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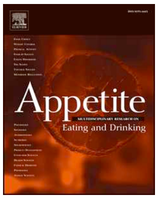

Food approach bias is moderated by the desire to eat specific foods

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ABSTRACT

In a post-scarcity world, energy intake and excesses therein are mediated by psychological mechanisms, such as implicit inclinations to approach certain foods. We investigated how food deprivation, calorie content and individual food preferences affect this approach bias. Sixty women performed a touchscreen-based approach-avoidance task featuring a wide range of food items, once while satiated and once while food-deprived for 15 h. We found an overall approach bias towards food that was not influenced by food deprivation or calorie density of the food items. Instead, we found that approach bias related to the participants' (lack of) desire to eat specific food items, and to a lesser extent to how much their general desire to eat changed due to food deprivation. Links with food preference were selective to trials in which foods had to be approached, and were absent in trials in which foods had to be avoided, pointing to selectivity to appetitive brain systems and clarifying the nature of the bias. Approach bias was unrelated to overall state or trait food craving. We conclude approach bias for appetitive stimuli may primarily express itself as speeded approach rather than slowed avoidance. Additionally, our results show there is merit in personalizing stimulus selection for approach bias measurement and retraining, as approach bias was concordant with individual food preferences, rather than objective calorie content.

1. Introduction

1.1. Overview

Despite the overabundance of cultural messaging encouraging weight loss, 51.6% of European citizens are overweight or obese (The European Commission, 2019). In the Western world, food availability no longer limits who can gain weight and who cannot; instead, it is psychosocial phenomena that mediate eating behavior and thereby weight gain in otherwise healthy people. One such phenomenon is the implicit and automatic tendency to approach desired substances. These automatic approach tendencies are thought to influence the decisions of whether to eat and what to eat in real time. Approach bias in the food domain has both been measured and modified using the approach-avoidance task (Rinck & Becker, 2007). In the approach-avoidance task (AAT), the participant pulls (approaches) or pushes (avoids) two different types of stimuli using a joystick. An approach bias is inferred if the target stimulus category is pulled faster than it is pushed, in comparison to the control stimulus category. Food approach bias has been found to be elevated in high food cravers (Brockmeyer, Hahn, Reetz, Schmidt, & Friederich, 2015a) and obese individuals (Kemps & Tiggemann, 2015), but decreased or even absent in patients with anorexia nervosa (Neimeijer, Roefs, Glashouwer, Jonker, & de Jong, 2019; Paslakis et al., 2016). Approach bias is not merely an emergent phenomenon however. Approach-Bias Modification (AppBM) studies have successfully modified approach-avoidance tendencies, leading to a reduction in chocolate cravings (Kemps, Tiggemann, Martin, & Elliott, 2013) chocolate intake (Schumacher, Kemps, & Tiggemann, 2016) (Maas, Keijsers, Rinck, Tanis, & Becker, 2015) and bulimic symptoms (Brockmeyer, Hahn, Reetz, Schmidt, & Friederich, 2015b). Despite its utility as a treatment mechanism, the concept of approach bias itself remains elusive: is there an overall, fixed approach bias tendency, or does it vary across stimuli and biological states, and if so, how?

1.2. Determinants of bias

Approach bias is thought to be influenced by the state of the individual, the characteristics of the object being approached, and their interaction. Evolutionary theory suggests that hunger should attune the senses, attention, and behavior to facilitate food search (Berthoud & Morrison, 2008), and several brain imaging studies supported this notion (Stockburger, Schmälzle, Flaisch, Bublatzky, & Schupp, 2009; Stockburger, Weike, Hamm, & Schupp, 2008). It is thus also in line with evolutionary thought that hunger should enhance approach bias. The literature on approach bias, however, has provided less support than one might expect: Piqueras-Fiszman, Kraus, and Spence (2014) and Höfling (2008) found that foods were approached equally fast among satiated and food-deprived participants, despite more self-reported

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desire to eat (DTE) in the latter group. Additionally, research from psychophysiology suggests that hunger promotes ambivalent responses to food: when viewing food images, hunger enhances zygomatic muscle activity, indicative of positive valence, but also startle responses, indicative of negative valence (Drobes et al., 2001). The impact of hunger on implicit responses to food remains poorly understood.

If homeostatic needs drive approach bias, then hunger should bias the organism to approach energy-dense foods. While high-calorie (HC) foods are associated with stronger and more widespread brain region activations than low-calorie (LC) foods (Killgore et al., 2003), studies have consistently failed to reveal a stronger approach bias for HC foods in healthy participants (Neimeijer, de Jong, & Roefs, 2015; Neimeijer et al., 2019; Paslakis et al., 2016). Two studies have also found no overall approach bias for HC foods compared to objects, indicating that such a bias for appetitive foods is not always there (Kemps & Tiggemann, 2015; Machulska, Zlomuzica, Adolph, Rinck, & Margraf, 2015). No study so far has examined the interaction between food deprivation and calorie content on approach bias. It is known that food deprivation causes greater responses to HC foods than LC foods in the ventral striatum, amygdala, anterior insula, and medial and lateral orbitofrontal cortex (Goldstone et al., 2009); in comparison, satiated individuals show greater reward processing in response to LC foods (Siep et al., 2009). It remains to be shown whether this translates to approach bias findings.

Lastly, no research group so far has examined the effect of individual food preferences on approach bias. Preferences influence real-life approach behavior, and have been assumed by many researchers to influence approach bias: approach bias modification studies in the broader field of addiction have used stimuli tailored to the patient (Boffo et al., 2018; Kopetz, MacPherson, Mitchell, Houston-Ludlam, & Wiers, 2017) but without examining whether preferences have any influence on bias.

