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Impact of olfactory priming on mental representations of food concepts and subsequent food choice

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ABSTRACT

Previous research suggests that food odors act as a prime and influence food choice outside of awareness. Little is known about how odors prime (healthy) food choices. We hypothesized that odors could activate mental representations of food concepts, interacting with cognitive processes underlying food decision-making. We tested this by examining which concepts (healthy, sensory, or product-specific) are activated by odors and how this impacts subsequent food choices. In a between-subjects design, 112 participants were divided into three conditions: healthy odor (apple or banana), unhealthy odor (chocolate or caramel), and non-odor (control). Participants were exposed to one condition for 5 min and then completed a lexical decision task and a screen-based food choice task. The lexical decision task included four word categories: healthy-related, sensory-related, neutral words, and non-words. Reaction times were recorded and computed for each category. Participants were asked to choose one food they wanted to eat from four (in-)congruent food word options and repeated it four times (one for each odor). Results showed participants responded slower to non-words than other words, and slower to healthy and sensory words than neutral words. However, odor exposure did not influence reaction times, nor did the interaction between odor condition and word category affect reaction times. Participants were more likely to choose unhealthy foods regardless of odor exposure. Thus, ambient sweet odors did not prime food-related information or choice. We recommend additional testing using a broader range of odors and word categories to fully validate the association of an odor with a concept.

1. Introduction

Odors play an anticipatory role in eating behavior (Boesveldt & de Graaf, 2017) and may thereby steer food choices. Previous studies have demonstrated that ambient odors have the ability to affect (healthy) food choices outside of awareness (Chambaron et al., 2015; Gaillet et al., 2013; Gaillet-Torrent et al., 2014; Sulmont-Rossé et al., 2018). For example, participants who were exposed to a pear odor were more likely to choose low-calorie fruity desserts than those in a no-odor control condition (Gaillet-Torrent et al., 2014). However, inconsistent findings regarding the effect of odors on food choice are reported as well. Morquecho-Campos et al. found that participants were more likely to choose sweet snacks regardless of the types of odor exposure (Morquecho-Campos et al., 2022). Moreover, a real-life study showed that odor exposure did not affect subsequent lunch choices (Mors et al., 2018). Due to these results, a better understanding of the mechanisms underlying the food decision-making process is crucial.

In our previous study, we addressed this question by focusing on visual attention (Yang et al., 2023). Results showed that participants did spend more time viewing the different food options before making a food decision under healthy odor exposure (apple and honey melon) compared with unhealthy odor exposure (chocolate and caramel). Although we did find that odor exposure affects visual attention, there was no effect on food choice. This result implied that odors do not always lead to congruent food choices and other (cognitive) factors may drive the final food choice.

Previous literature postulates that environmental cues may act as a so-called prime that influences subsequent behavior by activating mental representations without intent or awareness (Stöckli et al., 2016; Tal & Wansink, 2015). Priming is a psychological effect in which the

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prior stimulus may lead to an increase in the accessibility of semantically related concepts (Forwood et al., 2015). For example, exposure to skinny human-like sculptures activated weight-related representation and reduced chocolate consumption compared to being exposed to a more neutral work of art (Brunner & Siegrist, 2012). Similarly, for olfaction, we assume that semantically related concepts become more accessible upon odor exposure and then affect subsequent behavior. Holland et al. (2005) already demonstrated that exposure to citrus odor can prime the cleaning concept which results in increased cleaning-related activities (Holland et al., 2005). This 'clean' priming effect has also been confirmed by de Lange et al. (2012) who reported that people in a train environment showed less littering behavior after citrus odor exposure compared to those in a non-odor condition (de Lange et al., 2012).

A widely used method to investigate conceptual priming is the lexical decision task, in which participants have to decide whether a letter string is an existing word or not. For example, Muscarella et al. found that participants responded faster to the words "MCDONALDS" and "HAMBURGER" than other (unrelated) words after they were presented with the McDonald's logo, indicating that a brand logo is able to prime its name as well as related concepts (Muscarella et al., 2013). Holland et al. (2005) adapted this task to explore the processes underlying the priming effect of odors on behavior. In their study, participants were exposed to a citrus odor which is considered to be a typical scent of cleaning products, leading to participants responding faster to cleaning-relevant words (e.g., "tidying up") and cleaning more crumbs from a table than those who were not primed by the odor (Holland et al., 2005). This effect has been explained by the association of citrus odor with cleaning products that activates mental representations of the concept of cleaning, leading to quicker availability of -and responses to cleaning-related words, as well as subsequent increased relevant cleaning behavior, all without being aware of the presence of any citrus odor.

Moreover, lexical decision tasks have also been applied to the food domain to measure the conceptual priming effect of food cues. Fishbach et al. (2003) assigned female participants to three primes: diet prime (exercising/dieting magazines), food prime (fattening food and a Chocolatier magazine), and control (neutral magazines), and found that participants in the diet prime condition showed shorter reaction times for the word "diet" and more frequently chose apples than those in the control condition (Fishbach et al., 2003). Another example is a study conducted by Gaillet et al. (2013) where participants were required to complete a lexical decision task and a food choice task after 10-minute unaware melon odor exposure. The results showed that melon odor-primed participants responded to "melon" words faster than the control group, and they were more likely to choose starters with vegetables suggesting the odor might have activated a "fruit and vegetables" concept and elicited behavior that is congruent with that concept.

Based on these previous findings, it seems that ambient odors are able to activate mental representations that serve as the driving force behind food choice. However, it remains unclear which specific (food) concepts (e.g., 'healthy' or 'melon') are actually activated by odors and whether this affects subsequent food choices. In the current study, healthy (apple and banana) and unhealthy (chocolate and caramel) odors were presented as environmental prime, with non-odor as the control. A lexical decision task followed by a food choice task was designed to investigate which food-related concept was activated to serve as the bridge between food odors and congruent food choice. In experiments studying the effects of food odors on eating behavior, some use non-food odors as controls (Kemmotsu & Murphy, 2006; Zoon et al., 2014), while others use no odor as the control (Mors et al., 2018; Proserpio et al., 2019). We chose no odor as the control because it more closely resembles real-life conditions, providing better ecological validity for studying food choice.

We hypothesized that 1) participants exposed to food odors will respond faster to food-related words (both healthy- and sensory-related) than other (neutral) words in the lexical decision task; 2) participants exposed to healthy food odors will choose healthy food products more often, participants exposed to unhealthy food odors choose unhealthy food products more often; and 3) participants will choose odor-congruent food products after odor exposure. For example, participants will choose banana-flavored foods after being exposed to banana odor.

