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How sweet odors affect healthy food choice: An eye-tracking study

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ABSTRACT

How to make healthy food choices the preferred ones is a public health concern worldwide. A promising way could be to utilize the sensory food cues in the environment, such as odors. Previous studies have shown conflicting results on whether odors can impact food choice, and its underlying mechanism remains unclear. The current study aims to investigate the effect of sweet food odors on food choices. A total of 53 participants were recruited to complete two sessions of different sweet odor exposure: healthy (apple, honey melon) or unhealthy (chocolate, caramel). In each session, the participants were asked to choose from eight (in-)congruent food products (an unhealthy and healthy option for each of the odors) after 10 min odor exposure. Visual attention to the food products was measured by Tobii Pro Glasses 2 eye-tracker. Results showed that healthy food products were chosen more frequently regardless of the (healthiness of the) odor exposure. Moreover, participants fixated on all food products for a longer time and more often, and showed a longer time to first fixation on food products during healthy odor exposure compared to unhealthy odor exposure. These findings indicate that healthy odors can prime visual attention and orientation towards both healthy and unhealthy foods. However, this priming does not necessarily lead to congruent food choices, and other cognitive factors likely play a role in the final food decision-making.

1. Introduction

An unhealthy diet is one of the major risk factors for a range of diet-related chronic diseases (Ezzati & Riboli, 2013; Jayedi et al., 2020), including diabetes (Schwingshackl et al., 2017) and cardiovascular diseases (Reddy & Katan, 2004). Healthier food choices will enable people to lower the risk of such diseases and manage and maintain their health. Governments across the globe have published a series of health guidelines to guide people to eat a healthy, balanced diet and to encourage people to make healthy food choice options (Brambila-Macias et al., 2011; Gressier et al., 2020; Pretorius et al., 2021). Given the wide availability and accessibility of high-energy-dense foods, it is important to make it easier for people to choose healthier options (i.e. low in salt, sugar, or fat). One promising way is to take advantage of the so-called priming effect using environmental sensory food cues.

Priming, or the priming effect, occurs when an individual's exposure to a certain stimulus influences his or her response to a subsequent stimulus, without awareness of the connection (Doyen et al., 2012; Wheeler et al., 2014). Extensive research has shown that external cues could prime the selection of (un)healthy foods. For example, Reale & Flint (2016) demonstrated that participants tended to choose healthier meals on menus when they were cued by colorful calorific values rather than plain black text alone (Reale & Flint, 2016). In addition, Prinsen et al. (2013) reported that the presence of physical traces indicating what others have eaten (e.g., empty wrappers of unhealthy snacks) lead participants to choose and consume these snack foods as well (Prinsen et al., 2013). However, most studies investigating the environmental priming effect on food choice employed visual cues, whereas other sensory cues such as odors can be at least as relevant for eating behavior.

Odors can signal information about the nutrient content and flavor of the food (Boesveldt & Lundström, 2014; Ramaekers et al., 2014) even before ingestion, and thus play an anticipatory role in eating behavior (Boesveldt & de Graaf, 2017). Several studies have demonstrated that exposure to food odors can increase the appetite for congruent foods (Morquecho-Campos et al., 2020; Proserpio et al., 2019; Zoon et al., 2016). For example, participants reported an increased appetite for bananas and other sweet foods after exposure to a sweet banana odor (Ramaekers et al., 2014). Paralleling this impact on appetite, similar effects of odor exposure have been reported on food choice (Gaillet et al., 2013; Gaillet-Torrent et al., 2014). For example, when people

