Appetite 181 (2023) 106383

Contents lists available at ScienceDirect

Appetite

journal homepage: www.elsevier.com/locate/appet

Playing with temptation: Stopping abilities to chocolate are superior, but also more extensive

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ARTICLE INFO

Keywords:
Inhibitory control
Virtual reality
Chocolate craving

ABSTRACT

Cue-specific inhibitory control is assumed to support balanced food intake, but previous studies with established measures showed inconsistent results. We developed a novel kinematic stop task in virtual reality (VR) and report results from trajectory recordings. The primary objective of this explorative study was to assess the interrelationships between validated measures of food-related inhibitory control and novel measures from the VR task. We hypothesized that healthy female participants show worse inhibitory control when grasping attractive virtual chocolate, compared to non-edible color-and-shape matched objects. We further aimed to quantify the construct validity of kinematic measures (e.g., reaching extent/spatial displacement, movement time after stop-signal, velocity) with established measures of inhibitory control in a keyboard-based adaptive stop-signal task (SST). In total, 79 females with varying levels of chocolate craving participated in an experimental study consisting of self-report questionnaires, subjective chocolate craving, the conventional SST and the kinematic task in VR. Results showed superior stopping ability to chocolate in both tasks. In VR, participants successfully interrupted an initiated approach trajectory but terminated slightly closer to chocolate targets. Stop-signal delay (SSD) was adapted relative to movement onset and appeared later in chocolate trials, during which participants still stopped faster, as was also confirmed by shorter stop-signal reaction time (SSRT) in the conventional task. Yet, SSRT did not correlate with stopping in VR. Moreover, SSRT was related to depressive symptoms whereas measures from VR were related to chocolate craving and subjective hunger. Thus, VR stopping can provide deeper insights into healthy weight individuals' capacity to inhibit cue-specific approach behavior towards appetitive stimuli in simulated interactions. Furthermore, the results support a multi-faceted view of food-specific inhibitory control and behavioral impulsivity.

1. Introduction

Beyond homeostatic regulation, cognitive control processes are an essential part of food intake regulation, given the abundance of food (cues) and the easy availability of calorie-dense foods (Chen et al., 2016). Specifically, food-related inhibitory control may assist regulated food consumption and avoid excessive snacking. When exposed to attractive and palatable food, inhibitory control is required to resist its edible affordances especially given a generally enhanced approach motivation to food (Kahveci et al., 2020; Moore et al., 2022). As such, weakened inhibitory control may contribute to overeating. Indeed, deficits in food-related inhibitory control were shown in individuals with obesity (Lavagnino et al., 2016; Liu et al., 2022; Weller et al., 2008; Yang et al., 2018) and overweight (Guerrieri et al., 2008; Houben et al., 2014; Svaldi et al., 2015), in individuals with food addiction symptoms (Rodrigue et al., 2018), in children with loss of control eating or increased body weight (Levitan et al., 2015; Nederkoorn et al., 2006) and in restrained eaters at risk for disinhibition and weight gain (Bartholdy et al., 2016; Nederkoorn et al., 2004; Schroeder et al., 2022).

Among inhibitory control processes, reactive response inhibition - the ability to withhold a prepotent but unwanted response - seems particularly relevant to substance-related psychopathology in general (Lipszyc & Schachar, 2010; Smith et al., 2014), and food- and eating-related psychopathology specifically (Bartholdy et al., 2016). To assess response inhibition, two state-of-the-art neuropsychological, computerized paradigms are available: the go-/no-go task and the stop-signal task (SST). In the go-/no-go task, participants classify stimuli, e.g., by pressing a left-hand or right-hand key. In a minority of

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https://doi.org/10.1016/j.appet.2022.106383
Received 12 August 2022; Received in revised form 31 October 2022; Accepted 16 November 2022
Available online 24 November 2022

stop-trials, however, the stimulus is presented along with an additional stop-signal and the response must be withheld. In contrast, in the SST, the stop-signal is not presented at stimulus onset, but only with a short lag after stimulus presentation, the so-called stop-signal delay (SSD; Logan et al., 1984; Verbruggen et al., 2019). Accordingly, the key difference between the two paradigms is whether participants interrupt the response before initiation (go-/no-go), or whether they interrupt an already initiated response (SST). Results from continuous electromyography and neuroimaging support the view that stopping in the SST is achieved by fast integration in fronto-basal and sensorimotor systems (Raud et al., 2020; Rubia et al., 2001), thus leading to the interruption of the ongoing response in motor execution.

It is debatable whether deficits in response inhibition are specific to responses to food stimuli, or whether they reflect a general deficit in inhibition-control abilities. Previous studies on stopping abilities to highly appetitive stimuli were ambiguous. When a block manipulation of the SST was performed, overweight participants were particularly impaired in their inhibition to food stimuli (Houben et al., 2014). However, in a trial-wise manipulation of food vs. control stimuli, several studies could not reproduce this food-specific deficit in the stop-signal reaction time (SSRT), the SST's indirect measure of response inhibition latency (Manasse et al., 2016; Schroeder et al., 2021, 2022). Still, in a meta-analysis, pictures of appetitive cues more generally (i.e., food and alcohol) confirmed reduced inhibitory control with a small effect size, but food-related cues also led to more variable results (Jones et al., 2018). Possibly, inhibitory control could be generally impaired following the exposure to appetitive cues, a pattern masked by different block- and trial-wise task designs. Alternatively, due to the fact that stopping performance in the SST is inferred indirectly from repetitive adjustments of the SSD (Verbruggen et al., 2019), this outcome measure may not be sensitive to trial-wise cue presentations and fine-grained influences of attractive stimuli on stopping.

We attempt to address this potential shortcoming of the computerized SST in a virtual reality (VR) setup with extensive hand movement and continuous recording of stop trajectories. VR setups offer motion capture recordings with excellent precision and latency in relatively small areas at limited expense, at least in seated VR setups without free (full-body) movement (Niehorster et al., 2017). In SST experiments, this capacity enables a quantification of stopping directly in individual stop-trials. Namely, immediately following a stop-signal we can measure changes in behavior that are not directly observed by conventional parameters in computerized tasks. Previous research with food-stimuli and motion capture in VR has shown the potential of such setups to measure food-related behavioral biases (Schroeder et al., 2016). In the present study, we enabled a direct assessment of stopping through continuous motion capture; participants were asked to perform a grasping movement with a motion controller covering ~50 cm of mid-air movement towards a virtual food object, and to subsequently collect the virtual food according to a stimulus-irrelevant cue (an arrow pointing to one of two virtual plates). An eye-tracker integrated in the VR headset controlled initial gaze towards stimuli and measured dwell durations. In addition to this go-task, in a subset of trials and after movement onset, participants had to interrupt their movement. A dynamic starting procedure (Scherbaum & Kieslich, 2018) ensured that movements were always initiated before the stop-signal was shown. Through continuous spatial recordings of the hand controller, movement trajectories were used to quantify the timing, extent, and success of stopping directly. A similar rationale has previously been employed for the assessment of symptoms in attention deficit hyperactivity disorder (ADHD) with mouse-tracking, which returned a number of kinematic parameters with better prediction of impulsivity (Leontyev & Yamauchi, 2019). Here, we argue that the VR stop task may be better suited to incorporate motor approach to food (Loijen et al., 2020), because we hypothesize that approach movement is particularly relevant in the context of appetite and food behavior control. Moreover, three-dimensional displays of VR food cues generally (Ferrer-Garcia et al., 2015; Ledoux et al., 2013) and of chocolate specifically (van der Waal et al., 2021) can elicit subjective food and chocolate cravings in non-clinical samples, especially when using high-fidelity virtual models generated from photogrammetry (i.e., three-dimensional photorealistic scans).

The present validation study assessed food-specific response inhibition with a conventional, computerized SST and a kinematic SST in VR. Both tasks were adaptive and had food-specific adjustments of the SSDs. We also recorded measures related to (eating-related) psychopathology to explore different associations of conventional and novel parameters of response inhibition. In previous research, food-related inhibitory control deficits were predictive of subsequent food craving (Meule et al., 2014). Accordingly, for this very first validation study of our VR task we selected chocolate cues, as they represent the most craved food in Western societies (Hill & Heaton-Brown, 1994). Moreover, we tested a sufficiently large sample of healthy-weight women with varying levels of chocolate craving to detect moderate associations of kinematic parameters with the conventional measure of response inhibition in the conventional, keypress-based SST. We also expected worse response inhibition and longer initial fixations in chocolate trials relative to non-food control stimuli (Werthmann et al., 2013), possibly dependent on individual differences in trait impulsivity or chocolate craving.

In all, with this study, we aimed to (i) validate a VR-mediated kinematic SST, by investigating correlations between conventional parameters of inhibitory control (i.e., SSRT) and novel parameters from the kinematic VR, (ii) investigate and characterize chocolate-specific inhibitory control processes and (iii) explore their relationship to inhibition-related parameters (e.g., impulsivity) and to measures pertaining to (eating-related) psychopathology (e.g., chocolate craving, eating restraint, emotional eating, depressive symptoms).

2. Methods

The study was a within-subject design with repeated assessment of chocolate-vs. non-chocolate-related inhibitory control in a conventional, computerized SST and a novel, VR-mediated kinematic SST. All participants were tested in the afternoon in a fixed task order with intermediate assessments of subjective chocolate craving. Participants provided informed consent before experimentation. The study was approved by the local Ethical Committee for Psychological Research (Number of approval: Az: Schröder_2019_0919_166). This study was not preregistered.

2.1. Participants

Female right-handed healthy volunteers were invited to the study (age range: 18–35 years). Obesity was defined as exclusion criterion (i.e., BMI of 30 kg/m^2 or more). Further requirements were normal or corrected vision (preferably with contact lenses or sports glasses), absence of severe health or mental disorder (including absence of seizures, diabetes, and absence of a current eating disorder diagnosis), and pregnancy or lactation to avoid substantially altered food cravings. Sample size was determined according to the primary objective of this study. To detect positive correlations between conventional parameters of inhibitory control (i.e., SSRT) and novel parameters from the VR kinematic task (e.g., approach displacement, time to stop) with a moderate effect size ($r = 0.3$ (Cohen, 1988)), acceptable statistical power ($1 - \beta = 0.8$) and usual alpha error probability ($\alpha = 0.05$), a sample size of $N = 67$ participants was required per an a-priori power analysis. Unfortunately, a wrong version of the conventional SST was started for six participants with the same stimuli and general design, but an incorrect SSD adjustment. As such, no valid data was available for this task. Furthermore, VR assessments or recordings failed for another six participants and experiments were aborted (mostly due to issues with the eye-tracker). Accordingly, to replace these dropouts, a total of 79 participants were recruited to meet the sample size estimate. Demographic information is reported in Table 1.