2. Method

2.1. Participants

Participants were recruited through social media and flyers, advertising an alternative aim: to investigate the effects of hunger and satiety on attention. Interested individuals were screened via an online questionnaire using EyeQuestion (Logic8 BV) to assess eligibility. The screening questionnaire included questions related to general lifestyle and medical information. Also, eating behavior, measured by the Dutch Eating Behaviour Questionnaire (DEBQ, van Strien et al., 1986), impulsiveness, measured by the Barratt Impulsiveness Scale (BIS-11, Patton et al., 1995), and health and taste attitudes, measured by Health and Taste Attitude Scales (HTAS, Roininen et al., 1999) was assessed. Inclusion criteria were: aged between 18 and 35 years; Dutch-speaking; a self-reported normal weight (BMI: 18–25 kg/m^2). Exclusion criteria were: self-reported weight change (>5 kg) in the past two months; any food restriction; habitual smoking; pregnancy; participation in other medical studies or our previous studies.

Based on a previous experiment investigating the priming effect of odors employing a lexical decision task (Gaillet et al., 2013), we determined the number of participants, to approximately 40 per condition. A total of 126 participants who met the requirements took part in the study. Of these participants, 9 participants were excluded for low odor identification scores (<12 on the Sniffin Sticks), and 5 participants were excluded for guessing the real aim of the study (to investigate the priming effect of odor exposure on reaction time and food choice). The remaining 112 participants (93 females and 19 males) were distributed among three odor conditions: 37 in the healthy odor exposure group (Apple: 17, Banana: 20), 37 in the unhealthy odor exposure group

Table 1
Characteristics of the participants (N = 112).

	Mean	SD	Range
Age (years)	22.1	2.4	18.0–28.0
BMI (kg/m^2)	21.6	1.7	18.0–25.5
DEBQ			
Restrained eating	2.4	0.7	1.0–4.5
Emotional eating	2.5	0.6	1.1–3.9
External eating	3.5	0.5	2.6–4.6
BIS-11			
Attentional	2.2	0.3	1.5–3.1
Motor	1.9	0.3	1.3–2.9
Non-planning	2.6	0.3	1.9–3.5
HTAS			
General health interest	4.6	0.8	2.4–6.4
Natural product interest	3.3	1.1	1.0–5.8
Light product interest	3.8	1.0	1.3–6.0
Pleasure	4.7	0.8	2.2–6.7
Using food as a reward	4.7	0.9	1.2–7.0
Craving for sweet foods	4.1	1.1	1.7–7.0

Dutch Eating Behavior Questionnaire scale: 1–5, higher scores indicating a higher degree of restrained, emotional, and external eating styles (DEBQ, van Strien et al., 1986).
Barratt Impulsiveness scale: 1–4, higher scores indicating higher impulsiveness (BIS-11, Patton et al., 1995).
Health and Taste Attitude Scale: 1–7, higher scores indicating more interest in health and taste aspects of foods in the food choice process.

(Caramel: 17, Chocolate: 19), and 39 in the control group. The main characteristics of the participants are shown in Table 1. Participants were compensated €10 for completing the study. The study was conducted in accordance with the Declaration of Helsinki (revised in 2013) and approved by the Social Sciences Ethics Committee of Wageningen University (2022-118-SBSEB-prc).

2.2. Odor stimuli

A pilot study was conducted with participants who did not take part in the main study to select suitable odors and determine their concentration. Eight odors representing healthy (apple, honey melon, banana, pear) and unhealthy (chocolate, blond almond/caramel, cinnamon, vanilla) were diffused into the testing room by vaporizers (Iscent, Zeewolde, The Netherlands). 'Healthy' and 'unhealthy' refer to odors associated with foods generally perceived as healthy (nutrient-dense foods low in fat, sugar and/or calories) or unhealthy (indulgent, energy-dense foods high in fat and/or sugar), rather than implying the odors themselves possess inherent health qualities. Thirty participants were exposed to two odors (one per category) in a counterbalanced order. They were asked whether they noticed any odor in the room. If yes, they were asked to evaluate the odors' intensity, familiarity, liking, and healthiness on a 100-mm visual analogue scale (VAS, from 0 = "Not at all" to 100 = "Very"), and write down the odor-associated food products. On the basis of these results, apple (healthy; Symrise 651343; 4 % in propylene glycol (PG)); banana (healthy; Symrise 655348; 18 % in PG); Chocolate (unhealthy; Symrise 651007; 12 % in PG); Blond almond (unhealthy; Symrise 448023; 7 % in PG) were selected, in concentrations that were perceived as 40–50 mm intensity on 100 mm VAS, by the aware participants, ensuring that the odors were subtly noticeable in the subsequent main study (see supplementary materials Table S1). In our previous study, most participants associated the blond almond odor with caramel, thus we refer to it as caramel.

2.3. Procedure

A between-subjects design was used in which participants were randomly assigned to one of three odor conditions (healthy odor exposure, unhealthy odor exposure, and no-odor). To control for possible hunger effects, participants were required to eat their habitual meal no later than two hours and no sooner than 45 min before the experiment, and only drink water but no other beverages in the hour before the experiment. Moreover, they were instructed to refrain from wearing any perfume which could affect odor perception.

After an initial welcome, participants were asked to evaluate their general appetite and emotions (I-PANAS-SF; Thompson, 2007) in the waiting area. Then they were led to the testing room (Room 1) where the odors had been dispersed via vaporizers (Iscent, Zeewolde, The Netherlands) for 7 min before they entered. Participants resided in the testing room for 5 min while being exposed to the odor, during which they were instructed on the lexical decision task and completed the practice phase. Following this, they were asked to finish the lexical decision task and the food choice task. Subsequently, the participants were taken into an odorless room (Room 2) to complete the debriefing questionnaire including guessing the study's real aim and assessing the odors' and the food words' attributes. In addition, an odor identification test was taken to assess the olfactory capabilities of the participants (Hummel et al., 1997). After the study ended, we debriefed the participants via the lexical decision task and the food choice task were presented by using E-Prime (version 3.0). Fig. 1 shows the procedure of the experiment.