1.3. The current study

Based on this literature background, the present study investigated how calorie content and individual food preferences affect approach bias, and how these effects are modulated by food deprivation. Using an experimental touch-screen AAT, we assessed approach-avoidance tendencies for HC and LC foods twice, once during a food-deprived state and once during a satiated state. During each session, we collected ratings for palatability and DTE for all food stimuli used in the assessment. We analyzed the effects of these factors on the trial level using multilevel analysis.

The original AAT (Rinck & Becker, 2007) is limited in its range of applicability because it requires a computer and a joystick. As smartphones with touch screens are ubiquitous in modern society, some labs, including ours, have made the AAT easier to use in daily life by adapting it to touchscreen-based devices (Kakoschke, Hawker, Castine, de Courten, & Verdejo-Garcia, 2018; Meule, Richard, Dinic, & Blechert, 2019; Zech, Rotteveel, Van Dijk, & Van Dillen, 2020). Another reason to adapt the AAT to touchscreens is ecological validity: participants get to physically reach out and touch objects as they do in real life, rather moving stimuli indirectly by pulling a lever. So far, three of our touchscreen AAT experiments have revealed an overall approach bias for chocolate, and three have shown a relationship with trait chocolate craving (Meule, Lender, Richard, Dinic, & Blechert, 2019; Meule, Richard, Lender, et al., 2019). In the current study, we built upon these studies and assessed approach-avoidance tendencies with a touchscreen-based relevant-feature AAT, as the relevant-feature variant of this task was previously found to reveal stronger biases (Lender, Meule, Rinck, Brockmeyer, & Blechert, 2018; Phaf, Mohr, Rotteveel, & Wicherts, 2014). To contribute to the further development of the touchscreen-based AAT, we also assessed whether the task is reliable and correlates with overall state and trait food craving.

We hypothesized that (1) there is a greater approach-advantage for foods than for objects (i.e. an approach bias), that food deprivation and high calorie content (2, 3) independently and (4) interactively relate to stronger approach bias, if approach bias is driven by homeostatic needs. Lastly, we hypothesized that (5) approach bias would relate to state hunger, state craving, and/or trait craving. We made no specific predictions regarding reliability and the effects of DTE and palatability (and their changes through deprivation) on approach bias, as these were exploratory questions.

2. Method

2.1. Participants

We tested 60 adult female students of the University of Salzburg in Austria, with a mean age of 22.22 years and a mean body mass index of 21.08 kg/m^2. All participants had a meal within 2 h before the satiated testing session, and all except 1 participant had eaten their last meal 15 or more hours ago during the food-deprived testing session. As detailed in the Data Processing section, food-deprived session data of 5 participants was excluded, satiated-session data of 1 participant was excluded, and data from both sessions of 3 participants was excluded, all due to excessive error or outlier rates, or because they had eaten food within 15 h for the food-deprived session. We conducted the study with permission granted by the ethics committee of the Paris Lodron University of Salzburg, and in accordance with the Declaration of Helsinki.

2.2. Questionnaires

Cronbach's α has fallen out of favor among statisticians because it systematically underestimates reliability (Sijtsma, 2008). We report it alongside a more accurate measure of reliability (Revelle & Zinbarg, 2008), McDonald's ω (McDonald, 1978).

Food Craving Questionnaire-State (FCQ-S). Before and after administering the AAT, we administered a German version of the FCQ-S (Cepeda-Benito, Gleaves, Williams, & Erath, 2000; Meule, Lutz, Vögele, & Kübler, 2012), to measure the participant's real-time subjective hunger and food cravings. The scale consists of 15 statements, and participants indicated their agreement with these statements on a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Reliability scores, which we computed separately for pre-test and post-test administrations during the food-deprived and satiated sessions, were excellent ($\alpha = 0.90$ to 0.94, $\omega = 0.90$ to 0.95). We made use of two subscales, both of which had excellent reliability. The hunger scale consisted of the last 3 items ($\alpha = 0.75$ to 0.90, $\omega = 0.77$ to 0.91), for example "I am hungry", and "If I ate something right now, my stomach would not feel as empty"; these were summed to produce a state hunger score between 3 and 15. The remaining 12 items formed the craving scale ($\alpha = 0.87$ to 0.93, $\omega = 0.87$ to 0.93), with items such as "I'm craving one or more specific foods", and "I know I will keep thinking of specific foods until I actually have them"; these items were summed to produce a state craving score between 12 and 60.

Food Craving Questionnaire-Trait-reduced (FCQ-T-r). We administered the German version of the FCQ-T-r (Meule, Hermann, & Kübler, 2014) to measure the frequency and intensity of food craving in general. The scale consisted of 15 items which were scored from 1 (never) to 6 (always) and which were summed without recoding to yield a trait craving score ranging from 15 to 90. Examples of items include „When I crave something, I know I won't be able to stop eating once I start", and „I find myself preoccupied with food". The scale had excellent reliability in this study ($\alpha = .89$, $\omega = 0.89$). The FCQ-T-r was found to predict cue-elicited food craving, and to correlate with BMI and dieting success (Meule et al., 2014).

Other measures. We administered a sociodemographic questionnaire, inquiring the participant's age, gender, handedness, nationality and occupation. We measured participants' height, weight, and fat mass as well, and computed their body mass index. In both testing sessions, participants rated the AAT stimuli on how pleasant they would be to grasp; participants also rated each food on how much they would like to eat it if it were available in that moment (DTE) and how palatable they find it (palatability), on a Likert scale ranging from 1 (not at all) to 9 (very).

We additionally administered the Eating Disorder Examination Questionnaire-8 (EDEQ-8: Kliem et al., 2016), the Dutch Eating Behavior Questionnaire – Restrained eating subscale (DEBQ-restraint: van Strien, Frijters, Bergers, & Defares, 1986) and the Perceived Self-Regulatory Success in Dieting Scale (PSRS: Meule et al., 2012), as we planned to compare the current sample of healthy participants to a sample with patients with anorexia nervosa in the future. In the current study, however, these scales are not included in analyses.