Table 1
Study sample demographics. Reported are mean (standard deviation) and range of values in the present data. N = 67.

	M (SD)	Range
Age [years]	22.8 (3.51)	18–34
BMI [kg/m^2]	21.7 (2.24)	18.3–29.3
Fasting [hours]	4.24 (2.02)	1–18
Chocolate abstinence [days]	2.71 (2.27)	0–16
Depressive symptoms [PHQ-9]	4.88 (2.60)	1–13
Eating disorder symptoms [EDEQ]	0.99 (0.94)	0–4.43
Trait chocolate craving [FCQ-T-r-Ch]	36.4 (12.8)	16–69
State chocolate craving [VAS pre]	40.2 (25.0)	0–84
Trait impulsivity [BIS-15]	35.2 (3.76)	27–44

Table Note. *PHQ-9 = Patient Health Questionnaire-9, EDE-Q = Eating Disorder Examination Questionnaire, FCQ-T-r-Ch = Food Craving Questionnaire Trait revised Chocolate Version, VAS = Visual Analog Scales, BIS-15 = Barrat Impulsiveness Scales-15. Cut-offs scores: BMI. BMI < 18.5 kg/m^2: underweight, 18.5-24.9 kg/m: normal weight, 25-29.9 kg/m^2: overweight, BMI > 29.9 kg/m^2: obese (World Health Organization);. PHQ-9. < 5: healthy, 5–9: mild, 10–14: moderate, 15–19: moderate severe, and ≥ 20: severe (Gräfe et al., 2004). EDEQ.: global score ≥ 2.3: possible eating disorders (Mond et al., 2004); FCQ-T-r-Ch, VAS, BIS-15. No cut-offs.*

Participants were recruited through circular e-mails within the University of Tübingen. All participants were reimbursed for their participation with a small financial compensation or a corresponding amount of course credit.

2.2. Procedure

Participants were instructed not to eat any chocolate-containing food the day before and the day of the experiment, and not to consume any food other than water in the 3 h prior to the experiment. Most of them reported to have complied with this instruction (see Table 1). After signing the informed consent, participants filled out state-questionnaires (last meal, last chocolate meal, craving, mood) and trait-questionnaires (EDEQ, PHQ-9; see below). They were instructed and tested on the conventional SST (ca. 20 min) and filled out another set of state-questionnaires (craving, mood, simulator sickness). Next, the VR equipment was set up and the VR SST was completed after a brief guided practice. A final set of state-questionnaires was collected (craving, mood, simulator sickness, presence).[1]

To consider variability in chocolate craving which usually peaks between lunch and bedtime (Haynes et al., 2016; Reichenberger et al., 2018), all experiments were conducted between 1 p.m. and 6:30 p.m.

2.3. Stimuli

Stimuli for the conventional SST were pictures of chocolate-containing food (i.e., Chocolate Muffin, Brownie, Milka® Chocolate, Ritter Sport® Chocolate, and Twix®) and non-chocolate stimuli with comparable shape and color (computer mouse, chess figure, book, box, rubber eraser). The stimuli were color-matched for the two conditions (chocolate vs. neutral). The same stimuli were used as 3D models for the SST in VR. Photorealistic textures were generated from photogrammetric scans with a Nikon digital single-lens reflex camera, processed in Meshroom[2] and optimized with Meshlab[3] open source software (Cignoni et al., 2008; Griwodz et al., 2021). In a few cases, pre-existing scans were adjusted for size- and color from an open asset library.[4] All stimuli were rated in 3D after the experiment. Examples are shown in Fig. 1.

2.4. Response inhibition tasks

2.4.1. Conventional SST

The conventional SST was implemented by using Psychopy3 Software (Peirce et al., 2019), and close to previous food-specific SSTs (Schroeder et al., 2022; Svaldi et al., 2014). Stimuli were presented either on the left or right side of the screen in a box on grey background (Fig. 2). The task was to react as fast as possible to the side on which the stimulus appeared by pressing one of two keys. Answer keys were the left and right arrow keys. Participants were instructed to use the index and ring finger of their right hand to press the answer key. Each stimulus was presented until a key press occurred or 2000 ms passed. A black fixation dot appeared 250 ms before the stimulus in the middle of the screen and stayed there for the whole trial. In one fourth of the trials, a stop signal was presented in form of a blue box around the stimulus. When this stop-signal appeared, participants were instructed not to press the response keys. When the wrong key was pressed or a key press occurred despite a stop signal, error feedback was given (German "Fehler"/"error" for 500 ms). Error feedback (German "Zu langsam"/"too slow" for 500 ms) was also given for omitted responses in go-trials.

The SSD was adaptive to the previous stop signal as suggested by Verbruggen et al. (2019). If participants reacted correctly to the stop signal (i.e., successful stopping), the SSD was increased by 50 ms; if the reaction was incorrect, the SSD was decreased by 50 ms. This adaptive tracking versions of the SST will result in a broader range of SSDs and a more reliable SSRT estimate with fewer trials (Band et al., 2003; Verbruggen et al., 2019). The first SSD was 200 ms for all participants. The SSD was separately calculated and tracked for chocolate and neutral stimuli. Previous studies reported acceptable reliability (ICC = 0.71) and test-retest reliability (ICC = 0.72) for adaptive versions of the SST, at least for specific estimation methods with replacement of go omissions and with outlier exclusion. However, other studies have reported worse reliabilities of the SSRT especially if no outlier exclusion was incorporated (Congdon et al., 2012; Soreni et al., 2009; Verbruggen et al., 2019; Wöstmann et al., 2013).

The conventional SST consisted of two practice blocks with 5 and 20 trials and five experimental blocks with a total of 400 trials. In the practice trials, participants could repeat the task until all instructions were understood. In the practice blocks, an alternative set of pictures (food and musical instruments) were used as stimuli. In the experimental blocks, pictures of chocolate and non-chocolate stimuli were used (i.e., two-dimensional pictures of the VR stimuli). The proportion of stop trials was 25% and stop-trials were counterbalanced for responses and stimulus category. After each block, participants had the possibility to take a self-paced break and were informed about their mean reaction time and proportion of correct trials in the previous block. Participants were explicitly reminded not to wait for the stop-signal. Stimuli were presented in a randomized balanced order for each participant individually. The task took approximately 20 min.

2.4.2. Kinematic SST in VR

For the VR task, participants were equipped with a HTC-Vive head-mounted display (HTC Corporation, Taoyuan, Taiwan) with a built-in near infrared eyetracking plug-in by SMI (SensoMotoric Instruments, Teltow, Germany) and a single 6-degrees-of-freedom HTC Vive Wand controller for the tracking of their right hand. We implemented the Wand controller as a white right hand in the virtual environment and the position and movement of the controller continuously updated at refresh rate (120 Hz). With the grip button on the Wand controller participants were able to grab the virtual objects with their right index and middle finger. The eye-tracker was used to trigger stimulus presentation upon a central fixation (if the hand was also in the starting position) and to record initial and total dwell times. Participants were seated in a chair with enough space to freely move their arms and hands. Two opposing lighthouse boxes were firmly installed in the room to capture the

[1] https://gateway.euro.who.int/en/indicators/mn_survey_19-cut-off-for-bmi-according-to-who-standards/.
[2] https://github.com/alicevision/meshroom.
[3] https://www.meshlab.net/.
[4] https://sketchfab.com/.

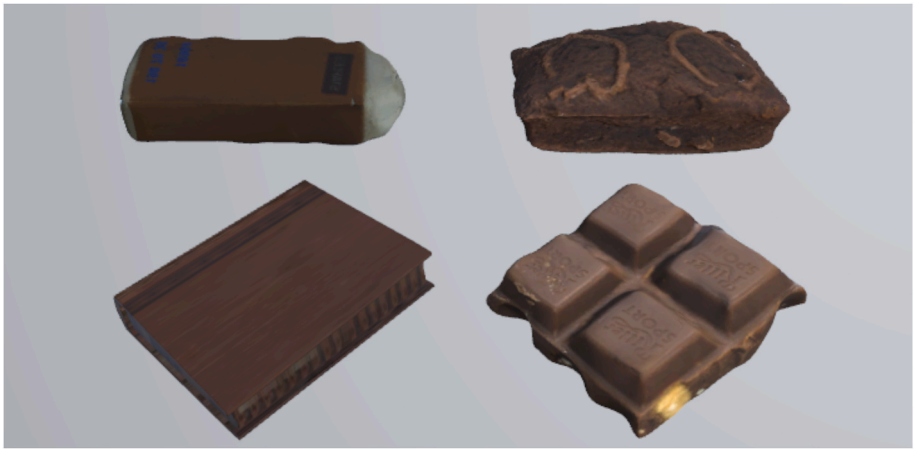

Fig. 1. Examples of control non-edible (left column) and chocolate stimuli (right column).

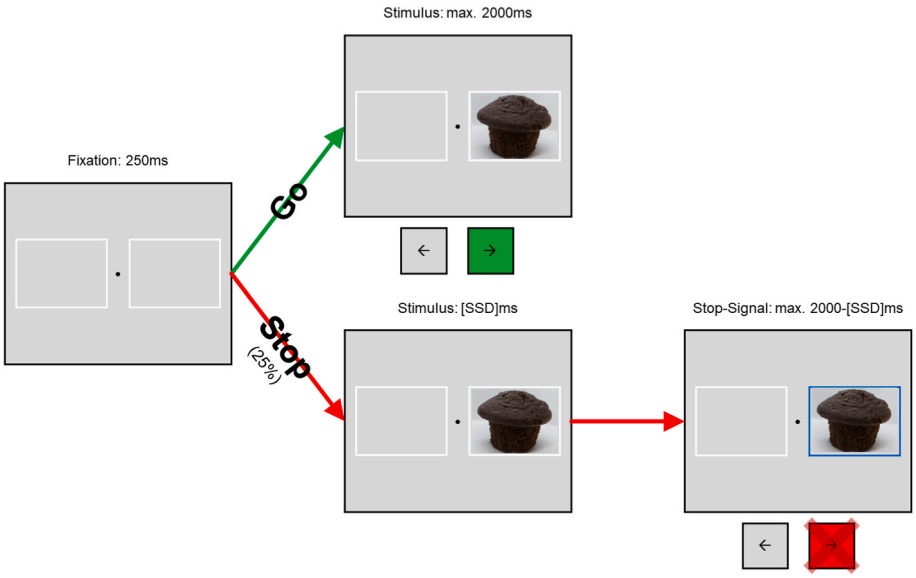

Fig. 2. Exemplary trials of the Stop-Signal-Task (SST). The upper panel shows a go-trial, the lower panel shows a stop-trial, including the stop signal (blue frame around the stimulus). SSD = Stop-signal delay.

movement data in accordance with the manufacturer's recommendations. The experiment was implemented using Unity3D 2018.4.17f1, the SteamVR 1.2 library, and custom C# code.