2.4. Measurements

2.4.1. Lexical decision task

A lexical decision task was adapted to investigate what type of food-related concepts can be primed by odors. We conducted a pilot study to

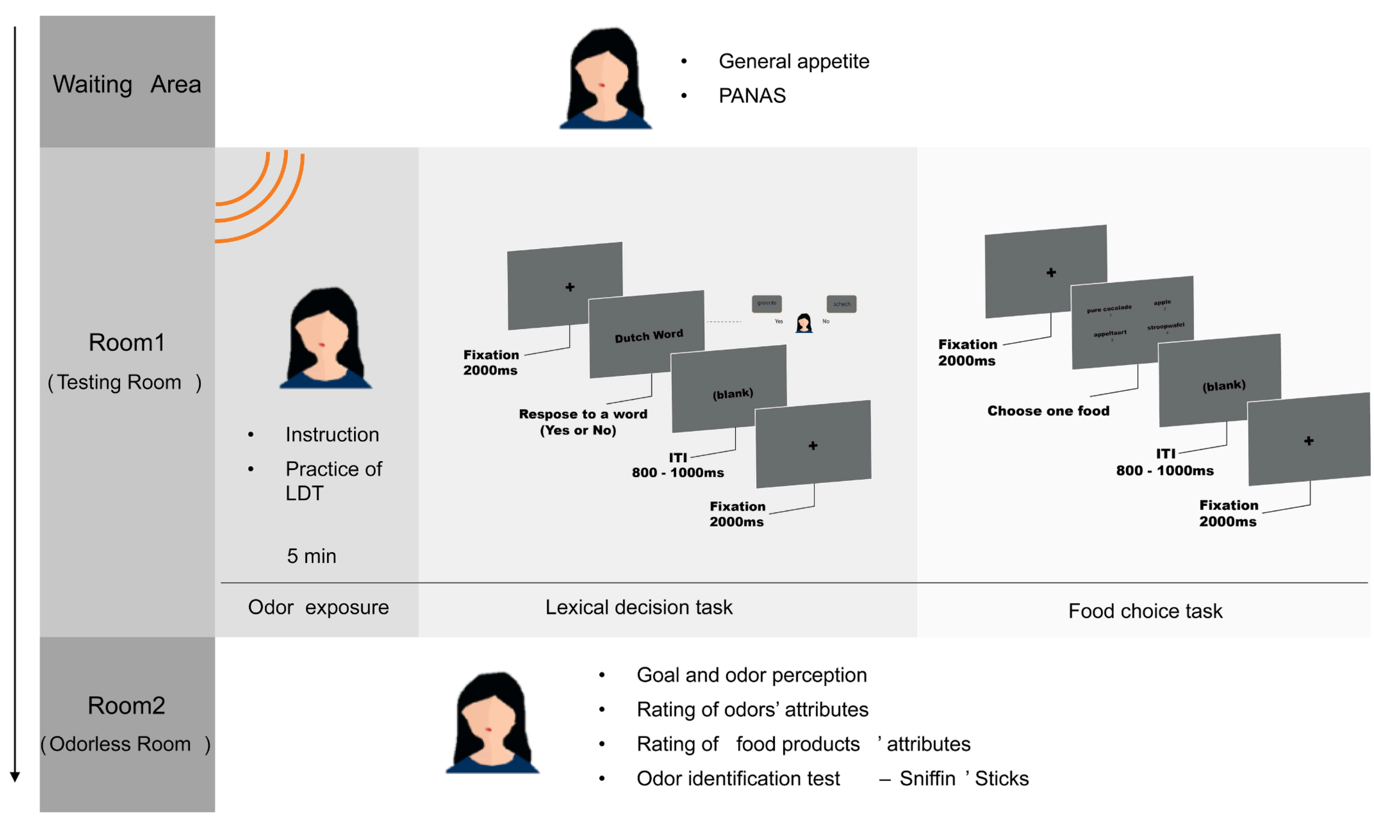

Fig.1. Procedure for the study. The orange waves indicate odor exposure. LDT = lexical decision task. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

select the word stimuli. For the word stimuli, we implemented two classifications: health-related words (longer-term goals) and sensory-related words (short-term goals). A total of 35 Dutch participants who did not participate in the main study were asked to classify 115 Dutch words into healthy food-related, unhealthy food-related, sensory-related, neutral words, and non-words, online via EyeQuestion (Logic8 BV). Non-words were generated by Wuggy software (Keuleers & Brysbaert, 2010), and neutral words were selected from CELEX lexical database (Baayen et al., 1995). We selected words with at least 70 % classified accuracy and took into account the number of letters (5–8), and syllables (1–3) across categories. Thirty-six real words including 12 healthiness-related (6 healthy food-related, e.g., groente, "vegetable" and 6 unhealthy food-related, e.g., snoep, "candy"), 12 sensory-related (e.g., pittig, "spicy"), and 12 neutral words (e.g., trein, "train") and 36 non-words (e.g., schech, "schech") were chosen. We then asked 16 other Dutch-speaking participants to classify these selected words to re-verify the category for each word as a last check. In the lexical decision task, participants were asked to decide whether a letter string is a word or not. Responses were made by pressing the "P" or "Q" keys representing yes or no, which were counterbalanced to control for any effect of handedness. The task includes a practice phase consisting of 10 trials to familiarize the procedure and an experimental phase during which participants performed 72 trials in random order. Each trial starts with a cross for 2 s, and then the stimuli were presented until the participants responded. A blank screen following appeared for an inter-trial interval (ITI) of either 800 ms, 1000 ms, or 1200 ms before the next trial (similar procedure as Gaillet et al. (2013) with a changeable ITI).

2.4.2. Food choice task

A pilot study was conducted to select food words for the food choice task. Twenty-three Dutch participants who did not take part in the main study were asked to assess the familiarity, liking, and healthiness of 33 food words using a 100-mm VAS. The food words matched the odors used in the main study; 8 apple-flavored, 8 banana-flavored, 8 chocolate-flavored, and 9 caramel-flavored food products. For healthier alternatives of foods (e.g., products with low energy, fat and/or sugar content), we refer to them as healthy foods for the sake of readability. Based on the results, we selected 8 Dutch food words (one healthy and one unhealthy food product per odor): apple, apple pie, banana, banana milkshake, caramel granola bar, stroopwafel (a typical Dutch cookie with caramel syrup filling), dark chocolate and chocolate brownie. The food choice task consists of four trials paired with four odors we used in the study. In each trial, 4 (in-)congruent food word options were displayed on the screen in a 2-by-2 format: one congruent in both healthiness and flavor to the exposed odor, one congruent only in flavor, one only in healthiness, and one fully incongruent to the exposed odor. For example, paired with the apple odor are apple (healthiness and flavor congruent), apple pie (flavor congruent), dark chocolate (healthiness congruent), and stroopwafel (healthiness and flavor incongruent). Participants were instructed to select one food product that they wanted to eat by pressing one of four keys (1, 2, 3, or 4), with each key corresponding to a specific location on the screen: upper-left, upper-right, lower-left, or lower-right.