2.3. AAT

We selected 12 HC and 16 LC vegetarian food stimuli from the food-pics_extended database (Blechert, Lender, Polk, Busch, & Ohla, 2019) and we retrieved 4 additional HC stimuli from the internet, because the food-pics_extended database did not have enough HC foods that were easily graspable with one hand and without requiring cutlery. The HC foods consisted of 8 sweet and 8 savory foods, while the LC foods consisted of crackers, fruits, raw and cooked vegetables, and salads.[1] We also retrieved two picture sets of 16 body care objects from the internet and matched them to the foods on color and size. For the food stimuli for which information and ratings were available, we could confirm that HC foods had thrice as many calories per 100 g as LC foods on average (t (22) = 5.08, $p < .001$, $M_{LC} = 143$ kcal, $M_{HC} = 423$ kcal), and were rated as equally familiar (t (26) = 0.01, $p = .991$) and recognizable (t (26) = 0.23, $p = .822$). All food stimuli selected from the food-pics_extended database had recognizability ratings above 90 (on a scale from 0 to 100).

The AAT was administered using a 23-inch iiyama ProLite T2336MSC-B2 touchscreen monitor with a resolution of 1920 × 1080 pixels, placed in portrait-format at a 45° slope towards the participant to ensure equal attention was given to stimuli presented at top and bottom of the screen.

The timeline for a single trial is depicted in Fig. 1. Participants were instructed to place their dominant hand on a symbol at the center of the screen, after which a food stimulus and an object stimulus appeared, one at the top of the screen and one at the bottom[2] (as was also done in Meule, Richard, Lender, et al., 2019). As movement direction was determined by stimulus position unlike in regular relevant-feature joystick-AATs, we had to make sure that stimulus content remain task-relevant and the participant process stimulus content. Therefore, pre-block instructions indicated whether the participant should interact with the food or object stimulus. After the stimulus appeared, participants lifted their hand and quickly placed it on the stimulus, which then ‘snapped’ to the hand. Stimuli appearing at the top (distal) of the screen were dragged towards the participant to the bottom of the screen (approach), where a shopping-basket icon was displayed to emulate purchasing the stimulus. Stimuli appearing at the bottom (proximal) of the screen were dragged to the top of the screen, away from the participant and the shopping-basket (avoid). After a stimulus reached the bottom, it zoomed in, and after it reached the top, it zoomed out.

The task consisted of 2 sets of 2 blocks. During the first block, either objects or foods needed to be interacted with (counterbalanced between participants); the reverse was true for the second block. HC and LC food items, and their matched object sets, were displayed in separate sets of blocks (their order also being counterbalanced between participants).

Each block consisted of 64 trials, within which each stimulus of the current stimulus set was displayed once at the top of the screen and once at the bottom. A single testing session consisted of 256 trials.

2.4. Procedure

Participants first provided informed consent. They then filled in the demographic questionnaire, as well as the FCQ-T-r, EDEQ8, DEBQ-restraint, and PSRS at home. After this, they were invited to participate in two testing sessions, planned exactly one week apart and scheduled between 12:00 and 16:00, during which they filled in the FCQ-S, performed the AAT, filled in the FCQ-S again, and provided ratings for pleasantness of grasping for all stimuli, and palatability and DTE ratings for food stimuli only. For the deprived session, participants were instructed not to eat anything from 20:00 on the following night. For the satiated session, they were instructed to eat enough food to feel satiated within 2 h before the start of the study. If they had not eaten anything within this time period, they were provided with a chocolate bar by the experimenter. The order of these sessions was counterbalanced.

2.5. Data processing

The *Reaching time* measure represents the time from stimulus onset until the moment the participant grabs the stimulus.[3] First, 2188 error trials (7.12%) were excluded. Participants with more than 15% errors during a food-deprived or satiated testing session were excluded from that session: this led to the exclusion of 7 participants from the food-deprived condition and 4 from the satiated condition. Another participant was excluded from the food-deprived condition because they had eaten food 8 h before testing, rather than 15 h. Further, only trials with reaching times between 200 ms and 2000 ms were retained, leading to the exclusion of 437 trials (1.42%). Next, trials with reaching times deviating more than 3 standard deviations from the participant's mean were discarded, leading to the exclusion of 1820 trials (5.93%). The final sample contained 25893 trials (84.32%), with 6 participants excluded from 1 session and 3 participants excluded from both sessions. To satisfy the normality assumption underlying linear multilevel modelling, we applied a log-transformation to the dependent variable, making it normally distributed.

2.6. Analysis

Manipulation checks were performed using *t*-tests and ANOVAs: it was expected that food deprivation should increase overall hunger and food craving, as well as overall DTE and subjective palatability of food, especially for HC foods. As food deprivation could also decrease the overall performance of the participants, we examined whether error rates and overall reaching times differed between food-deprived and satiated sessions.

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[1] The LC food-pics_extended image IDs were 0193, 0209, 0226, 0228, 0258, 0380, 0413, 0429, 0459, 0502, 0513, 0763, 0804, 0819, 0829, and 0831. The HC food-pics_extended image IDs were 0004, 0008, 0009, 0018, 0104, 0110, 0111, 0120, 0154, 0296, 0363, and 0510. The additional HC stimuli included a sandwich, a pretzel, a burrito, and a pizza slice in carton packaging.

[2] A previous relevant-feature touchscreen-AAT from our lab (Meule, Lender, et al., 2019) involved manipulating a single stimulus which appeared directly underneath the hand. While the measured approach bias correlated with craving, the fact that the stimulus was partially obscured by the hand led us to try new touchscreen-AAT variants.