The VR SST followed a similar structure as the conventional SST, albeit in a more complex motor go-task and a more naturalistic context. The virtual environment was shown from a first-person perspective. It showed a furnished living room including a couch, a cupboard, a window with view of the local mountain. Directly in front of participants there was a table with the task environment, i.e., two plates and one central tray (Fig. 3, see also Supplementary Fig. 1). The plates were located to the right and left of the participant and the tray floated in front of the participant. A green start button was placed 60 cm in front of the tray. The start button was implemented as a dynamic starting line, as recommended by Scherbaum et al. (2018). Stimuli appeared only when the hand was in the starting position and when the eye-tracker confirmed a central fixation (cf. Schroeder et al., 2016). A red ball was used as a fixation point at the stimulus position over the tray. Furthermore, the stop-signal appeared only after an initial movement of the hand had been detected (i.e., the SSD started at movement initiation, and not at stimulus presentation). Continuous recording of the hand position started when participants pressed the start button.

Participants started each trial by moving the virtual hand into the green start-button and focusing on the red fixation ball above the tray. Then, a stimulus appeared on the tray while an arrow on the table indicated the reaction side (see Fig. 3). Participants had to reach for the stimulus and place it onto the correct plate. Participants were instructed to reach for the stimulus in one motion without stopping or hesitating. In one fourth of the trials a stop signal was shown (the tray turned blue and the arrow was crossed out), and participants had to stop their movement, i.e. not reach further for the stimulus. Error feedback was given after incorrect trials (German "Fehler"/"error", or German "Zu langsam"/"too slow" for responses exceeding 2,000 ms, displayed at the position of the arrow on the table until the next trial was manually started by the participant). The SSD was adjusted after each stop-trial in steps of 50 ms for each category separately, identical to the conventional SST. To accommodate for an overall later presentation of the SSD due to the additional contingency of the dynamic starting line, we selected a lower initial SSD at 100 ms for the beginning of the practice-trials and for task initiation.

Participants first performed two practice blocks, one with and one without the stop-signal. Each practice block comprised ten trials. In the stop signal practice trials, the proportion of stop signals was higher than

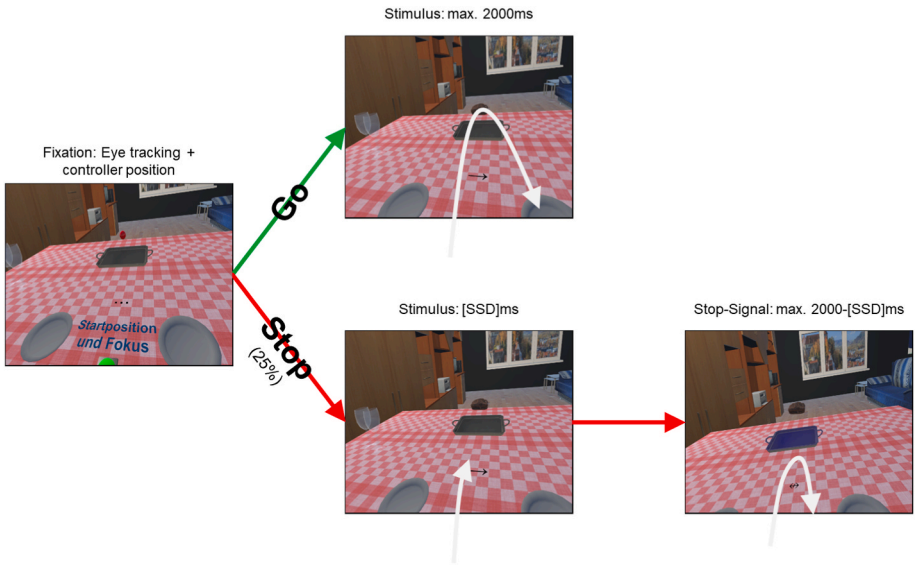

Fig. 3. Exemplary Stop-Signal Task (SST) trial in virtual reality (VR). The left panel shows the start position with a green start button and a red fixation point. The upper panel illustrates a go-trial, the lower panel illustrates stop-trial. SSD = Stop-signal delay.

in the experiment, and the stop signal was shown at least every third trial. This ensured a minimum of 3/10 practice trials with a stop signal, which allowed the experimenter to highlight that both successful and unsuccessful stops are desired in the task. The subsequent experiment comprised 400 trials, each object was presented equally frequently and in 25% of the trials the stop signal was shown. For each participant, the order of the stimuli was randomized. The VR task took about 40–50 min.

2.5. Stimulus ratings

All stimuli were rated on valence, arousal, and palatability on a visual analog scale (VAS) in VR after the task (recorded from 0.00 (not at all) - 1.00 (a lot) by *float* variables in Unity3D). Participants used the hand controller to move a rating bar that was presented in parallel to the rotating stimulus. They answered three questions on craving and palatability (Cronbach's $\alpha = 0.91$) and one question on each valence and arousal. Ratings from one participant were accidentally missed.

2.6. State questionnaires

2.6.1. State chocolate craving

Before the experiment, after the SST and after VR, we assessed state chocolate craving on 1-item VAS that asked for participants' momentary urge for food in general, for salty food, for sweets, and for chocolate. VAS were anchored from 0 (not strong at all) to 1 (very strong).

2.6.2. State experience

Before the experiment, after the SST and after VR, we assessed experiential states on 1-item VAS that asked for participants' momentary sleepiness and concentration. VAS were anchored from 0 (not at all) to 1 (extremely).

2.6.3. Presence

The Igroup Presence Questionnaire (IPQ) is a 14-item measure of spatial presence, involvement, realness, and sense of being in a place (Schubert et al., 2001). This is a standard outcome of VR and assesses the subjective experience of "being there" in a virtual environment. Internal consistency of the subscales was acceptable in this sample (Cronbach's $\alpha > 0.73$).

2.6.4. Simulator sickness

The Simulator Sickness Questionnaire (SSQ) assesses possible symptoms from VR such as disorientation, nausea, vertigo or dizziness by 20 items (Kennedy et al., 1993). We used the SSQ twice in this study (pre- and post-VR) to be able to assess changes in pre-existing symptoms. Internal consistency in this sample was acceptable (Cronbach's $\alpha = 0.63$ [pre-VR] and $\alpha = 0.83$ [post-VR]).

2.7. Trait questionnaires

2.7.1. Trait chocolate craving

The Chocolate version of the Food Cravings Questionnaire (revised; trait version) was administered (Meule & Hormes, 2015) to assess trait chocolate craving in the sample. This version included 15 items of chocolate craving with a two-factor structure to differentiate hunger for chocolate and craving. Internal consistency in this sample was excellent for the total score (Cronbach's $\alpha = 0.94$) and good-to-excellent for the subscales ($\alpha = 0.79$ [hunger] and $\alpha = 0.92$ [craving]).

2.7.2. EDEQ

The Eating-Disorder Examination Questionnaire (EDEQ) is a 28-item self-report measure of eating disorder symptoms (Hilbert et al., 2007). The EDEQ has excellent psychometric properties, normative data for populations are available (Quick & Byrd-Bredbenner, 2013). Internal consistency of the total EDEQ score in this sample was excellent (Cronbach's $\alpha = 0.92$).

2.7.3. PHQ-9

We used the 9-item depression module of the Patient-Health-Questionnaire (PHQ-9) (Gräfe et al., 2004) to screen for depressive symptomatology with a good subthreshold sensitivity. The brief PHQ-9 has shown good psychometric properties and sensitivity in healthy student populations (Zhou et al., 2020). Internal consistency in this sample was weak (Cronbach's $\alpha = 0.66$).

2.7.4. Handedness

We assessed right-handedness with the Oldfield's handedness questionnaire (Oldfield, 1971). The questionnaire consists of 10 items on hand preferences and is used to compute a laterality index ranging from −100 (exclusively left-handed) to +100 (exclusively right-handed). Internal consistency in this sample was acceptable (Cronbach's $\alpha = 0.74$).

2.7.5. Impulsivity

The Barratt Impulsiveness Scale (BIS-15) is a validated 15-item short-

version of trait impulsivity (Meule et al., 2011). Questionnaire items assess impulsiveness in several everyday situations (e.g., "I act spontaneously", "I plan for the future [inverted]"). Internal consistency of the global score was acceptable in this sample (Cronbach's $\alpha = 0.79$).

2.7.6. Other questionnaires

For reasons unrelated to the study's hypotheses, we also collected responses on the 27-item intolerance of uncertainty scale (Freeston et al., 1994; Gerlach et al., 2008), the 20-item Positive And Negative Affective Schedule (Watson et al., 1988), an 11-item adapted version of the Game Preferences Questionnaire (Manero et al., 2016), the 14-item questionnaire for intuitive use (Hurtienne & Naumann, 2010) and a 10-item self-control questionnaire. In the supplementary materials, we also report exploratory results from the 30-item Dutch Eating Behavior Questionnaire (DEBQ) (van Strien et al., 1986), from the 21-item Power-of-Food Scale (PFS) (Lowe et al., 2009), the 10-item Restraint Scale (Dinkel et al., 2005). Height and weight were self-reported in this study to calculate a BMI [weight in kg/(height in cm)^2]. All questionnaires were provided in German language.