2.4.3. Questionnaires

The Dutch Eating Behavior Questionnaire (DEBQ, van Strien et al., 1986) is a 33-item questionnaire used to assess eating behavior including three subscales: Emotional Eating (13 items), External Eating (10 items), and Restrained Eating (10 items). Responses were scored on a 5-point Likert scale ranging from 1 = 'Never' to 5 = 'Very often'. Higher scores indicate a greater tendency for the three subscale eating styles.

Barratt Impulsiveness Scale (BIS-11, Patton et al., 1995) is a 30-item questionnaire used to measure impulsiveness which can be associated with unhealthy eating (Jasinska et al., 2012). It includes three subscales: 8 items for attentional impulsiveness, 11 items for motor impulsiveness, and 11 items for non-planning impulsiveness. Responses were ranged on a 4-point Likert scale from 1 = 'Never'/'Rarely' to 4 = 'Almost always'/'Always'.

Health and Taste Attitude Scale (HTAS, Roininen et al., 1999) is a 38-item questionnaire used to assess consumers' health and taste attitudes towards food products and measures the importance of health and taste aspects of foods in the food choice process which has been validated in the Dutch population (Roininen et al., 2001). It has three health-related subscales including 8 items assessing general health interest, 6 items assessing light product interest, and 6 items assessing natural product interest, and three taste-related subscales including 6 items assessing craving for sweet foods, 6 items assessing using food as a reward, and 6 items assessing pleasure. Responses were ranged on a 7-point Likert scale from 1 = 'Strongly disagree' to 7 = 'Strongly agree'.

General appetite was measured by hunger, satiation, desire to eat, prospective consumption, and thirst on 100-mm VAS anchored by 1 = 'Not at all' to 100 = 'Very', and as these measures were highly correlated (Cronbach's alpha = 0.85), a general appetite score was computed by averaging the hungry state, satiated state (reverse-scored), desire for food, and prospective consumption scores.

The International Positive and Negative Affect Schedule Short Form (I-PANAS-SF; Thompson, 2007) is a 10-item questionnaire used to measure positive affect (PA; 5 items) and negative affect (NA; 5 items). Responses were ranged on a 5-point Likert scale from 1 = 'Never' to 5 = 'Always'. Emotions play an important role in food intake (Patel & Schlundt, 2001), and healthy food is less likely to be chosen under negative emotions (Aguiar-Bloemer & Diez-Garcia, 2018).

Debriefing questionnaire. Firstly, participants were asked to guess the real aim of the study and whether they noticed an odor during the experiment. If yes, they were asked to assess their liking, intensity, familiarity, desire to eat a product with this odor, mouthwatering sensation, healthy and unhealthy associations, and pleasure on a 100-mm VAS anchored by 'Not at all' to 'Very'. In addition, they had to identify the odor by choosing one option amongst five (Chocolate, Apple, Caramel, Banana, and Odorless) and rate how well the odor matched that product on a 100-mm VAS scale anchored by 'Not at all' to 'Very'. Then the participants were asked to assess their familiarity, liking, and health associations for the food words used in the food choice task on a 100-mm VAS scale anchored by 'Not at all' to 'Very'.

To assess the participant's ability to identify odors, we used the identification subtest of the Sniffin' Sticks test (Hummel et al., 1997). Sixteen common odors were presented via pens to the participants, and they were asked to choose one option that they thought fit the odor best from 4 options. Participants with less than 12 correct answers were regarded as normosmic (Oleszkiewicz et al., 2019) and were excluded from the data analysis.

2.5. Statistical analysis

All statistical analyses were performed in RStudio (version 4.1.0) running R (version 4.2.2). The results reported significance at a level of 0.05.

In the lexical decision task, incorrect responses (2.5 %) and responses shorter than 300 ms or longer than 2500 ms (0.4 %) were excluded from the analyses (Wagenmakers et al., 2008). A linear mixed model in the lmerTest package was conducted to test the priming effect of odor exposure on reaction time for different word categories. The dependent variables in the model were the reaction times, and the independent variables in the model were odor condition (healthy odor, unhealthy odor, and no-odor) and word categories (health-related words, sensory-related words, neutral words, and non-words). Both independent variables were dummy coded (odor condition: 0 = "non-odor", 1 = "healthy odor", 2 = "unhealthy odor"; word categories: 0 = "non-words", 1 = "health-related words", 2 = "sensory-related words", 3 = "neutral words"). Gender, age, BMI, DEBQ subscales, HTAS subscales, BIS subscales, PA, NA, and general appetite were considered as covariates. We conducted the analysis in two steps. Firstly, a model with only odor exposure and word categories was fitted. Secondly, gender, age, and BMI were included in the final model, while a forward selection process was used to determine other potential covariates. Through this process, HTAS – General health interest and PA were selected and included in the final model. Participants were regarded as a random effect (Reaction time ~ Odor exposure * Word category + covariates + (1 | Participant)). A normality test showed that average scores were non-normally distributed. Thus, data were transformed to log (x + 1) into normal. Tukey's HSD post hoc comparisons were conducted using the emmeans package in R.

With regard to the food choice task, a Poisson generalized linear model (GLM) was performed to investigate the priming effect of odor exposure on the healthiness of food choices. The dependent variable in the model was the frequency of healthy food choices in the food choice task (between 0 and 4). The independent variable in the model was odor exposure and it was dummy coded (0 = "non-odor", 1 = "healthy odor", 2 = "unhealthy odor"). Same as the previous LMM, we analyzed the data without and with covariates. Gender, age, and BMI were included in the final model, while a forward selection process identified HTAS – Craving for sweet foods as an additional covariate (The frequency of healthy food choices ~ Odor exposure + all covariates). In addition, a Wilcoxon test was carried out to examine the difference between the number of healthy food choices and unhealthy food choices.

Moreover, an exploratory analysis was performed to assess the odor congruence effects of odor exposure on food choice. We conducted a Chi-Square test to examine the relation of the congruence of choices related to specific odor exposure. "Congruent" and "incongruent" were defined according to the 'odor consistency' between the food products and the exposed odors. For example, apple pie was defined as "congruent" upon apple odor exposure and "incongruent" upon chocolate odor exposure.