[3] We did not examine the time from stimulus onset until first participant movement (decision time) or the time from first participant movement until stimulus grasping (grabbing time) due to the existence of different strategies to perform the task: some participants lifted their hand immediately, then decided which stimulus to interact with; others kept their hand on the screen until they had decided on the appropriate response. This led to a negative correlation between these two measures, r (25193) = -0.16, $p < .001$, which in some participants exceeded $r = -0.60$. Thus, the difficulty of the decision-making process was captured by decision time for some participants, and by grabbing time for others. Summing up the two circumvented this issue.

Fig. 1. Visual depiction of a single trial. Two stimuli appear, the participant identifies which stimulus should be grabbed, lifts their hand, grabs the stimulus (which makes the other stimulus disappear) and moves it to the other side of the screen. Distal-to-proximal movements represent approach and proximal-to-distal movements represent avoidance.

Hypotheses were examined with multilevel modelling using R (R Core Team, 2019) and the R package lme4 (Bates, Mächler, Bolker, & Walker, 2015). To examine the contribution of a highest-order effect, a likelihood ratio test was performed comparing a model with the effect against a model without the effect (Bates et al., 2015). A highest-order effect was deemed significant if the likelihood ratio test indicated that the model without the term fit significantly worse ($\alpha = 0.05$). All trial-level fixed effects were also modelled as random effects, following recommendations by Barr, Levy, Scheepers, and Tily (2013).

3. Results

All data and analysis scripts, as well as power analyses for the main analyses of this study, are freely available at this study's Open Science Framework repository: https://osf.io/v6x7j/

3.1. Manipulation checks

In Table 1, we displayed mean Reaching time, error rates, DTE and palatability ratings, and FCQ-S hunger and craving scores for the satiated and deprived session.

3.1.1. Reaching times

Hunger did not affect task performance: overall reaching time was not affected by food deprivation (paired t (50) = 0.15, p = .880), and neither were error rates, both after participant exclusion (t (50) = 1.00, p = .300) and before, (t (59) = 0.20, p = .900).

3.1.2. Hunger and craving

Food deprivation successfully increased hunger (t (59) = 23.71, $p < .001$; $M_{satiated} = 4.12$; $M_{deprived} = 12.32$) and food craving (t (59) = 13.83, $p < .001$; $M_{satiated} = 20.67$; $M_{satiated} = 39.53$) as measured using the FCQ-S. In the satiated session, no participants indicated they were hungry on a FCQ-S hunger scale question that specifically asks about hunger, and all scored between 3 and 7 (on a scale from 3 to 15).

Table 1
Descriptive statistics contrasting the deprived and satiated conditions.

Variable (Range/unit)	Deprived *M* (*SD*)	Satiated *M* (*SD*)
DTE for HC foods (1–9)*	6.36 (1.79)	3.80 (1.53)
DTE for LC foods (1–9)*	5.90 (1.49)	3.97 (1.43)
Palatability for HC foods (1–9)*	7.20 (1.02)	6.64 (1.06)
Palatability for LC foods (1–9)	6.65 (1.10)	6.30 (0.98)
FCQ-S craving (12–60)*	39.53 (8.90)	20.67 (6.59)
FCQ-S hunger (3–15)*	12.32 (2.27)	4.12 (1.30)
Reaching time (ms)	792.44 (152.46)	793.23 (141.21)
Errors	18.43 (22.61)	18.03 (23.77)

DTE = desire to eat; HC = high-calorie; LC = low-calorie; FCQ-S = Food Craving Questionnaire – State; * = p < .05 for a t-test comparing deprived scores to satiated scores.

3.1.3. Desirability and palatability

Next, we investigated whether food deprivation caused significant changes in the participants' desire to eat HC and LC foods and their subjective judgment of HC and LC foods' palatability. As displayed in Fig. 2, we found with 2 × 2 ANOVAs that food deprivation strongly increased participants' DTE (main effect of food deprivation, F (1, 59) = 88.15, $p < .001$, $\eta^2_p = .60$) and led to higher subjective palatability ratings (F (1, 59) = 28.15, $p < .001$, $\eta^2_p = .32$). Participants showed no overall higher desire to eat HC foods (main effect of calories, F (1, 59) = 0.92, p = .341, $\eta^2_p = .02$) despite rating them as more palatable (F (1, 59) = 12.66, p = .001, $\eta^2_p = .18$). Calorie content interacted with food deprivation in both DTE, (F (1, 59) = 16.19, $p < .001$, $\eta^2_p = .22$), and palatability (F (1, 59) = 5.91, p = .018, $\eta^2_p = .09$). HC foods were more desired than LC foods when participants were food-deprived (t (59) = 2.50, p = .015) but not when satiated (t (59) = 1.17, p = .247); HC foods were rated as more palatable in both states ($p \leq .018$). An exploratory 2 × 2 × 2 ANOVA comparing DTE and palatability ratings for HC and LC foods in food-deprived and

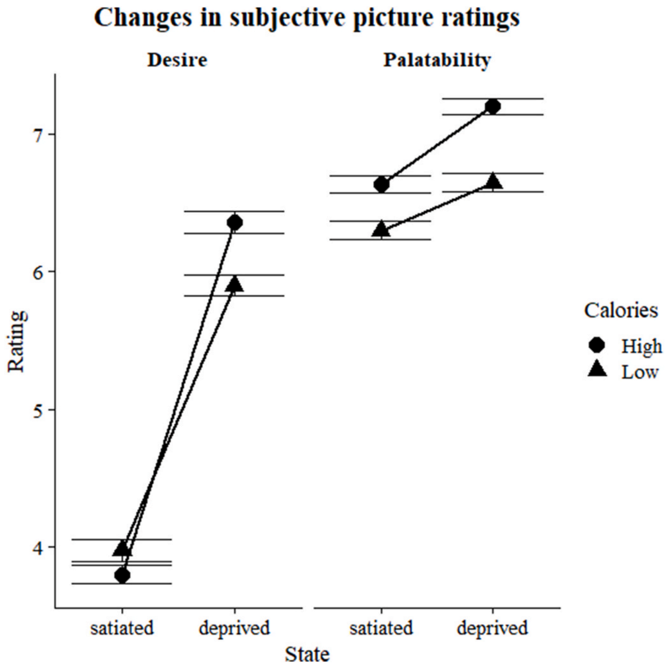

Fig. 2. Changes in subjective palatability and DTE between food-deprived and satiated states for low-calorie and high-calorie foods. Error bars represent standard errors.