2.8. Data processing

2.8.1. SSRT

We used the integration algorithm with replacement of response omissions to compute the SSRT from the conventional SST because this method showed the highest reliability (Verbruggen et al., 2019). According to the recommendations, SSRT was only estimated for participants with a response probability in stop trials between 25 and 75% p (response|stop), which led to exclusion of three participants for all analyses comprising the SSRT (construct validity and stimulus effects). Furthermore, we checked if RTs on failed stop-trials were longer than RTs on go-trials, which is considered a second criterion for the validity of the horse race model underlying the SSRT estimation.

The SSRT is an indirect estimate of the time required to stop a response. The formula for its computation is:

$$SSRT = RTn - M(SSD)$$

with n = p(response|stop) * number of trials, and RT = distribution of all RTs in the relevant go trials, and M(SSD) as the mean SSD across all relevant stop-trials.

The SSD was separately adjusted for pictures of chocolate and control pictures, accordingly two SSRT estimates were available for each participant.

2.8.2. Kinematic parameters

Continuous hand recordings were retrieved at 120 Hz. For preprocessing, we used the mousetrap()-package for visualization of full trajectories (Kieslich & Henninger, 2017) and custom MATLAB script for extraction of parameters (see Wirth et al., 2020 for an overview). Trials were segmented from stimulus onset to reaching the maximal depth displacement to identify parameters in the first movement phase (i.e., before grasping or stopping to targets). Trajectories were centered to the exact starting position in frame 1 (0/0/0), which removed technical between-subject variability that was not related to the stimulus and task (SD between 2.3 and 2.9 cm). For statistical analyses, we removed data from four participants who never correctly stopped in either of the conditions.

2.8.2.1. Spatial displacement. The most excessive hand position was extracted from each trial's segmented data (start-to-onset). Because the x_1 - dimension would reflect approach movements in this experiment, we hypothesized spatial displacement in the VR environment x_1 - axis (depth) to reflect successful stopping in stop-trials. As the starting position was slightly lower than the target position, we also explored spatial displacement in the x_3 - axis (height). For each participant and condition, an outlier filter of 2.5 SDs was applied before computation of mean approach (1.16%) and height (1.35%).

2.8.2.2. Time to stop (TTS). The time to stop a previously initiated movement was determined from correct stop trials. In the trajectories, the maximal spatial displacement (see above) was first determined. We then calculated the time difference between stop-signal onset and the time-stamp for this position as the direct stopping latency TTS. For each participant and condition, an outlier filter of 2.5 SDs was applied (2.1%) before computation of mean TTS.

2.8.2.3. Movement derivatives (peak acceleration, peak velocity). We considered both time-standardized and absolute acceleration and velocity profiles. Details are reported in the supplementary materials.

2.8.3. Eye-tracking measures

Eye-movement recordings were resampled online to 120 Hz. A C# script in Unity3D detected collisions between gaze and stimulus through the internal physics engine. From the recordings, the number and duration of initial and total dwell time was available for each trial. An outlier filter removed trials exceeding 2.5 SDs from the respective cell mean from mean initial dwell duration (1.9%), mean total dwell duration (1.76%) and number of dwells (3.11%).

2.9. Statistical analysis

Statistical analyses were performed in R (R Core Team, 2020) and using the packages *tidyverse* (Wickham et al., 2019), *ez* (Lawrence, 2016), *apaTables* (Stanley, 2021), *magrittr* (Stefan Milton Bache & Hadley Wickham, 2022), and *schoRsch* (Pfister & Janczyk, 2016). This study design included the two repeated-measures factors stimulus (chocolate vs. control) and trial-type (go-trial vs. stop-trial). We first discriminated stop- and go-trials based on spatial displacement in trajectories. Next, we tested stimulus effects within and across trial-types, dependent on the different outcome variables, and investigated the construct validity between established and novel measures of inhibitory control. Finally, we explored interrelations with individual trait- and state-variables related to chocolate and eating.

3. Results

3.1. Validity of VR stopping

Fig. 4 shows approach- and height-coordinates in stop and go-trials (left panel) and the time-course of successful stop vs. go-trials (right panel, standardized time units). The mean SSD in VR was 70 ms (SD = 63 ms) and stopping accuracy was relatively high, considering the adaptive SSD (M = 64.5%, SD = 14.9%). Correct go- and stop-trials differed significantly in terms of the maximum spatial displacement in stimulus approach, $t(68) = 16.34$, $p < .001$, $d = 1.97$, and in terms of maximum movement height, $t(68) = -2.45$, $p = .017$, $d = -0.30$.

3.2. Stimulus ratings

Mean stimulus ratings are shown in Supplementary Table S2. As expected, chocolate objects elicited significantly higher cravings, $t(65) = 29.25$, $p < .001$, $d = 3.60$. Moreover, chocolate was liked better, $t(65) = 9.63$, $p < .001$, $d = 1.19$, and was rated to be more exciting, $t(65) = 11.17$, $p < .001$, $d = 1.37$.

3.3. State ratings

Throughout the experiment, participants reported increases in chocolate craving, food craving, and sleepiness. Self-reported concentration decreased. Fig. 5 displays the trajectories of subjective ratings of

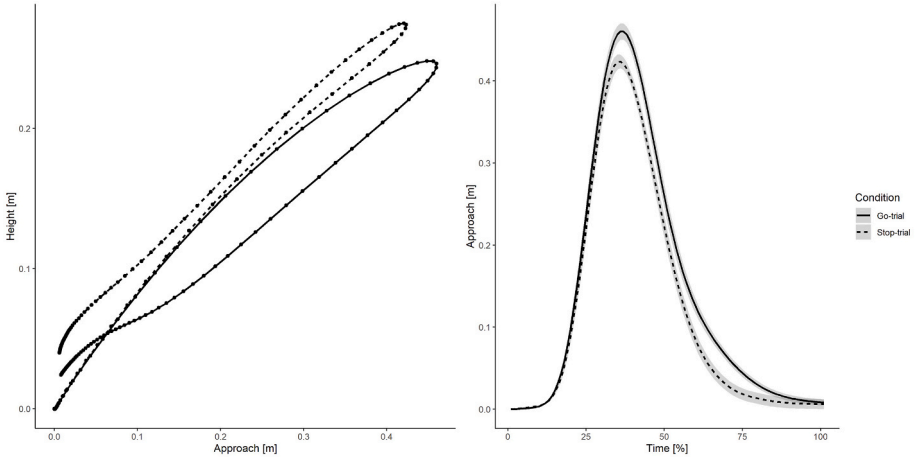

Fig. 4. *Movement trajectories in stop-vs-go trials of the kinematic stop-signal task (SST). All trajectories were recentered and time-interpolated (standardized) before parameter extraction to account for different movement durations. Trajectories in the left panel display the grand mean trajectories on approach by height for 100 time-points, averaged across all participants. Trajectories in the right panel display mean approach ± standard error across time (% of movement length). N = 69.*

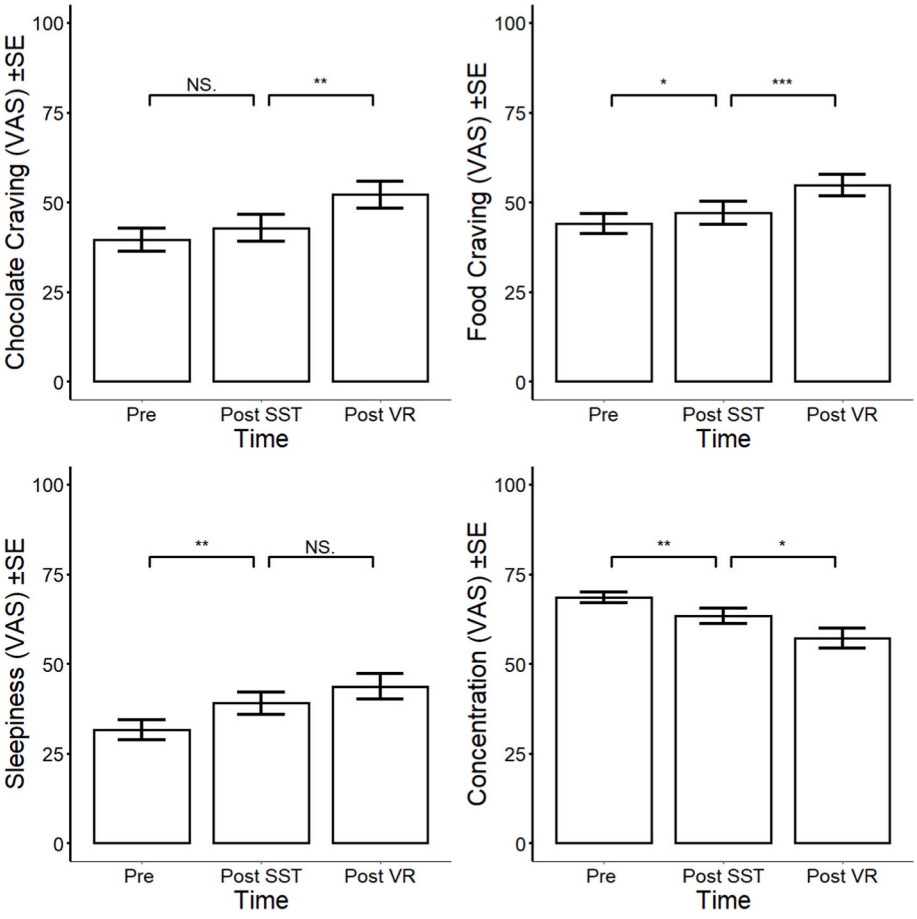

Fig. 5. *State ratings across the experimental procedure. Visual analog scale (VAS) ratings were refactored to 0–100 for readability (0 = not strong at all, 100 = very strong). Paired-samples t-tests showed significant state changes following the stop-signal task (SST) and preceding the virtual reality SST. N = 61. NS = not significant, *p < .05, **p < .01, ***p < .001.*

participants who entered correlational analyses.

3.4. Effects of stimulus category

3.4.1. Indirect assessment of stopping in the conventional SST

For the conventional SST, three participants did not meet criteria for the SSRT estimation (see data treatment). Opposed to our hypothesis, the mean SSRT was significantly shorter for pictures of chocolate (247 ms) vs. control pictures (258 ms), $t(63) = -2.17$, $p = .034$, $d = -0.27$. The results also showed shorter mean RTs and slightly more false alarms in chocolate trials (see Table 2).