3. Results

3.1. Lexical decision task

A log-transformed linear mixed model without covariates showed a significant main effect of word category on reaction times ($\chi^2 = 431.75$, $p < 0.001$, Fig. 2). Tukey's HSD post-hoc comparisons showed that participants responded slowest to non-words than the other words, and slower to healthy-related words and sensory-related words than neutral words. However, there was no main effect of odor exposure ($\chi^2 = 0.33$, $p = 0.85$) nor an interaction effect between odor exposure and word category ($\chi^2 = 3.65$, $p = 0.72$). The descriptive statistics are shown in Table 2. A generalized linear mixed model including covariates showed a significant main effect of word category on reaction times ($\chi^2 = 431.75$, $p < 0.001$).

3.2. Food choice task

The generalized linear model without covariates to test the priming effect of odor exposure on the healthiness of food choices showed that odor exposure did not prime the healthiness of the chosen food products ($\chi^2 = 0.81$, $p = 0.67$). A generalized linear mixed model including covariates showed a similar result ($\chi^2 = 1.38$, $p = 0.50$). The Wilcoxon test showed that participants were more likely to choose unhealthy food products regardless of the healthiness of the odor exposure ($p < 0.001$, Fig. 3).

The Chi-Square Test assessing the odor congruency effect of odor exposure on food choice did not show a significant difference ($\chi^2 = 3.67$, $p = 0.30$).

4. Discussion

This study aimed to unravel the mechanisms underlying how sweet odors activate food-related concepts and influence subsequent food choices. Based on previous research (Gaillet et al., 2013; Holland et al., 2005), we assumed that odors can prime food-related concepts, and thereby affect subsequent food choices. In the specifically designed lexical decision task, participants showed the slowest reaction time (RT) to non-words. RTs to healthy-related words and sensory-related words did not differ from each other, but both categories were slower responded to than neutral words. We observed no significant difference in RTs to the different categories of words between odor-exposed and non-odor conditions. In the subsequent food choice task, participants preferred to choose unhealthy foods, regardless of the healthiness of the odor presented. Moreover, we did not find the odor-congruent effect of odor exposure on food choice.

In the lexical decision task, the longer RTs for non-words were in line with findings from prior studies (Hoedemaker & Gordon, 2014; Lima & Huntsman, 1997). However, the absence of significant differences between the odor and non-odor conditions in our study, suggests that food odors may not readily prime corresponding food-related concepts,

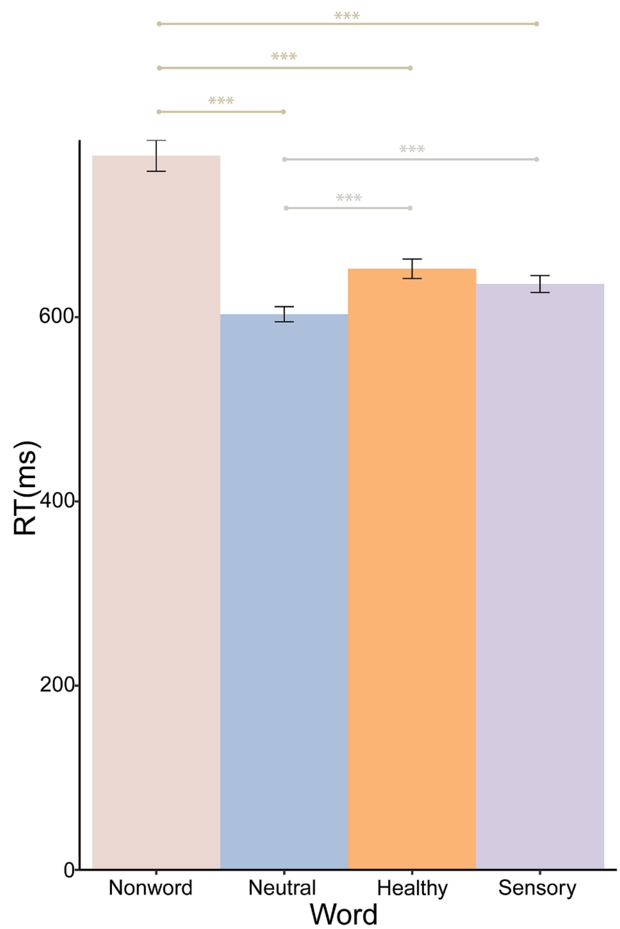

Fig.2. The mean reaction time for the four word categories. Error bars represent the standard error of the reaction time (RT).

Table 2
Reaction times (ms) in the lexical decision task for each odor condition. Values are expressed as means and standard errors.

Word category	Healthy Odor (N = 37)	Unhealthy Odor (N = 36)	Neutral Odor (N = 39)
Healthy	660.0 ± 120.6	640.2 ± 100.5	656.6 ± 116.5
Sensory	646.3 ± 109.3	626.1 ± 85.5	635.2 ± 98.9
Neutral	602.8 ± 88.0	594.5 ± 83.4	611.3 ± 92.3
Nonword	763.1 ± 173.2	772.8 ± 177.2	788.9 ± 190.6

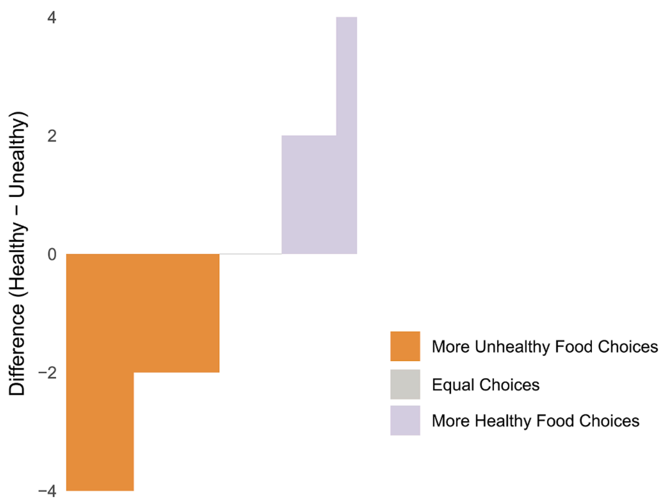

Fig.3. Differential preference for healthy vs. unhealthy food choices.

