals attempt to restrict cognitively, while behaviourally deregulating their food intake (Herman & Mack, 1975). Decreased inhibitory control is often offered as an explanation for the latter (Bartholdy et al., 2016), even though results, especially with regard to food-specificity, have been inconsistent (Watson & Le Pelley, 2021). Here, we used food and non-food stimuli in modal (picture) and amodal (word) formats in a SST, with the hypothesis that RE would have difficulties inhibiting modal food stimuli. This hypothesis could not be confirmed. Rather, we found that in RE, inhibitory control of food and non-food stimuli is differentially effective depending on the stimulus modality. Specifically, the pattern found suggests relatively good inhibitory control for modal, compared to amodal food stimuli. Although our results thus diverge from the concept of (general or food-specific) inhibitory control as a driver of unregulated eating in RE, they also offer a possible contribution to inconsistencies in the literature.

Specifically, studies seem to favour a general inhibitory deficit in RE (Dong et al., 2014; Jansen et al., 2009; Nederkoorn et al., 2004; Schroeder et al., 2022), with more diverse results found concerning the idea of food-specific inhibitory deficits (Houben et al., 2012; Schroeder et al., 2022). Here, we found neither general nor food-specific deficits. Rather, our results indicate that abstract stimuli (words) may elicit different levels of inhibitory control in RE than sensory (pictures) stimuli, depending on stimulus type (e.g., food, non-food). As

such, the variety of stimuli used in previous studies may contribute to heterogeneity in the literature. For example, symbolic (e.g., letter) stimuli are often used to measure general inhibitory capacity (e.g., Dong et al., 2014; Houben et al., 2012; Jansen et al., 2009; Nederkoorn et al., 2004), whereas pictures are often chosen to test food-specificity (e.g., Houben et al., 2012; Schroeder et al., 2022). Of the two studies that directly compared food and non-food stimuli within the same modality (pictures), one found general inhibitory deficits in RE (Schroeder et al., 2022), whereas the other found enhanced inhibition for food, and decreased inhibition for non-food stimuli (Ganor-Moscovitz et al., 2018). Crucially, the latter used a different measure of dietary restraint that, unlike the Restraint Scale (Herman & Mack, 1975), reflects *successful* restriction of food intake (Adams et al., 2019). In line with this, successful dieters inhibited ongoing responses more effectively when presented with a stop-cue than non-dieters (Veling et al., 2011). In addition, successful dieters, relative to non-dieters were also shown to snack less following food-specific stop-signal based inhibition training (Lawrence et al., 2015). Thus, despite indications for a general inhibitory deficit, cognitive control in successful dietary restraint could be enhanced for (modal) food stimuli.

The relatively improved cognitive control over food in modal stimuli in the present study resembles these findings, even though we used a measure of *unsuccessful* restraint. One explanation could be related to the participation requirements for our current sample. As part of our recruitment process, participants had to confirm that they were willing to fast for 16 h. The requirement could have produced a bias on individuals who are not only willing, but also able to exert restraint for prolonged periods of time. In combination with the exclusion of people who are overweight, our sample may have been relatively successful at restraining their food intake, which was then reflected in our results. Alternatively, based on dual process theories, inhibitory control could be considered a variable process, as it is thought to be mediated by available cognitive resources and the motivational salience of the goal (Strack & Deutsch, 2004). Despite generally attempted heightened control for diet-relevant cues (e.g., modal food stimuli), if the resources are momentarily unavailable or the goal of losing weight is currently not a priority, RE could still loosen their grip on their food intake. Such temporary lapses could then result in bouts of overeating. Indeed, in one study, RE were found to have a lower inhibitory capacity only after expending cognitive resources (Zhou et al., 2017). Our current results may therefore reflect transient cognitive control for modal, but not amodal, food cues, which is weakened at times of overeating.

Future studies should thus address whether food-specific inhibitory control varies over time and contexts, to characterise the relationship between restrained eating and dietary lapses.

Relative to the modal condition, RE were worse at inhibiting food compared to non-food amodal cues. We theorise that this relative decrease in cognitive control over modal food cues reflects a heuristic of RE to elicit higher cognitive control for cues that signal the requirement to regulate approach behaviours (Strack & Deutsch, 2004). Amodal cues, on the other hand, may not form an immediate threat, as there are no actionable (food) items available. Still, these cues (e.g., in the form of spoken or written words) may be associated with similar neural activation as the objects themselves (Glenberg, 2010). Therefore, when RE do not restrict their reaction to these cues as they do to modal cues, as we find here, these activations could contribute to (over)eating once food becomes available. Since this would imply that training and therapies designed to help effectively restrict food intake need to take modality into consideration, it is imperative to explore further how amodal cues can undermine inhibitory control. At this point, however, it remains unclear whether modal food stimuli indeed lead to a heightened cognitive control in RE. Therefore, rather than using generally palatable stimuli, future studies should additionally include idiosyncratic modal cues. Such an approach could include personally relevant pictures, but also odours.

Several limitations should be considered when interpreting these findings. Critically, this study was a re-analysis, that re-assigned a sample of fasted and satiated individuals into RE and URE. Although we did not see any differences in average hunger levels, nor any effect of the original group assignment within our results, these original states may have elicited different mindsets. Regarding the fasted group, food restriction schemata may have been particularly active in RE, as this behaviour overlaps with their abstract goal intentions (Strack & Deutsch, 2004). In the satiated state, however, the degree to which RE had meals consistent with this goal could yield different mindsets. For instance, a diet-compatible salad may allow for a continuation of a behaviourally restrictive schema, whereas a rule-breaking portion of fries may elicit further disinhibition (Herman & Polivy, 1980). As we did not control for nor record food intake, we cannot say to which degree these 'states of control' may have influenced our results, particularly regarding RE. Confirmatory research with standardized satiety conditions is thus required to validate the obtained results. Second, the original study only included individuals with normal weight. Since RE is associated with higher BMIs (Adams et al., 2019), excluding overweight and obese individuals may have created a selection bias

for individuals who are more successful at their restraint (see above). Third, we used the upper and lower tertials of the sample to conform to other pre-registered studies. This sampling method may have led to an overestimation of effect size, and limited the generalisability to individuals with middle scores (Preacher, 2015). Fourth, the SST specifically measures late stopping, and as such it remains unclear whether this effect applies to other stimulus-response relations as assessed by, for example, the Go/No-go task (e.g., Batterink et al., 2010; Meule et al., 2011), the mental flexibility task (e.g., Mobbs et al., 2011), or antisaccade paradigms (e.g., Schag et al., 2013). Finally, the results were obtained in an online study. Although this allowed us to recruit a large sample of participants easily, methodological shortcomings must be considered given the hypothesised importance of environmental cues and food intake on control mechanisms—aspects that cannot be controlled within an online study. To determine under which conditions cognitive control may be relatively stronger in modal, and relatively weaker in amodal food stimuli, future studies should therefore focus on laboratory studies where these factors can be manipulated.

In summary, we found evidence that RE exert cognitive control differentially for food and non-food cues, depending on the format used to depict them. We saw that while cognitive control for food pictures is enhanced relative to non-food pictures, the reverse is true for food words. In other words, it seems that RE preferentially control sensory, but not abstract food cues over non-food cues. Therefore, future studies need to probe food cues ranging from sensory (e.g., real food) to abstract (words). Prospectively, this will deepen our understanding of how our food environment undermines weight regulation.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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