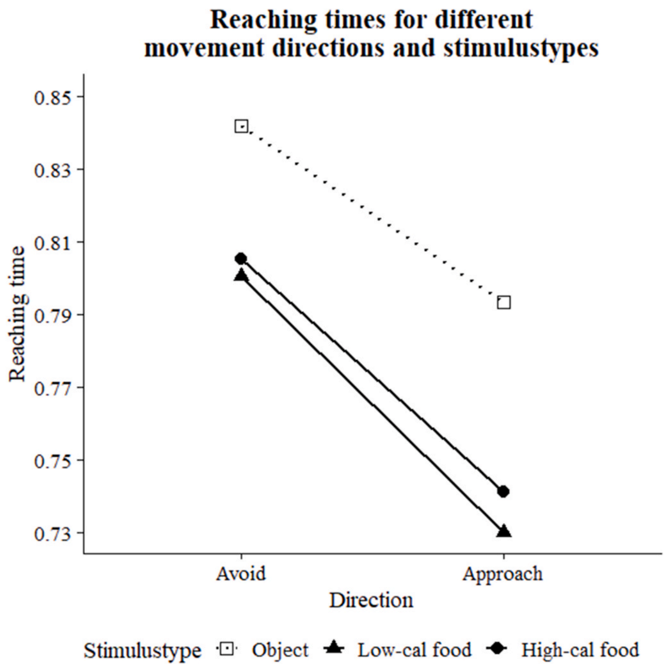

Fig. 3. Differences in approach and avoidance reaching times for low-calorie and high-calorie foods, as well as objects for comparison.

satiated states confirmed that food deprivation affected DTE more strongly than it affected subjective palatability ratings (F (1, 59) = 7.50, p = .008, η^2_p = .11).

3.2. Approach bias for food and the effect of food deprivation

Our first hypothesis was that there is an overall approach bias for food (that is, a Stimulus-type × Movement-direction interaction). To test this, trial-level log reaching time was predicted using a multilevel model with fixed and random predictors (nested under participant) for Direction (*approach* or *avoid*), Stimulus-type (*food* or *object*), and their interaction, as well as random intercepts per stimulus, as displayed in lme4 Equation (1). There was a strong Direction × Stimulus-type effect: while both foods and objects were approached faster than avoided, this effect was stronger for foods (χ^2 = 23.19, p < .001; Fig. 3).

Our second hypothesis was that approach bias is amplified by food deprivation. To test this, log reaching time was predicted using fixed and random predictors for Direction, Stimulus-type, Deprivation (*satiated* or *deprived*), and their interactions, as well as random intercepts for each stimulus, as displayed in lme4 Equation (2). There was no three-way interaction between Direction, Stimulus-type, or Deprivation (χ^2 (1) = 0.30, p = .583).

$$\mathit{logReachingtime} \sim \mathit{Direction} * \mathit{Stimulustype} + (\mathit{Direction} * \mathit{Stimulustype} \mid \mathit{Subject}) + (1 \mid \mathit{Stimulus}) \tag{1}$$

$$\mathit{logReachingtime} \sim \mathit{Direction} * \mathit{Stimulustype} * \mathit{Deprivation} + (\mathit{Direction} * \mathit{Stimulustype} * \mathit{Deprivation} \mid \mathit{Subject}) + (1 \mid \mathit{Stimulus}) \tag{2}$$

3.3. Effect of calories

Our third hypothesis was that HC foods should elicit a larger difference between approach and avoidance reaching times than LC foods. To test this, log reaching time for food[4] stimuli was predicted using a multilevel model with fixed and random slopes for Direction, Calories (*HC* and *LC*), and their interactions, as well as random intercepts per stimulus, as displayed in lme4 Equation (3). HC foods were not approached faster than LC foods (χ^2 (1) = 2.26, p = .133; Fig. 3).

Our fourth hypothesis was that food-deprived participants, compared to satiated participants, would show a larger advantage for approaching rather than avoiding HC foods compared to LC foods. To test this, we predicted log reaching time for food stimuli using a multilevel model with fixed and random effects for Direction, Calories, Deprivation, their interactions, and random intercepts per stimulus, as displayed in lme4 Equation (4). The three-way interaction was not significant (χ^2 (1) = 0.92, p = .337).

$$\mathit{logReachingtime} \sim \mathit{Direction} * \mathit{Calories} + (\mathit{Direction} * \mathit{Calories} \mid \mathit{Subject}) + (1 \mid \mathit{Stimulus}) \tag{3}$$

$$\mathit{logReachingtime} \sim \mathit{Direction} * \mathit{Calories} * \mathit{Deprivation} + (\mathit{Direction} * \mathit{Calories} * \mathit{Deprivation} \mid \mathit{Subject}) + (1 \mid \mathit{Stimulus}) \tag{4}$$

3.4. The effect of individual image ratings on approach bias

We explored whether individual food DTE and palatability ratings affected approach bias for those foods on a trial level. DTE and palatability were analyzed separately due to collinearity (r = 0.67).