which would translate to faster reaction times as these concepts would then be more readily available. This contrasts with the findings of Holland et al., who showed that participants who were exposed to citrus odors responded more quickly to cleaning-related words, suggesting an association between odors and concept activation (Holland et al., 2005). A possible explanation is that not all odors are equally effective in activating their corresponding concepts, especially given that odors possess inherent ambiguity. For example, a certain odor in an earlier study could be labeled either as a body odor or as an odor of French cheese (de Araujo et al., 2005). These associations, and thus how odors are perceived, may depend on personal characteristics such as personal memories, past experiences (Arshamian et al., 2013; Stevenson & Boakes, 2003; Wilson & Stevenson, 2003), and cultural influences (Chrea et al., 2004; Ferdenzi et al., 2013; Herz, 2009). It is noteworthy that our study specifically included Dutch-speaking participants to limit the potential influence brought by cultural background. Nonetheless, in our study, the apple odor could evoke different associations, such as raw apples or apple pie. We also took this into account in our experimental design, where subjects exposed to the apple odor were asked to make a choice involving apple and apple pie. Overall, this complexity makes it challenging to associate odors with specific, uniform concepts, a key aspect of conceptual priming. The effect of odors might depend on how prototypical or representative the odors are of a certain category (Smeets & Dijksterhuis, 2014). Indeed, the specificity of the odor seems to play a crucial role. For example, one study demonstrated that the melon odor facilitated faster responses to the word 'melon', with no parallel effect observed for pear odor (Gaillet et al., 2013). Furthermore, our findings might also suggest that odors, albeit food-related, do not prime 'general' food concepts. This aligns with Gaillet et al. (2013), who found no accelerated generalized responses to fruit and vegetable-related words compared to other word categories, but only a faster reaction to the specific word'melon' (Gaillet et al., 2013).

In the lexical decision task, we also found that participants responded fastest to neutral words, followed by food-related words, with the slowest response to non-words. It is widely accepted that word frequency significantly influences response time in word recognition tasks (Connine et al., 1990; Gernsbacher, 1984). Therefore, non-words, which could be considered low-frequency words, elicited the slowest responses in our lexical decision task. This might also explain why we observed that reaction times for food-related words were comparatively slower than for neutral words. Neutral words, more commonly encountered in daily language, are processed quicker due to their higher familiarity (Kuperman & Van Dyke, 2013). Indeed, in the process of word selection from the CELEX lexical database, it was observed that the frequency of neutral words (aggregated word and lemma counts, derived from contemporary and representative text corpora) consistently exceeded a threshold of 1000. In contrast, words related to health and sensory within the same database exhibited frequencies below 1000. Despite these disparities, in our view, the current selection of words represents the best balance in terms of letter count, syllable count, and word frequency.

Contrary to our hypothesis, the current study did not find a healthy-congruent effect of odor exposure on food choice. For example, exposure to apple odor did not significantly increase the likelihood of choosing healthy food products. This finding diverges from previous research, such as Gaillet-Torrent et al. (2014), which indicated that exposure to pear odors inclined participants towards choosing relatively lower-energy-dense food products with fruits or vegetables (Gaillet-Torrent et al., 2014). However, the effects in that study were specific to the odor and meal courses. For example, participants exposed to melon odor showed a preference for low-energy-dense starters containing fruits and vegetables, yet this preference did not extend to main courses or desserts. Similarly, those in the pear odor condition were more inclined to choose fruit-based desserts, but not starters or main courses (Gaillet et al., 2013). These observations suggest a nuanced and complex relationship between olfactory cues and the subsequent selection of (health-congruent) foods.

In contrast to our previous work (Yang et al., 2023), which indicated a tendency among participants to select healthier food options, our current study reveals a preference for unhealthy food choices, regardless of the healthiness of the odor exposure. This discrepancy may be due to whether differential levels of consciousness was involved in the process of food selection. Kahneman proposed that decision-making involves two systems: a fast, automatic, intuitive, and emotion-driven intuition system, and a slower, more deliberate, and logical reasoning system (Kahneman, 2006). Our previous study (Yang et al., 2023), which utilized actual, packaged food items in the food choice task and allowed for more time for decision-making during an eye-tracking task, likely engaged more conscious, deliberative processes. On the contrary, the current study exclusively involved the use of food-related words, rendering it more likely that participants were more prone to rely on intuitive and automatic decision-making. A study on children reported similar results, where both fruity and fatty-sweet odors decreased the likelihood of choosing a fruit compared to the no-odor condition (Marty et al., 2017). A possible explanation is that sweet odors might be more associated with the food pleasure concept, thereby steering choices towards sweet, unhealthy foods typically associated with pleasure.

Moreover, our findings did not indicate that food odor exposure led to an increased preference for odor-congruent food choices. This contrasts with a previous study by Ramaekers et al. (2014) showed a higher selection of banana products compared to a non-odor condition (Ramaekers et al., 2014). Consequently, further study is required to determine whether this phenomenon is exclusive to certain odors.

A potential limitation of the current study design could be that we utilized a between-subject design, involving three odor conditions with each participant exposed to only one. Although a within-subject design might have more effectively controlled for individual differences, we chose a between-subject design to minimize the risk of practice effects and reduce the likelihood of participants deducing the real aim of the study. To mitigate the potential impact of individual variation and enhance the reliability of our findings, we used a sufficiently large participant pool that exceeds the sample sizes typically reported in similar between-subject design studies (Gaillet et al., 2013; Holland et al., 2005), thereby strengthening our study's statistical power. Additionally, we made efforts to match participants by gender, age, and BMI across conditions to further address potential individual differences.

5. Conclusion

In conclusion, our study contributes to the intricate understanding of how olfactory cues interact with cognitive processing, particularly concerning semantic priming. We found that the sweet odors did not affect the selection of healthy-congruent foods or activate food-related concepts. This suggests a limitation in the potential for semantic priming by (sweet) odors. To further elucidate the extent and specifics of how odors are associated with conceptual processing, we recommend future research using a wider variety of odors. Such studies could more comprehensively validate the connections between odors and their corresponding conceptual associations.

Ethical statements

Participants gave informed consent via the statement "I give consent to collect and use my data for answering the research question in this study" where an affirmative reply was required to participate in the study. They were able to ask questions and quit the study at any time without providing any reason. The study was harmless and conducted in accordance with the Declaration of Helsinki and approved by the Social Sciences Ethics Committee of Wageningen University (2022-118-SBSEB-prc).