Table 2
Behavioral results from the computerized stop-signal task (SST) for chocolate vs. control pictures. N = 64.

	Chocolate		Control			
	M	SD	M	SD	*t*(63)	*Cohen's d*
SSRT [ms]	246.94	53.37	257.62	47.62	−2.17*	−0.27
RT [ms]	542.35	143.54	549.25	143.26	−3.02**	−0.38
False alarms [%]	52.32	5.96	51.63	5.49	2.72**	0.34
SSD [ms]	291.95	142.25	283.48	140.15	1.92	
Failed Stop RT [ms]	456.39	103.99	462.82	109.65	−1.71	

Table Note. *$p < .05$, **$p < .01$.

3.4.2. *Direct assessment of stopping in the kinematic SST*

For the kinematic SST in VR, data from four participants who never correctly stopped had to be rejected, but we also recovered data from six participants with global SSD adjustment in the conventional SST. Thus, data from 69 participants were available to investigate effects of stimulus category on kinematics and on eye-tracking.

The time course of spatial displacement in the approach dimension is shown in Fig. 6. For the maximum spatial displacement in approach, a two-way interaction between stimulus (chocolate vs. control) and trial-type (go-trial vs. stop-trial) emerged, $F(1, 68) = 11.77$, $p = .001$, $\eta_p^2 = 0.15$ (Fig. 6). For stop-trials, participants moved closer to chocolate (M = 51.18 cm, SD = 3.44 cm) than to control objects (M = 50.35 cm, SD = 3.53 cm), $t(68) = 3.54$, $p = .001$, $d = 0.43$. In contrast, for go-trials, no difference was observed $t(68) = 0.17$, $p = .868$, $d = 0.02$. As expected, the main effect trial-type was significant and spatial displacement discriminated well between stop- and go-trials, $F(1, 68) = 352.16$, $p < .001$, $\eta_p^2 = 0.84$. The main effect stimulus was also significant, $F(1, 68) = 12.60$, $p = .001$, $\eta_p^2 = 0.16$.

We also explored several other parameters gathered from VR (see Supplementary Table S1). To measure stopping time directly, we extracted TTS in stop-trials (time after stop-delay until peak approach position) as a potential parameter for inhibitory control. Again, in contrast to our hypothesis, we observed shorter TTS for chocolate (M = 356 ms, SD = 50 ms) compared to control objects (M = 366 ms, SD = 48 ms) and this difference was statistically significant, $t(68) = -2.88$, $p = .005$, $d = -0.35$.

For movement derivatives (peak velocity, peak acceleration, movement onset), no significant stimulus effects were found in go-trials (see Supplementary Table S3 for details).

Similar to the results from the conventional SST, false alarm rates in stop-trials were higher for chocolate objects (M = 37.8%, SD = 12.6%) than for control objects (35.4%, SD = 13.9%), $t(68) = 3.66$, $p < .001$, $d = 0.44$. Interestingly, the mean SSD was still slightly longer for chocolate (M = 80 ms, SD = 66 ms) than for control objects (M = 66 ms, SD = 60 ms, $t(68) = 4.29$, $p < .001$, $d = 0.52$).

Overall, although responses to chocolate were also characterized by more lapses (false alarms), the SSD could be adjusted to a slightly later appearance. In successful stop trials and after stop signal appearance, however, participants were able to terminate their ongoing hand movements slightly faster (TTS) and at a position slightly closer to the target stimulus (spatial displacement).

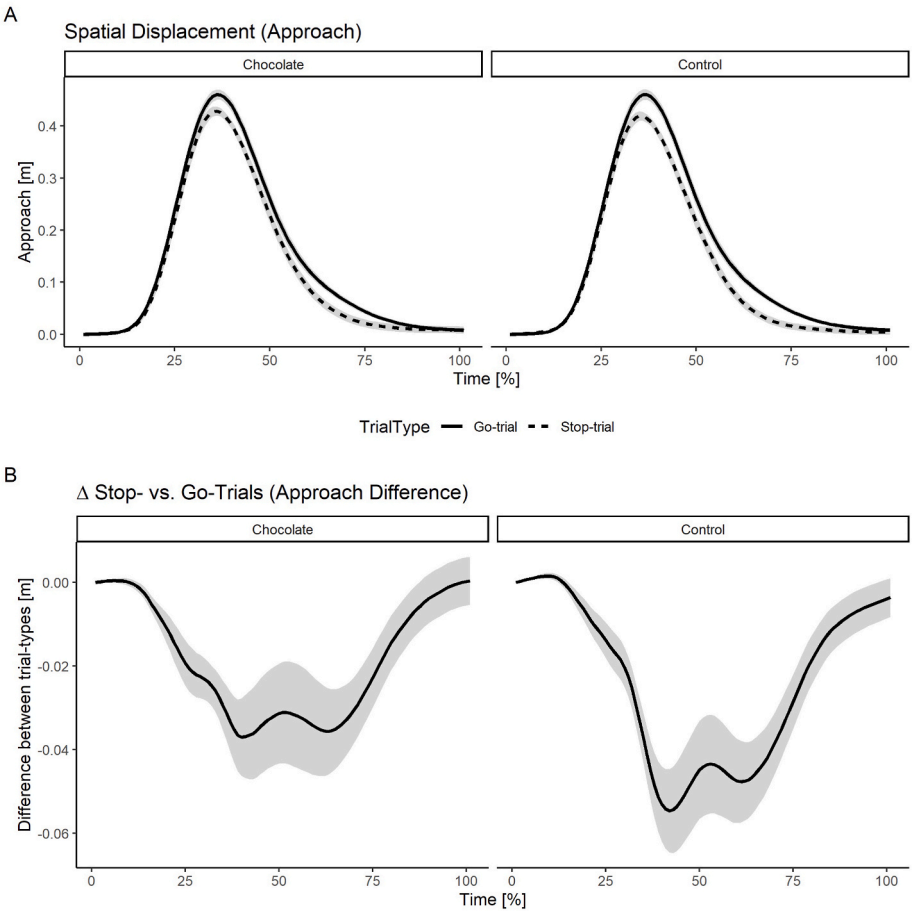

Fig. 6. *Time course of spatial displacement in the approach dimension for chocolate trials (left panel) and control trials (right panel), grouped by stop condition (go vs. stop). Panel A displays go- and stop-trial separately, whereas Panel B displays the differences in approach coordinates. N = 69.*

3.4.3. Eye-tracking

The initial gaze duration in VR was longer for chocolate (M = 333 ms, SD = 149 ms) than for control stimuli (M = 307 ms, SD = 157 ms), $t(68) = 3.47$, $p = .001$, $d = 0.42$. However, the total gaze duration and number of gazes were not different between categories, $ts < 1.83$, $ps > .071$.

3.5. Construct validity of kinematic measures with SSRT

Only data with valid SSRT estimation and extraction of kinematic parameters could be considered from both tasks, which led to a reduced sample of $N = 61$ for correlational analyses. There was no noticeable correlation of the SSRT with any measure from VR for neither stimulus category. Precisely, for chocolate, all associations between SSRT and TTS ($r(59) = -0.16$, $p = .234$), SSRT and spatial displacement ($r(59) = 0.01$, $p = .926$), and other indices ($|rs| < 0.17$, $p > .213$) were small and not significant. Similar results were obtained for control objects and all associations between SSRT, TTS, and spatial displacement were small and not significant ($|rs| < 0.07$, $ps > .593$).

3.6. Pearson correlations of behavioral measures with trait impulsivity, state- and trait chocolate craving, depression

Finally, we also explored a set of other eating- and psychopathology-related correlations. Detailed results are reported in Table 3. Regarding the conventional SST, SSRT only showed a small correlation with depressive symptoms, $r(59) = 0.29$, $p = .022$. Regarding VR-based measures, TTS in chocolate stop-trials was shorter for higher chocolate craving, $r(26) = -0.26$, $p = .046$, specifically for the craving subscale, $r(59) = -0.28$, $p = .031$, but not the hunger subscale, $r(59) = -0.14$, $p = .281$. In contrast, higher trait chocolate hunger levels indicated shorter first dwell, $r(59) = -0.29$, $p = .021$. Trait impulsivity was correlated with false alarms in VR, $r(59) = 0.26$, $p = .047$, but not with false alarms in the conventional SST, $r(59) = -0.06$, $p = .644$. Eating disorder symptoms (EDEQ) were not correlated with any measure in the present healthy sample.

4. Discussion

The goal of the study was to investigate a novel kinematic SST in VR with motion tracking and to establish its correlation with an established measure of inhibitory control, i.e., the SSRT. To this end, we collected data from healthy female participants on both a conventional SST and the kinematic SST. As expected, kinematic recordings of approach revealed distinct movement patterns in stop-vs. go-trials for the kinematic SST. We also observed superior response inhibition to chocolate stimuli compared to matched control objects in both tasks, with more detailed behavioral signatures revealed by the motion tracking. The SSRT did not correlate with stopping in VR. These results and diverging correlations with eating-related variables will be discussed in depth below.

Response inhibition and impulsivity have consistently shown associations with real-world behaviors. Previous studies generally support the critical role of inhibitory control in psychopathology, and in food- and eating-related psychopathology specifically (Bartholdy et al., 2016; Lipszyc & Schachar, 2010; Smith et al., 2014). However, not all studies corroborated the cue-specificity of response inhibition. Moreover, it was not clearly specified how varying inhibitory control abilities translate into deviant appetitive behavior. Existing taxonomies of inhibitory control stress the distinctions between attentional and response inhibition, and highlighted response inhibition as the ability to interrupt an already initiated, ongoing motor response (Diamond, 2013; Verbruggen et al., 2019). Enabling a direct assessment of inhibitory control in controlled virtual environments with motion capture might help to address the inconsistent transfer of basic neuroscientific results to clinical settings. Data from the kinematic SST can augment the existing measurements and the present investigation explicates this behavior for the case of highly attractive, palatable, and favorably evaluated chocolate.