3.4.1. DTE

We predicted log reaching time for food stimuli in a multilevel model using fixed and random predictors (nested within participant) for Direction, DTE rating, and their interaction, as well as random intercepts per stimulus, see lme4 Equation (5). DTE affected the difference in reaching times between approach and avoidance (χ^2 (1) = 17.12, p < .001). We examined the main effect of DTE on approach and avoid trials separately in a set of exploratory follow-up analyses, see lme4 Equation (6). Food items were approached faster if they were desired more (χ^2 (1) = 8.86, p = .003), but they were not avoided faster or slower if they were desired more (χ^2 (1) = 0.05, p = .820; Fig. 4).

$$\mathit{logReachingtime} \sim \mathit{Direction} * \mathit{ImageRating} + (\mathit{Direction} * \mathit{ImageRating} \mid \mathit{Subject}) + (1 \mid \mathit{Stimulus}) \tag{5}$$

$$\mathit{logReachingtime} \sim \mathit{ImageRating} + (\mathit{ImageRating} \mid \mathit{Subject}) + (1 \mid \mathit{Stimulus}) \tag{6}$$

3.4.2. Palatability

We performed the same analyses for palatability instead of DTE. Palatability affected reaching times for approach and avoidance trials differently (χ^2 (1) = 12.12, p < .001). More palatable stimuli were approached faster (χ^2 (1) = 17.78, p < .001), but were not avoided faster or slower (χ^2 (1) = 0.61, p = .435; Fig. 4).

We explored the relative contribution of these two variables to model fit. The Likelihood Ratio test, which has been used for all other multilevel analyses in this article, could not be used here as the models were not nested, so models were instead compared using the Akaike Information Criterion (AIC). We computed the AIC difference for the aforementioned models using DTE as predictor with the model using palatability, finding that the DTE model performed much better ($\Delta AIC = -91$): DTE explained more variance in AAT reaching times than palatability.

3.5. Image ratings: disentangling stimulus-specific effects from food deprivation effects

Our previous analysis revealed that DTE predicts faster approach for food items, but we also found before that food-deprived individuals have higher overall DTE. We sought to disentangle the effect of overall DTE per session (between-session DTE) from the effect of between-

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[4] We excluded object trials from this analysis as it is both unneccesary and incorrect to include two sets of objects in an analysis that seeks to examine only the difference between HC and LC foods.

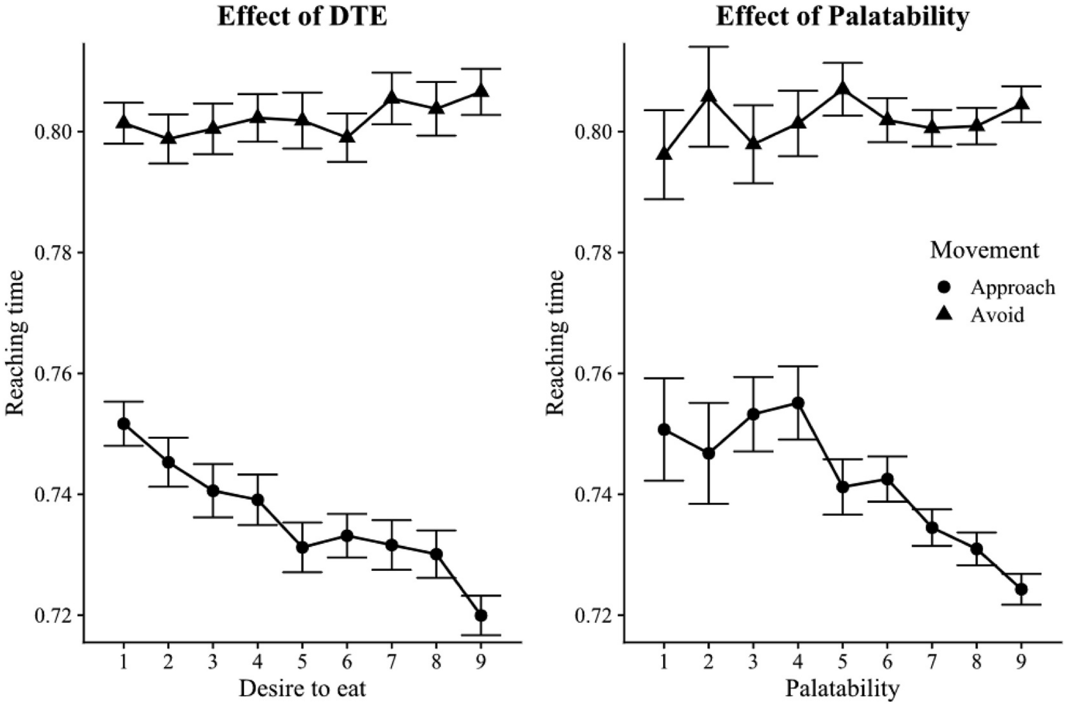

Fig. 4. Effect of DTE and palatability on approach and avoidance reaching times. Mean differences in reaching time between participants have been removed, as is done by random intercepts per participant in multilevel analysis. Error bars represent standard errors.

stimulus variability in DTE ratings within participants (between-stimulus DTE) in an exploratory analysis. To compute between-session DTE, we averaged participants' DTE ratings for each session, and to compute between-stimulus DTE, we subtracted between-session DTE from DTE ratings for individual images in each session. We predicted log reaching time in a model in which Direction interacts with between-session DTE and with between-stimulus DTE, as fixed and random effects, as displayed in lme4 Equation (7).