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to revise writing. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Xinmeng Yang: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sanne Boesveldt:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Elizabeth H. Zandstra:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: EHZ is an employee of Unilever Foods Innovation Centre Wageningen, the Netherlands, a company which markets food products. The authors XY and SB declare no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2024.105351.

Data availability

Data will be made available on request.

References

Aguiar-Bloemer, A. C., & Diez-Garcia, R. W. (2018). Influence of emotions evoked by life events on food choice. *Eating and Weight Disorders - Studies on Anorexia, Bulimia and Obesity, 23*(1), 45–53. https://doi.org/10.1007/s40519-017-0468-8

Arshamian, A., Iannilli, E., Gerber, J. C., Willander, J., Persson, J., Seo, H.-S., Hummel, T., & Larsson, M. (2013). The functional neuroanatomy of odor evoked autobiographical memories cued by odors and words. *Neuropsychologia, 51*(1), 123–131. https://doi.org/10.1016/j.neuropsychologia.2012.10.023

Baayen, Piepenbrock, R, & Gulikers, L. (1995). *CELEX2* (p. 287744 KB). Linguistic Data Consortium. https://doi.org/10.35111/GS6S-GM48.

Boesveldt, S., & de Graaf, K. (2017). The Differential Role of Smell and Taste For Eating Behavior. *Perception, 46*(3–4), 307–319. https://doi.org/10.1177/0301006616685576

Brunner, T. A., & Siegrist, M. (2012). Reduced food intake after exposure to subtle weight-related cues. *Appetite, 58*(3), 1109–1112. https://doi.org/10.1016/j.appet.2012.03.010

Chambaron, S., Chisin, Q., Chabanet, C., Issanchou, S., & Brand, G. (2015). Impact of olfactory and auditory priming on the attraction to foods with high energy density. *Appetite, 95*, 74–80. https://doi.org/10.1016/j.appet.2015.06.012

Chrea, C., Valentin, D., Sulmont-Rossé, C., Ly Mai, H., Hoang Nguyen, D., & Abdi, H. (2004). Culture and odor categorization: Agreement between cultures depends upon the odors. *Food Quality and Preference, 15*(7), 669–679. https://doi.org/10.1016/j.foodqual.2003.10.005

Connine, C. M., Mullennix, J., Shernoff, E., & Yelen, J. (1990). Word familiarity and frequency in visual and auditory word recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16*(6), 1084–1096. https://doi.org/10.1037/0278-7393.16.6.1084

de Araujo, I. E., Rolls, E. T., Velazco, M. I., Margot, C., & Cayeux, I. (2005). Cognitive modulation of olfactory processing. *Neuron, 46*(4), 671–679. https://doi.org/10.1016/j.neuron.2005.04.021

de Lange, M. A., Debets, L. W., Ruitenburg, K., & Holland, R. W. (2012). Making less of a mess: Scent exposure as a tool for behavioral change. *Social Influence, 7*(2), 90–97. https://doi.org/10.1080/15534510.2012.659509

Ferdenzi, C., Roberts, S. C., Schirmer, A., Delplanque, S., Cekic, S., Porcherot, C., Cayeux, I., Sander, D., & Grandjean, D. (2013). Variability of affective responses to odors: Culture, gender, and olfactory knowledge. *Chemical Senses, 38*(2), 175–186. https://doi.org/10.1093/chemse/bjs083

Fishbach, A., Friedman, R. S., & Kruglanski, A. W. (2003). Leading us not into temptation: Momentary allurements elicit overriding goal activation. *Journal of Personality and Social Psychology, 84*(2), 296.

Forwood, S. E., Ahern, A. L., Hollands, G. J., Ng, Y.-L., & Marteau, T. M. (2015). Priming healthy eating. You can't prime all the people all of the time. *Appetite, 89*, 93–102. https://doi.org/10.1016/j.appet.2015.01.018

Gaillet, M., Sulmont-Rossé, C., Issanchou, S., Chabanet, C., & Chambaron, S. (2013). Priming effects of an olfactory food cue on subsequent food-related behaviour. *Food Quality and Preference, 30*(2), 274–281. https://doi.org/10.1016/j.foodqual.2013.06.008

Gaillet-Torrent, M., Sulmont-Rossé, C., Issanchou, S., Chabanet, C., & Chambaron, S. (2014). Impact of a non-attentively perceived odour on subsequent food choices. *Appetite, 76*, 17–22. https://doi.org/10.1016/j.appet.2014.01.009

Gernsbacher, M. A. (1984). Resolving 20 years of inconsistent interactions between lexical familiarity and orthography, concreteness, and polysemy. *Journal of Experimental Psychology: General, 113*(2), 256–281. https://doi.org/10.1037/0096-3445.113.2.256

Herz, R. S. (2009). Aromatherapy facts and fictions: A scientific analysis of olfactory effects on mood, physiology and behavior. *International Journal of Neuroscience, 119*(2), 263–290. https://doi.org/10.1080/00207450802333953

Hoedemaker, R. S., & Gordon, P. C. (2014). It takes time to prime: Semantic priming in the ocular lexical decision task. *Journal of Experimental Psychology: Human Perception and Performance, 40*(6), 2179.

Holland, R. W., Hendriks, M., & Aarts, H. (2005). Smells like clean spirit: Nonconscious effects of scent on cognition and behavior. *Psychological Science, 16*(9), 689–693. https://doi.org/10.1111/j.1467-9280.2005.01597.x

Hummel, T., Sekinger, B., Wolf, S. R., Pauli, E., & Kobal, G. (1997). "Sniffin" sticks': Olfactory performance assessed by the combined testing of odor identification, odor discrimination and olfactory threshold. *Chemical Senses, 22*(1), 39–52. https://doi.org/10.1093/chemse/22.1.39

Jasinska, A. J., Yasuda, M., Burant, C. F., Gregor, N., Khatri, S., Sweet, M., & Falk, E. B. (2012). Impulsivity and inhibitory control deficits are associated with unhealthy eating in young adults. *Appetite, 59*(3), 738–747. https://doi.org/10.1016/j.appet.2012.08.001

Kahneman, D. (2006). A perspective on judgment and choice: Mapping bounded rationality. In *Progress in psychological science around the world. Volume 1 neural, cognitive and developmental issues.* Psychology Press.