Surprisingly, although participants made slightly more commission errors for chocolate in both tasks, the indirect and direct measures of stopping latency showed increased chocolate-specific inhibitory control (i.e., shorter SSRT and shorter TTS). In this study, we adjusted SSD relative to stimulus category, which led to slightly longer SSDs for chocolate and, in the case of VR, we observed that participants successfully stopped closer to chocolate than to control cues. From this, we conclude that less time and space was required for inhibiting chocolate grasping in VR, as hand movements had progressed already further at the appearance of the stop-signal. To the best of our knowledge, superior stopping abilities to highly attractive and appetitive food in healthy females have not been described before. Intuitively, superior response inhibition to chocolate relative to other, less attractive stimuli may enable healthy and balanced eating behavior control. It is important to highlight that this observation of increased, food-specific stopping ability was present in both tasks despite significant changes in chocolate craving, hunger, and fatigue with time. Nevertheless, since the tasks were not counterbalanced, we cannot rule out the possibility that the kinematic patterns in the second task were exaggerated due to previous performance in the conventional SST. Accordingly, task order and the influence of participants' chocolate-abstinence warrant further replication of the present results in other samples.

Food craving is theoretically distinct from hunger and deprivation in

Table 3
Pearson correlations (r) of behavioral indices (variables 8–13) with trait variables (1–7). Reported are only chocolate-specific results. N = 61.

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1 Trait impulsivity [BIS-15]												
2 Trait Chocolate Craving [FCQ-T-r-Ch]	.40*											
3 Trait Chocolate Craving-Craving [FCQ-T-r-Ch]	.41*	.99**										
4 Trait Chocolate Craving-Hunger [FCQ-T-r-Ch]	.29*	.85**	.75**									
5 State Chocolate Craving [Δ VAS]	.29*	.07	.05	.12								
6 Depressive symptoms [PHQ-9]	.21	.42**	.43**	.32*	−.26*							
7 Eating disorder symptoms [EDEQ]	−.06	.20	.17	.26*	−.15	.48**						
8 SSRT (PC)	−.14	−.03	−.06	.05	−.12	.29*	.13					
9 TTS (VR)	.07	−.26*	−.28*	−.14	−.12	−.14	−.07	−.16				
10 Spatial displacement (VR)	−.16	−.16	−.15	−.14	−.01	−.16	.03	.01	.02			
11 First dwell (VR)	−.08	−.14	−.09	−.29*	.06	.11	−.10	−.13	−.14	−.03		
12 False alarms (VR)	.26*	.10	.15	−.09	.14	−.04	−.21	−.04	−.29*	−.03	.28*	
13 False alarms (PC)	−.06	.06	.05	.10	−.06	.31*	.07	.70**	−.30*	−.07	−.01	.12

Table Note. *$p < .05$, **$p < .01$.
PHQ-9 = Patient Health Questionnaire-9, EDE-Q = Eating Disorder Examination Questionnaire, FCQ-T-r-Ch = Food Craving Questionnaire Trait revised Chocolate Version, VAS = Visual Analog Scales, BIS-15 = Barrat Impulsiveness Scales-15, PC = Personal Computer (computerized task), VR = Virtual Reality, SSRT = Stop-Signal Reaction Time, TTS = Time To Stop.

its intense desire, specificity, but at the same time relatively low level of consumption (Hill, 2007). While consumption is rewarding and enjoyable, intake, particularly of energy-dense foods such as chocolate quickly escalates and turns into negative experiences such as guilt. Accordingly, especially chocolate cravers might plan for long-term chocolate avoidance, yielding highly trained inhibition around chocolate products. Of note, the present results were gathered in all participants after a period of successful chocolate abstinence, comprising at least the day of testing. It is possible that chocolate cravers in this study might have had more practical experience with chocolate-specific stopping and thus have generally high trained inhibition. This corresponds with findings from ecological momentary assessment in which state and trait chocolate craving interacted with hunger in their influence on chocolate intake or implicit responses to chocolate (Richard et al., 2017). Experimentally, we have previously shown that restrained eaters inhibitory control was impaired following breakfast due to activity in prefrontal cortex regions (Schroeder et al., 2022).

Explorative correlational analyses with several eating- and psychopathology-related variables revealed further differences between the established SSRT and novel kinematic measures. Previous research showed associations of the SSRT with trait impulsivity and depressive symptoms (Aker et al., 2016; Lipszyc & Schachar, 2010; Logan et al., 1997), which was partially supported in the present sample by conventional measures of the SSRT and false alarms in VR. By contrast, some kinematic parameters were more strongly associated with trait chocolate craving. Precisely, higher trait chocolate craving was associated with shorter stopping latencies in chocolate stop trials. Thus, shorter stopping latencies might indicate better controlled chocolate interactions, presumably enabling healthy and balanced consumption in the long run. Interestingly, the eye-tracking data in this VR study confirmed earlier studies of prolonged initial fixations to chocolate (Werthmann et al., 2013), which illustrates the relevance of fundamental psychophysical mechanisms (e.g., attention) in more complex behavioral interactions. Due to their explorative character, future studies need to confirm the distinct associations of gaze duration with hunger and of VR stopping with craving.

Of note, the number of commission errors was still slightly higher in the chocolate condition of the conventional task (52.3 vs. 51.6%), similar to the pattern observed in individuals with binge eating disorder (Svaldi et al., 2014). Our data thus suggest a tradeoff between faster stopping at the cost of more frequent stop failures. Inhibitory control has been considered a multi-faceted construct and commission errors might capture a different aspect of inhibition. To date, however, it is still unclear how and which of these inhibitory control facets translate into problematic behavior. To further investigate which aspects of control are most predictive of real-world control failures (e.g., binge eating episodes), future studies with the kinematic stop task should test how the various parameters transfer to actual food intake, e.g., in a bogus taste test. Such studies should include both populations characterized by increased craving and overeating (e.g., restrained eaters, individuals with binge eating disorder), but also populations characterized by high successful dietary restraint (e.g., anorexia nervosa). Possibly due to the dynamic starting line in the kinematic SST, SSD adjustment did not lead to a balanced distribution of correct and incorrect stop trials; in fact, only approximately 30% of all stop trials were failed in VR and the stop-signal appeared very briefly after movement onset. We designed the task this way to ensure that hand movements were already initiated before stopping, and thus to ensure that the kinematic recordings revealed differences. However, due to the high stopping probability, we refrained from estimating SSRT from the VR task.

Although both SSTs in this study were designed to assess inhibitory control, we failed to observe strong interrelations. At least two methodological aspects could have affected this result. First, we did not counterbalance the order of tasks to maximize potential associations and keep possible effects of task practice, novelty, hunger, and fatigue stable across participants. Conversely, these confounding variables could have affected one task more than the other and results showed that participants had higher chocolate cravings during the longer VR task, which could be an effect of time. Still, measures of inhibitory control were not related. Second, although both tasks were designed to share most critical features (e.g., a clear and lateralized go-task, adaptive tracking of the SST, identical stimuli), the additional space for the go- and stop-process could enable alternative motor strategies for stopping such as reversing the movement. At this point we can only speculate whether this led to additional recruitment of other (more strategic) processes, e.g., avoidance motivation, and future research is needed to identify why stopping performance in VR was so weakly predicted by performance in the preceding SST.

Several other limitations should be mentioned. Because of the exploratory character of the correlation analyses, further replications, especially pertaining to associations with eating-related variables, are needed. As our primary kinematic outcomes from VR were tested for the first time here, this study and its analyses were not preregistered. However, future studies should consider more confirmatory approaches and sample size estimations that can be based on the obtained exploratory results. It should be highlighted that the observed stimulus effects were of small-to-moderate effect size. In this study, task order was kept fixed across participants to maximize individual differences and reduce within-individual error variance, assuming constant carryover effects. Notably, this should be taken into consideration when interpreting associations with state variables (e.g., changes in state chocolate craving). Another possible limitation was that the study did not include any covert assessment and that participants could have willfully exerted more effort and control in chocolate trials, especially given that subjective craving was repeatedly assessed. A previous study by Kreusch et al. (2013) showed higher false alarms to alcohol even when participants were unaware of the study aim, but it is not clear whether their results generalize to food and to the SST in VR. To the best of our knowledge, this is the first investigation of stopping in kinematic approach behavior. We demonstrated that the parameters from motion capture showed divergent validity compared with the SSRT in conventional SSTs (but see Leontyev & Yamauchi, 2019; Wirth et al., 2020 for comparable approaches with mouse- or finger-tracking). Through standardization and other preprocessing steps, trajectory analyses enable the distinct investigation of the spatial parameters of response stopping next to time parameters or movement kinematics. Thereby, we can differentiate particular aspects of between subject variability within the same task. Next to a rich kinematic characterization of behavior, the novel task enables the direct assessment of stopping to highly standardized and immersive stimuli. In future studies the role of other contextual cues (e.g., environment, social cues, other modalities) can be experimentally manipulated with little effort and high standardization.

To conclude, healthy female participants showed superior response inhibition latency, but slightly more false alarms to chocolate. Two subsequent response inhibition tasks showed increased stopping abilities to chocolate compared to control objects in a variety of parameters and in varying states of chocolate craving and fatigue. Kinematic data suggest this to be due to faster basal-motor response to the stop-signal, which led to punctual yet closer interruption of the movement. The construct validity between kinematic measures and SSRT was low. Kinematic measures, SSRT, and eye-tracking may indicate different aspects of reactive inhibitory control. Future studies should further explore how this translates into appetitive behavior.

Ethical statements

Participants provided informed consent before experimentation and the study was approved by the local Ethical Committee for Psychological Research (Number of approval: Az: Schröder_2019_0919_166).

CRediT statement

Philipp A. Schroeder: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – Original Draft, Visualization, Project administration, Funding acquisition.

Katja Mayer: Formal analysis, Investigation, Writing – Review & Editing.

Robert Wirth: Methodology, Resources, Writing – Review & Editing.

Jennifer Svaldi: Conceptualization, Resources, Writing – Review & Editing, Supervision.

Declaration of competing interest

The authors declare no conflict of interest. The funding agency was not involved in study design, interpretation of the results or in the decision to submit the manuscript for publication.

Data availability

Data and scripts can be retrieved from https://osf.io/t435x.

Acknowledgments

This project was supported by a grant from the Program for the Promotion of Junior Researchers of the University of Tübingen to PS. The sponsor was not involved in the study design or interpretation.

We want to thank all participants and we are especially thankful for the support of many students who helped with programming and experimentation, in alphabetical order: Marie Diekmann, Luca Dreiling, Meret Häusler, Nadine Koch, David Rohde. We also wish to thank Mechteld van den Hoek Ostende for critical proofreading and language editing. Several bars of chocolate have been devoured in the course of this project.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appet.2022.106383.