Higher overall DTE during a session (between-session DTE) predicted a larger difference between avoidance and approach reaching times (χ^2 (1) = 4.76, p = .029), and so did stimulus-specific DTE ratings per session (between-stimulus DTE; χ^2 (1) = 7.08, p = .008). That is, the food deprivation-related increases in overall DTE were related to a concordant increase in approach bias for foods, and when one food was more desired than another food, this also related to a stronger approach bias.

*logReachingtime ~ Direction * BetweenSessionDTE + Direction * BetweenStimulusDTE + (Direction * BetweenSessionDTE + Direction * BetweenStimulusDTE | Subject) + (1 | Stimulus)* (7)

We explored the relative contribution of these two variables to model fit using the AIC. The model without between-session DTE performed slightly better than the model without between-stimulus DTE ($\Delta AIC = -3$), indicating that for trial-level approach bias, the participant's overall DTE per session (between-session DTE) is less important than the participant's realtime food preferences (between-stimulus DTE).

As with DTE, we found that palatability ratings were higher on average in food-deprived participants. To dissociate this overall change from individual differences between individual food ratings, we computed the average palatability per session (between-session palatability), and mean-centered palatability for each stimulus per session (between-stimulus palatability). We predicted log reaching time with these variables and their interaction with Direction as fixed and random effects. Between-session palatability did not affect differences in avoid and approach trial reaching times (χ^2 (1) = 2.72, p = .099), but between-stimulus palatability did (χ^2 (1) = 7.74, p = .005).

3.6. Relationship with state craving, trait craving, and hunger

Our fifth hypothesis was that there is a relationship between approach bias and one or more of state hunger (FCQ-S-hunger), state food craving (FCQ-S-craving), and trait food craving (FCQ-T-r). To examine this, we ran three multilevel analyses predicting log reaching time using random intercepts per stimulus, random effects per participant for Direction, Stimulus-type and their interaction, and fixed effects for Direction, Stimulus-type, questionnaire score, and their interactions, as displayed in lme4 Equation (8). There was no evidence for relationships of state hunger or craving, nor trait craving, with approach bias (p's > 0.087).

*logReachingtime ~ Direction * Stimulustype * QuestionnaireScore + (Direction * Stimulustype | Subject) + (1 | Stimulus)* (8)

3.7. Reliability

Lastly, we estimated the reliability of the AAT. For this purpose, we used the bootstrapped split-half reliability functionality available in the AATtools package (Kahveci, 2020) for R (R Core Team, 2019). First, we performed 1000 random splits on the data. In each split, we excluded outliers and errors as described in the methods section. Unlike in the Methods section we did not exclude entire participants' sessions if they had excessive error/outlier rates; if we did, the halved size of the samples would lead to the exclusion of a high number of participants. Next, we computed an approach bias score for each half of each split by subtracting the mean reaching time difference of approach-object and avoid-object trials from the mean reaching time difference between approach-food and avoid-food trials. We excluded participants in each half that had an approach bias score deviating more than 3 *SD* from the sample mean. We then computed the correlation between the two resulting approach bias scores for each participant. After obtaining 1000 such correlations, we computed the mean correlation coefficient and applied a Spearman-Brown correction to account for the halved test length, thereby obtaining a split-half reliability value that is not biased due to the arbitrariness of a single split, or due to outliers that disproportionately affect the correlation.

The split-half reliability of the full dataset (2 sessions per participant) was acceptable, (r_{SB} = 0.58). When sessions were analyzed separately, reliability was lower (food-deprived r_{SB} = .48, satiated r_{SB} = 0.49). The test-retest reliability between food-deprived and satiated sessions was low (r_{retest} = 0.23).

Using the same methodology as described above, we additionally computed the bootstrapped split-half reliability for raw pull and push reaction times for foods and objects, as well as reliabilities for push-pull difference scores for foods and objects separately. The reliabilities for single conditions were close to 1 (pull food: r_{SB} = 0.98; push food: r_{SB} = 0.99; pull objects: r_{SB} = 0.97; push objects: r_{SB} = 0.99) and the reliabilities for push-pull difference scores were also very high (push food – pull food: r_{SB} = 0.95; push object – pull object: r_{SB} = 0.89).

4. Discussion

The present study was the first to experimentally test the effect of food deprivation on approach bias towards HC and LC foods. We will discuss and interpret all findings in turn.

4.1. A role for desire, not homeostasis, in approach bias

Manipulation checks confirmed that food deprivation successfully increased subjective palatability and DTE ratings, particularly so for HC foods. In line with some previous findings but in contrast to our hypotheses, we found that food-deprived individuals do not have a stronger food approach bias (Höfling, 2008; Piqueras-Fiszman et al., 2014) and that individuals do not have a stronger approach bias for HC foods (Paslakis et al., 2016). We extended these findings by showing that food deprivation does not cause a difference between approach bias for HC and LC foods, despite increasing the subjective desire to eat HC foods. These results suggest that, unlike food cue reactivity in the ERP and fMRI domains, differences in approach bias do not neatly map onto differences in homeostatic needs (Goldstone et al., 2009; Siep et al., 2009; Stockburger et al., 2009, 2008). This casts doubt on explanations suggesting that approach bias for food is closely controlled by the need to replenish energy supplies. However, it is not inconsistent with evolutionary theory more broadly: for our prehistoric ancestors, it may have been beneficial to approach food regardless of homeostatic need, as they were able to consume or store food at any given moment, and future food availability was not guaranteed.

However, these results are put into context by our finding that approach bias co-varied with fluctuations in DTE (but not hunger), induced by experimentally manipulated food deprivation. Interestingly, we also found that participants' desire to eat different foods predicted their approach bias for these specific foods, independently of their overall desire to eat food. These food-specific preferences held more explanatory power than did the individual's overall DTE, demonstrating the importance of specific momentary preferences in understanding approach bias. Our results thus reveal that the implicit approach bias towards foods is closely linked to the explicit desire to eat them.