Kemmotsu, N., & Murphy, C. (2006). Restrained eaters show altered brain response to food odor. *Physiology & Behavior, 87*(2), 323–329. https://doi.org/10.1016/j.physbeh.2005.10.008

Keuleers, E., & Brysbaert, M. (2010). Wuggy: A multilingual pseudoword generator. *Behavior Research Methods, 42*(3), 627–633. https://doi.org/10.3758/BRM.42.3.627

Kuperman, V., & Van Dyke, J. A. (2013). Reassessing word frequency as a determinant of word recognition for skilled and unskilled readers. *Journal of Experimental Psychology: Human Perception and Performance, 39*(3), 802–823. https://doi.org/10.1037/a0030859

Lima, S. D., & Huntsman, L. A. (1997). Sequential dependencies in the lexical decision task. *Psychological Research Psychologische Forschung, 60*(4), 264–269.

Marty, L., Bentivegna, H., Nicklaus, S., Monnery-Patris, S., & Chambaron, S. (2017). Non-conscious effect of food odors on children's food choices varies by weight status. *Frontiers in Nutrition, 4*. https://www.frontiersin.org/articles/10.3389/fnut.2017.00016.

Morquecho-Campos, P., Hellmich, I. M., Zwart, E., de Graaf, K., & Boesveldt, S. (2022). Does odour priming influence snack choice? – An eye-tracking study to understand food choice processes. *Appetite, 168*, Article 105772. https://doi.org/10.1016/j.appet.2021.105772

Mors, M. R., Polet, I. A., Vingerhoeds, M. H., Perez-Cueto, F. J. A., & de Wijk, R. A. (2018). Can food choice be influenced by priming with food odours? *Food Quality and Preference, 66*, 148–152. https://doi.org/10.1016/j.foodqual.2018.01.019

Muscarella, C., Brintazzoli, G., Gordts, S., Soetens, E., & den Bussche, E. V. (2013). Short- and long-term effects of conscious, minimally conscious and unconscious brand logos. *PLoS One, 8*(5), Article e57738. https://doi.org/10.1371/journal.pone.0057738

Oleszkiewicz, A., Schriever, V. A., Croy, I., Hähner, A., & Hummel, T. (2019). Updated Sniffin' Sticks normative data based on an extended sample of 9139 subjects. *European Archives of Oto-Rhino-Laryngology, 276*(3), 719–728. https://doi.org/10.1007/s00405-018-5248-1

Patel, K. A., & Schlundt, D. G. (2001). Impact of moods and social context on eating behavior. *Appetite, 36*(2), 111–118. https://doi.org/10.1006/appe.2000.0385

Patton, J. H., Stanford, M. S., & Barratt, E. S. (1995). Factor structure of the Barratt impulsiveness scale. *Journal of Clinical Psychology, 51*(6), 768–774. https://doi.org/10.1002/1097-4679(199511)51:6<768::AID-JCLP2270510607>3.0.CO;2-1

Proserpio, C., Invitti, C., Boesveldt, S., Pasqualinotto, L., Laureati, M., Cattaneo, C., & Pagliarini, E. (2019). Ambient odor exposure affects food intake and sensory specific appetite in obese women. *Frontiers in Psychology*, Article 10.

Ramaekers, M. G., Boesveldt, S., Lakemond, C. M. M., van Boekel, M. A. J. S., & Luning, P. A. (2014). Odors: Appetizing or satiating? Development of appetite during odor exposure over time. *International Journal of Obesity, 38*(5), Article 5. https://doi.org/10.1038/ijo.2013.143

Roininen, K., Lähteenmäki, L., & Tuorila, H. (1999). Quantification of consumer attitudes to health and hedonic characteristics of foods. *Appetite, 33*(1), 71–88. https://doi.org/10.1006/appe.1999.0232

Roininen, K., Tuorila, H., Zandstra, E. H., de Graaf, C., Vehkalahti, K., Stubenitsky, K., & Mela, D. J. (2001). Differences in health and taste attitudes and reported behaviour among Finnish, Dutch and British consumers: A cross-national validation of the Health and Taste Attitude Scales (HTAS). *Appetite, 37*(1), 33–45. https://doi.org/10.1006/appe.2001.0414

Smeets, M., & Dijksterhuis, G. (2014). Smelly primes – When olfactory primes do or do not work. *Frontiers in Psychology, 5*. https://www.frontiersin.org/articles/10.3389/fpsyg.2014.00096.

Stevenson, R. J., & Boakes, R. A. (2003). A mnemonic theory of odor perception. *Psychological Review, 110*(2), Article 340.

Stöckli, S., Stämpfli, A. E., Messner, C., & Brunner, T. A. (2016). An (un)healthy poster: When environmental cues affect consumers' food choices at vending machines. *Appetite, 96*, 368–374. https://doi.org/10.1016/j.appet.2015.09.034

Sulmont-Rossé, C., Gaillet, M., Raclot, C., Duclos, M., Servelle, M., & Chambaron, S. (2018). Impact of olfactory priming on food intake in an Alzheimer's disease unit. *Journal of Alzheimer's Disease, 66*(4), 1497–1506. https://doi.org/10.3233/JAD-180465

Tal, A., & Wansink, B. (2015). An apple a day brings more apples your way: Healthy samples prime healthier choices. *Psychology & Marketing, 32*(5), 575–584. https://doi.org/10.1002/mar.20801

Thompson, E. R. (2007). Development and validation of an internationally reliable short-form of the positive and negative affect schedule (PANAS). *Journal of Cross-Cultural Psychology, 38*(2), 227–242. https://doi.org/10.1177/0022022106297301

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

Wagenmakers, E.-J., Ratcliff, R., Gomez, P., & McKoon, G. (2008). A diffusion model account of criterion shifts in the lexical decision task. *Journal of Memory and Language, 58*(1), 140–159. https://doi.org/10.1016/j.jml.2007.04.006

Wilson, D. A., & Stevenson, R. J. (2003). Olfactory perceptual learning: The critical role of memory in odor discrimination. *Neuroscience and Biobehavioral Reviews, 27*(4), 307–328. https://doi.org/10.1016/s0149-7634(03)00050-2

Yang, X., Zandstra, E. H., & Boesveldt, S. (2023). How sweet odors affect healthy food choice: An eye-tracking study. *Food Quality and Preference, 109*, Article 104922. https://doi.org/10.1016/j.foodqual.2023.104922

Zoon, H. F. A., He, W., de Wijk, R. A., de Graaf, C., & Boesveldt, S. (2014). Food preference and intake in response to ambient odours in overweight and normal-weight females. *Physiology & Behavior, 133*, 190–196. https://doi.org/10.1016/j.physbeh.2014.05.026