References

Aker, M., Bø, R., Harmer, C., Stiles, T. C., & Landrø, N. I. (2016). Inhibition and response to error in remitted major depression. *Psychiatry Research, 235*, 116–122. https://doi.org/10.1016/j.psychres.2015.11.038

Bache, S. M., & Wickham, H. (2022). Magrittr: A forward-pipe operator for R (R package version 2.0.3) https://CRAN.R-project.org/package=magrittr.

Band, G. P. H., van der Molen, M. W., & Logan, G. D. (2003). Horse-race model simulations of the stop-signal procedure. *Acta Psychologica, 112*(2), 105–142. https://doi.org/10.1016/S0001-6918(02)00079-3

Bartholdy, S., Dalton, B., O'Daly, O. G., Campbell, I. C., & Schmidt, U. (2016). A systematic review of the relationship between eating, weight and inhibitory control using the stop signal task. *Neuroscience & Biobehavioral Reviews, 64*, 35–62. https://doi.org/10.1016/j.neubiorev.2016.02.010

Chen, J., Papies, E. K., & Barsalou, L. W. (2016). A core eating network and its modulations underlie diverse eating phenomena. *Brain and Cognition, 110*, 20–42. https://doi.org/10.1016/j.bandc.2016.04.004

Cignoni, P., Callieri, M., Corsini, M., Dellepiane, M., Ganovelli, F., & Ranzuglia, G. (2008). MeshLab: an Open-Source Mesh Processing Tool. *Sixth Eurographics Italian Chapter Conference* (pp. 129–136).

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* Lawrence Erlbaum Associates, Inc.

Congdon, E., Mumford, J. A., Cohen, J. R., Galvan, A., Canli, T., & Poldrack, R. A. (2012). Measurement and reliability of response inhibition. *Frontiers in Psychology, 3*. https://doi.org/10.3389/fpsyg.2012.00037

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Dinkel, A., Berth, H., Exner, C., Rief, W., & Balck, F. (2005). Deutsche Adaptation der Restraint Scale zur Erfassung gezügelten Essverhaltens. *Diagnostica, 51*(2), 67–74. https://doi.org/10.1026/0012-1924.51.2.67

Ferrer-Garcia, M., Gutierrez-Maldonado, J., Treasure, J., & Vilalta-Abella, F. (2015). Craving for food in virtual reality scenarios in non-clinical sample: Analysis of its relationship with body mass index and eating disorder symptoms. *European Eating Disorders Review, 23*(5), 371–378. https://doi.org/10.1002/erv.2375

Freeston, M. H., Rhéaume, J., Letarte, H., Dugas, M. J., & Ladouceur, R. (1994). Why do people worry? *Personality and Individual Differences, 17*(6), 791–802. https://doi.org/10.1016/0191-8869(94)90048-5

Gerlach, A. L., Andor, T., & Patzelt, J. (2008). Die Bedeutung von Unsicherheitsintoleranz für die Generalisierte Angststörung Modellüberlegungen und Entwicklung einer deutschen Version der Unsicherheitsintoleranz-Skala. *Zeitschrift für Klinische Psychologie und Psychotherapie, 37*(3), 190–199. https://doi.org/10.1026/1616-3443.37.3.190

Gräfe, K., Zipfel, S., Herzog, W., & Löwe, B. (2004). Screening psychischer Störungen mit dem "Gesundheitsfragebogen für Patienten (PHQ-D). *Diagnostica, 50*(4), 171–181. https://doi.org/10.1026/0012-1924.50.4.171

Griwodz, C., Gasparini, S., Calvet, L., Gurdjos, P., Castan, F., Maujean, B., & Lanthony, Y. (2021, June). AliceVision Meshroom: An open-source 3D reconstruction pipeline. *Proceedings of the 12th ACM Multimedia Systems Conference* (pp. 241–247).

Guerrieri, R., Nederkoorn, C., & Jansen, A. (2008). The interaction between impulsivity and a varied food environment: Its influence on food intake and overweight. *International Journal of Obesity, 32*(4), 708–714. https://doi.org/10.1038/sj.ijo.0803770

Haynes, A., Kemps, E., & Moffitt, R. (2016). Is cake more appealing in the afternoon? Time of day is associated with control over automatic positive responses to unhealthy food. *Food Quality and Preference, 54*, 67–74. https://doi.org/10.1016/j.foodqual.2016.07.004

Hilbert, A., Tuschen-Caffier, B., Karwautz, A., Niederhofer, H., & Munsch, S. (2007). Eating disorder examination-questionnaire. *Diagnostica, 53*(3), 144–154. https://doi.org/10.1026/0012-1924.53.3.144

Hill, A. J. (2007). The psychology of food craving: Symposium on 'Molecular mechanisms and psychology of food intake. *Proceedings of the Nutrition Society, 66*(2), 277–285. https://doi.org/10.1017/S0029665107005502

Hill, A. J., & Heaton-Brown, L. (1994). The experience of food craving: A prospective investigation in healthy women. *Journal of Psychosomatic Research, 38*(8), 801–814. https://doi.org/10.1016/0022-3999(94)90068-X

Houben, K., Nederkoorn, C., & Jansen, A. (2014). Eating on impulse: The relation between overweight and food-specific inhibitory control. *Obesity, 22*(5), 2013–2015. https://doi.org/10.1002/oby.20670

Hurtienne, J., & Naumann, A. (2010). QUESI A questionnaire for measuring the subjective consequences of intuitive use. *Focus Theme: Play, Act and Learn. Sankt Augustin: Fraunhofer Gesellschaft*, 539.

Jones, A., Robinson, E., Duckworth, J., Kersbergen, I., Clarke, N., & Field, M. (2018). The effects of exposure to appetitive cues on inhibitory control: A meta-analytic investigation. *Appetite, 128*, 271–282. https://doi.org/10.1016/j.appet.2018.06.024

Kahveci, S., Meule, A., Lender, A., & Blechert, J. (2020). Food approach bias is moderated by the desire to eat specific foods. *Appetite, 154*, Article 104758. https://doi.org/10.1016/j.appet.2020.104758

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology, 3*(3), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

Kieslich, P. J., & Henninger, F. (2017). Mousetrap: An integrated, open-source mouse-tracking package. *Behavior Research Methods, 49*(5), 1652–1667. https://doi.org/10.3758/s13428-017-0900-z

Kreusch, F., Vilenne, A., & Quertemont, E. (2013). Response inhibition toward alcohol-related cues using an alcohol go/no-go task in problem and non-problem drinkers. *Addictive Behaviors, 38*(10), 2520–2528. https://doi.org/10.1016/j.addbeh.2013.04.007

Lavagnino, L., Arnone, D., Cao, B., Soares, J. C., & Selvaraj, S. (2016). Inhibitory control in obesity and binge eating disorder: A systematic review and meta-analysis of neurocognitive and neuroimaging studies. *Neuroscience & Biobehavioral Reviews, 68*, 714–726. https://doi.org/10.1016/j.neubiorev.2016.06.041

Lawrence, M. (2016). ez: Easy analysis and visualization of factorial experiments. https://CRAN.R-project.org/package=ez.

Ledoux, T., Nguyen, A. S., Bakos-Block, C., & Bordnick, P. (2013). Using virtual reality to study food cravings. *Appetite, 71*, 396–402. https://doi.org/10.1016/j.appet.2013.09.006

Leontyev, A., & Yamauchi, T. (2019). Mouse movement measures enhance the stop-signal task in adult ADHD assessment. *PLoS One, 14*(11), Article e0225437. https://doi.org/10.1371/journal.pone.0225437

Levitan, R. D., Rivera, J., Silveira, P. P., Steiner, M., Gaudreau, H., Hamilton, J., Kennedy, J. L., Davis, C., Dube, L., Fellows, L., Wazana, A., Matthews, S., & Meaney, M. J. (2015). Gender differences in the association between stop-signal reaction times, body mass indices and/or spontaneous food intake in pre-school children: An early model of compromised inhibitory control and obesity. *International Journal of Obesity, 39*(4), 614–619. https://doi.org/10.1038/ijo.2014.207

Lipszyc, J., & Schachar, R. (2010). Inhibitory control and psychopathology: A meta-analysis of studies using the stop signal task. *Journal of the International Neuropsychological Society, 16*(6), 1064–1076.

Liu, Z.-N., Jiang, J.-Y., Cai, T.-S., & Zhang, D.-L. (2022). A study of response inhibition in overweight/obesity people based on event-related potential. *Frontiers in Psychology, 13*(March). https://doi.org/10.3389/fpsyg.2022.826648

Logan, G. D., Cowan, W. B., & Davis, K. A. (1984). On the ability to inhibit simple and choice reaction time responses: A model and a method. *Journal of Experimental Psychology: Human Perception and Performance, 10*(2), 276–291. https://doi.org/10.1037/0096-1523.10.2.276

Logan, G. D., Schachar, R. J., & Tannock, R. (1997). Impulsivity and inhibitory control. *Psychological Science, 8*(1), 60–64. https://doi.org/10.1111/j.1467-9280.1997.tb00545.x

Loijen, A., Vrijsen, J. N., Egger, J. I. M., Becker, E. S., & Rinck, M. (2020). Biased approach-avoidance tendencies in psychopathology: A systematic review of their assessment and modification. *Clinical Psychology Review, 77*(February), Article 101825. https://doi.org/10.1016/j.cpr.2020.101825

Lowe, M. R., Butryn, M. L., Didie, E. R., Annunziato, R. A., Thomas, J. G., Crerand, C. E., Ochner, C. N., Coletta, M. C., Bellace, D., Wallaert, M., & Halford, J. (2009). The Power of Food Scale. A new measure of the psychological influence of the food environment. *Appetite, 53*(1), 114–118. https://doi.org/10.1016/j.appet.2009.05.016

Manasse, S. M., Goldstein, S. P., Wyckoff, E., Forman, E. M., Juarascio, A. S., Butryn, M. L., Ruocco, A. C., & Nederkoorn, C. (2016). Slowing down and taking a second look: Inhibitory deficits associated with binge eating are not food-specific. *Appetite, 96*, 555–559. https://doi.org/10.1016/j.appet.2015.10.025