This conclusion is also consistent with clinical findings, which indicate that patients with anorexia nervosa, who have a low desire to eat foods in general and HC foods in particular (Stoner, Fedoroff, Andersen, & Rolls, 1996), also have a reduced approach bias towards foods in general (Paslakis et al., 2016) and towards HC foods in particular (Neimeijer et al., 2015, 2019). Future research could clarify the causal relationship between these variables through approach bias modification training in patients with anorexia nervosa. Additionally worth investigating is whether approach bias predicts future states of extreme desire to eat, such as binges, in patients with bulimia nervosa, who often have co-morbid alexithymia and may thus be unable to predict such episodes (Nowakowski, McFarlane, & Cassin, 2013).

Our current findings suggest that individual preferences should be taken into account in future AAT studies. Our current results underline that personalization of AAT interventions is not only intuitively, but also empirically justified. AAT interventions only reduce symptoms if there is an underlying bias that is successfully reduced (Clarke, Notebaert, & MacLeod, 2014). It is therefore prudent to retrain approach bias only for those stimuli which the individual desires.

4.2. Faster approach, not slower avoidance, as the driver of appetitive approach bias

Interestingly, DTE and palatability only facilitated approach movements, while leaving avoidance movements unaffected. These findings echo a previous study in the alcohol domain, which showed that pre-treatment alcohol use predicts speed of alcohol approach, but not alcohol avoidance (Barkby, Dickson, Roper, & Field, 2012). Together, these results suggest that approach bias for appetitive stimuli might be driven primarily by facilitated approach rather than impaired avoidance, and that this facilitation of approach does not interfere with the ability to avoid. This lack of interference implies that approach movements may be facilitated only once it has been determined that approach is the appropriate response. Future research is needed to elucidate when approach bias expresses itself within the neurocognitive chain of events that starts with stimulus perception and culminates in approach and avoidance responses.

Desired foods may be approached faster because individuals approach the foods they desire more often than foods they do not desire, and thus gradually develop an 'approach expertise' for certain foods, either through pavlovian-to-instrumental transfer, or associative learning of food and approach (Watson, De Wit, Hommel, & Wiers, 2012). Momentary cravings may also activate these approach memories and further facilitate approach behavior. In comparison, one might speculate that active physical avoidance of desired foods in the AAT may represent a less practiced behavior that is therefore driven more by executive function than by habit (Sharbanee et al., 2013; Wiers et al., 2007). Passive avoidance of food (i.e. non-responding) is learned more easily than active avoidance, and may thus better reflect avoidance tendencies in the food domain (Guitart-Masip et al., 2012).

Regardless of the possible explanations, this finding has implications for the design of future AAT trainings. Current retraining studies attempt to reduce approach bias by associating target stimuli with avoidance movements. Future studies should instead seek to disrupt the facilitated approach towards those stimuli. Additionally, similar trial-level analyses should be performed on AAT data with aversive stimuli, to see whether avoidance biases for aversive stimuli are driven by impaired approach or enhanced avoidance.

4.3. Reliability and validity of the current paradigm

The split-half reliability of the current AAT was excellent for an implicit task, especially when the outcome measure was the contrast of mean food approach and avoidance reaction times (r = 0.95). It was also acceptable when the outcome measure was the contrast of approach-avoidance reaction time differences between foods and objects (r = 0.58), as was done in previous touchscreen-AAT studies (Meule, Richard, Lender, et al., 2019). This was also our first opportunity to explore the test-retest reliability of the touchscreen-AAT, which was much lower (r = 0.23) than its split-half reliability. This is unsurprising, given that participants were food-deprived in one session and satiated in the other, thereby predictably leading to divergent AAT scores.

Unlike a previous version of our touchscreen AAT, the current task was sensitive to an overall approach bias for foods, even when participants were satiated (Meule, Lender, et al., 2019). Also unlike this previous version however, approach bias was not modulated by state or trait craving. This might be due to the fact that this previous study measured approach bias for chocolate and found a correlation with craving for chocolate, while the current study used a wide range of food items and measured nonspecific craving for food in general. The validity of the current AAT implementation is supported by the demonstrated relationship of stimulus-specific DTE and palatability ratings with approach bias.

Although we have demonstrated the validity of the current paradigm with its touchscreen input and with 2 stimuli per trial (see also Meule, Richard, Lender, et al., 2019), it differs from regular joystick AATs, thereby limiting the generalizability of the current results to the wider AAT literature. Further research with more traditional AAT paradigms is needed to verify that food deprivation and calorie content indeed do not affect approach bias directly, irrespective of the AAT variant used.

4.4. Summary

In sum, we found that participants had an overall approach bias towards food, which was influenced neither by the food's calorie content, nor by the participant's food-deprived state. Instead, specific food preferences enhanced approach bias for specific foods: the desire to eat a specific food and the subjective palatability of that food predicted a larger approach bias for that food, and food deprivation affected approach bias indirectly by greatly increasing the overall desire to eat foods in some people, but less so in others. Taken together, the current results suggest a strong link between DTE and approach bias, they demonstrate the value of taking into account participants' preferences, and they indicate that unhealthy eating may be reduced by disrupting automatic approach behavior rather than training avoidance.

Ethics

We declare that all authors accept full responsibility for all aspects of to the work described, the manuscript is not under review elsewhere, and the corresponding author can provide all original data for review. The study was conducted with permission granted by the ethics committee of the Paris Lodron University of Salzburg, and in accordance with the Declaration of Helsinki.

CRediT authorship contribution statement

Sercan Kahveci: Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Adrian Meule:** Conceptualization, Investigation, Data curation, Formal analysis. **Anja Lender:** Investigation, Data curation. **Jens Blechert:** Conceptualization, Supervision, Writing - review & editing.

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