Manero, B., Torrente, J., Freire, M., & Fernández-Manjón, B. (2016). An instrument to build a gamer clustering framework according to gaming preferences and habits. *Computers in Human Behavior, 62*, 353–363. https://doi.org/10.1016/j.chb.2016.03.085

Meule, A., & Hormes, J. M. (2015). Chocolate versions of the Food Cravings Questionnaires. Associations with chocolate exposure-induced salivary flow and ad libitum chocolate consumption. *Appetite, 91*, 256–265. https://doi.org/10.1016/j.appet.2015.04.054

Meule, A., Lutz, A. P. C., Vögele, C., & Kübler, A. (2014). Impulsive reactions to food-cues predict subsequent food craving. *Eating Behaviors, 15*(1), 99–105. https://doi.org/10.1016/j.eatbeh.2013.10.023

Meule, A., Vögele, C., & Kübler, A. (2011). Psychometrische Evaluation der deutschen Barratt Impulsiveness Scale – kurzversion (BIS-15). *Diagnostica, 57*(3), 126–133. https://doi.org/10.1026/0012-1924/a000042

Mond, J. M., Hay, P. J., Rodgers, B., Owen, C., & Beumont, P. J. V. (2004). Validity of the Eating Disorder Examination Questionnaire (EDE-Q) in screening for eating disorders in community samples. *Behaviour Research and Therapy, 42*(5), 551–567. https://doi.org/10.1016/S0005-7967(03)00161-X

Moore, S., Rudaizky, D., MacLeod, C., & Dondzilo, L. (2022). Healthiness matters: Approach motivation for healthy food in overweight and obese individuals. *Appetite, 168*, Article 105760. https://doi.org/10.1016/j.appet.2021.105760

Nederkoorn, C., Braet, C., Van Eijs, Y., Tanghe, A., & Jansen, A. (2006). Why obese children cannot resist food: The role of impulsivity. *Eating Behaviors, 7*(4), 315–322. https://doi.org/10.1016/j.eatbeh.2005.11.005

Nederkoorn, C., Van Eijs, Y., & Jansen, A. (2004). Restrained eaters act on impulse. *Personality and Individual Differences, 37*(8), 1651–1658. https://doi.org/10.1016/j.paid.2004.02.020

Niehorster, D. C., Li, L., & Lappe, M. (2017). The accuracy and precision of position and orientation tracking in the HTC vive virtual reality system for scientific research. *I-Perception, 8*(3), Article 2041669517708205. https://doi.org/10.1177/2041669517708205

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Pfister, R., & Janczyk, M. (2016). schoRsch: An R package for analyzing and reporting factorial experiments. *The Quantitative Methods for Psychology, 12*(2), 147–151. https://doi.org/10.20982/tqmp.12.2.p147

Quick, V. M., & Byrd-Bredbenner, C. (2013). Eating disorders examination questionnaire (EDE-Q): Norms for US college students. *Eating and Weight Disorders: EWD, 18*(1), 29–35. https://doi.org/10.1007/s40519-013-0015-1

R Core Team. (2020). R: A language and environment for statistical computing. In *R Foundation for statistical computing*. Vienna, Austria https://www.r-project.org/.

Raud, L., Westerhausen, R., Dooley, N., & Huster, R. J. (2020). Differences in unity: The go/no-go and stop signal tasks rely on different mechanisms. *NeuroImage, 210*(January). https://doi.org/10.1016/j.neuroimage.2020.116582

Reichenberger, J., Richard, A., Smyth, J. M., Fischer, D., Pollatos, O., & Blechert, J. (2018). It's craving time: Time of day effects on momentary hunger and food craving in daily life. *Nutrition, 55–56*, 15–20. https://doi.org/10.1016/j.nut.2018.03.048

Richard, A., Meule, A., Reichenberger, J., & Blechert, J. (2017). Food cravings in everyday life: An EMA study on snack-related thoughts, cravings, and consumption. *Appetite, 113*, 215–223. https://doi.org/10.1016/j.appet.2017.02.037

Rodrigue, C., Ouellette, A. S., Lemieux, S., Tchernof, A., Biertho, L., & Bégin, C. (2018). Executive functioning and psychological symptoms in food addiction: A study among individuals with severe obesity. *Eating and Weight Disorders, 23*(4), 469–478. https://doi.org/10.1007/s40519-018-0530-1

Rubia, K., Russell, T., Overmeyer, S., Brammer, M. J., Bullmore, E. T., Sharma, T., Simmons, A., Williams, S. C. R., Giampietro, V., Andrew, C. M., & Taylor, E. (2001). Mapping motor inhibition: Conjunctive brain activations across different versions of go/no-go and stop tasks. *NeuroImage, 13*(2), 250–261. https://doi.org/10.1006/nimg.2000.0685

Scherbaum, S., & Kieslich, P. J. (2018). Stuck at the starting line: How the starting procedure influences mouse-tracking data. *Behavior Research Methods, 50*(5), 2097–2110. https://doi.org/10.3758/s13428-017-0977-4

Schroeder, P. A., Farshad, M., & Svaldi, J. (2022). Anodal stimulation of inhibitory control and craving in satiated restrained eaters. *Nutritional Neuroscience*, 1–11.

Schroeder, P. A., Lohmann, J., Butz, M. V., & Plewnia, C. (2016). Behavioral bias for food reflected in hand movements: A preliminary study with healthy subjects. *Cyberpsychology, Behavior, and Social Networking, 19*(2), 120–126. https://doi.org/10.1089/cyber.2015.0311

Schroeder, P. A., Lohmann, J., & Ninaus, M. (2021). Preserved inhibitory control deficits of overweight participants in a gamified stop-signal task: Experimental study of validity. *JMIR Serious Games, 9*(1), Article e25063. https://doi.org/10.2196/25063

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: Factor Analytic insights. *Presence: Teleoperators and Virtual Environments, 10*(3), 266–281. https://doi.org/10.1162/105474601300343603

Smith, J. L., Mattick, R. P., Jamadar, S. D., & Iredale, J. M. (2014). Deficits in behavioural inhibition in substance abuse and addiction: A meta-analysis. *Drug and Alcohol Dependence, 145*, 1–33. https://doi.org/10.1016/j.drugalcdep.2014.08.009

Soreni, N., Crosbie, J., Ickowicz, A., & Schachar, R. (2009). Stop signal and conners' continuous performance tasks: Test—retest reliability of two inhibition measures in ADHD children. *Journal of Attention Disorders, 13*(2), 137–143. https://doi.org/10.1177/1087054708326110

Stanley, D. (2021). apaTables: Create American psychological association (APA) style tables (R package version 2.0.8) https://CRAN.R-project.org/package=apaTables.

van Strien, T., Frijters, J. E. R., Bergers, G. P. A., & Defares, P. B. (1986). The Dutch Eating Behavior Questionnaire (DEBQ) for assessment of restrained, emotional, and external eating behavior. *International Journal of Eating Disorders, 5*(2), 295–315. https://doi.org/10.1002/1098-108X(198602)5, 2<295::AID-EAT2260050209>3.0.CO;2-T.

Svaldi, J., Naumann, E., Biehl, S., & Schmitz, F. (2015). Impaired early-response inhibition in overweight females with and without binge eating disorder. *PLoS One, 10*(7), Article e0133534. https://doi.org/10.1371/journal.pone.0133534

Svaldi, J., Naumann, E., Trentowska, M., & Schmitz, F. (2014). General and food-specific inhibitory deficits in binge eating disorder. *International Journal of Eating Disorders, 47*(5), 534–542. https://doi.org/10.1002/eat.22260

Verbruggen, F., Aron, A. R., Band, G. P., Beste, C., Bissett, P. G., Brockett, A. T., Brown, J. W., Chamberlain, S. R., Chambers, C. D., Colonius, H., Colzato, L. S., Corneil, B. D., Coxon, J. P., Dupuis, A., Eagle, D. M., Garavan, H., Greenhouse, I., Heathcote, A., Huster, R. J., … Boehler, C. N. (2019). A consensus guide to capturing the ability to inhibit actions and impulsive behaviors in the stop-signal task. *Elife, 8*, Article e46323. https://doi.org/10.7554/eLife.46323

van der Waal, N. E., Janssen, L., Antheunis, M., Culleton, E., & van der Laan, L. N. (2021). The appeal of virtual chocolate: A systematic comparison of psychological and physiological food cue responses to virtual and real food. *Food Quality and Preference, 90*(December 2020), Article 104167. https://doi.org/10.1016/j.foodqual.2020.104167

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology, 54*(6), 1063–1070. https://doi.org/10.1037/0022-3514.54.6.1063

Weller, R. E., Cook, E. W., Avsar, K. B., & Cox, J. E. (2008). Obese women show greater delay discounting than healthy-weight women. *Appetite, 51*(3), 563–569. https://doi.org/10.1016/j.appet.2008.04.010

Werthmann, J., Roefs, A., Nederkoorn, C., & Jansen, A. (2013). Desire lies in the eyes: Attention bias for chocolate is related to craving and self-endorsed eating permission. *Appetite, 70*, 81–89. https://doi.org/10.1016/j.appet.2013.06.087

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., … Yutani, H. (2019). Welcome to the tidyverse. *Journal of Open Source Software, 4*(43), 1686. https://doi.org/10.21105/joss.01686

Wirth, R., Foerster, A., Kunde, W., & Pfister, R. (2020). Design choices: Empirical recommendations for designing two-dimensional finger-tracking experiments. *Behavior Research Methods, 52*(6), 2394–2416. https://doi.org/10.3758/s13428-020-01409-0

Wöstmann, N. M., Aichert, D. S., Costa, A., Rubia, K., Möller, H.-J., & Ettinger, U. (2013). Reliability and plasticity of response inhibition and interference control. *Brain and Cognition, 81*(1), 82–94. https://doi.org/10.1016/j.bandc.2012.09.010

Yang, Y., Shields, G. S., Guo, C., & Liu, Y. (2018). Executive function performance in obesity and overweight individuals: A meta-analysis and review. *Neuroscience & Biobehavioral Reviews, 84*, 225–244. https://doi.org/10.1016/j.neubiorev.2017.11.020

Zhou, Y., Xu, J., & Rief, W. (2020). Are comparisons of mental disorders between Chinese and German students possible? An examination of measurement invariance for the PHQ-15, PHQ-9 and GAD-7. *BMC Psychiatry, 20*(1), 480. https://doi.org/10.1186/s12888-020-02859-8