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were exposed to a pear odor, they were more likely to choose low-energy-dense, fruity desserts (Gaillet-Torrent et al., 2014). And when people were exposed to chocolate odor, they were more likely to choose congruent high-energy–density desserts without fruits or vegetables (Chambaron et al., 2015). In addition, odor exposure may also exert an effect on food intake. For example, ad libitum consumption of chocolate rice was higher during chocolate odor exposure than no odor exposure (Proserpio et al., 2017). However, this priming effect of odor exposure was not always found. Mors et al. (2018) demonstrated that exposure to bread and cucumber odor did not increase the choice of congruent foods during lunch (Mors et al., 2018), and de Wijk et al. (2018) illustrated that exposure to citrus odor did not affect fruit sales in real-life supermarkets (de Wijk et al., 2018). A possible explanation is that the perception and intensity of the odors may play a crucial role in the priming effect: unconscious odor exposure is expected to evoke more behavioral responses than a conscious one. When odors become easier to recognize along with the increasing concentrations, the subsequent cognitive processing is no longer implicit or automatic and other cognitive processes will be involved that can counter the behavioral effect (Smeets & Dijksterhuis, 2014). Indeed, ambient odors seem to need to be unconsciously perceived to exert any impact on food choice (Boesveldt & de Graaf, 2017; Chambaron et al., 2015; Gaillet et al., 2013; Gaillet-Torrent et al., 2014). Although it is clear that odors may exert influences on various parts of eating behavior, a better understanding of the underlying mechanisms is needed to effectively steer food choices in healthier directions.

Visual attention is an essential element of the decision-making process that enables individuals to acquire information before making a decision (Orquin et al., 2018; Van Loo et al., 2018). Visual attention can be assessed by analyzing eye movements (Hoffman & Subramaniam, 1995) which are physiological responses that cannot easily be controlled with conscious effort (Bates & Istance, 2002). Eye-trackers are used to monitor eye movements and can therefore be regarded as an accurate and reliable method of measuring visual attention (Casado-Aranda et al., 2020; Van Loo et al., 2018). Eye-trackers have been increasingly used to study the underlying cognitive processes of food choice. According to the gaze bias theory, individuals tend to fixate longer on items that are subsequently chosen (Manippa et al., 2019; Schotter et al., 2010). Fixation duration and the number of dwells have also been shown to predict whether products would be purchased in a virtual supermarket (Melendrez-Ruiz et al., 2022) and a real-life supermarket (Gidlöf et al., 2017). Based on previous findings, there has been an increasing interest in investigating the priming effect of sensory cues on visual attention and food choice. Manippa et al. (2019) used body shapes as primes and found that an overweight body shape increased participants' visual attention towards high-calorie food, but did not affect food choice (Manippa et al., 2019). Moreover, Peng-Li and colleagues (2020) used 'sweet' and 'salty' soundtracks as prime and found that these affected participants' eye movements and food choices for taste-congruent food products (Peng-Li et al., 2020). To our knowledge, few studies have investigated the effect of odor priming on visual attention and food choice. Morquecho-Campos et al. (2022) suggested an effect of odor exposure on the first fixation towards congruent snacks, but not on other eye-tracking matrices and food choices. Interestingly, sweet snacks were always fixated on more often, and for a longer time, and were chosen most often, regardless of the odor exposure (Morquecho-Campos et al., 2022). However, they did not investigate whether the healthiness of the odor exposure affects visual attention and induces healthy-congruency food choices. Exploring the potential for the health priming of odors is important to develop a new strategy to steer people's eating behavior towards healthier food choices without awareness, which is beneficial in preventing obesity and the relevant disease.

In view of this seeming visual attention bias for sweet products, the current study investigated the impact of sweet odor exposure on (healthy) food choices. Moreover, to further validate the role of visual attention in the food decision-making process, we also explore the relationship between visual attention metrics and food choice. We hypothesized that odors can prime visual attention and food choice towards healthy congruent foods, e.g., participants are more likely to fix on and choose healthy foods after healthy odor exposure compared to unhealthy odor exposure.

2. Method

2.1. Participants

Participants aged between 18 and 35 years old were recruited within the Wageningen area via social media. Based on a previous study which has a similar study procedure (Morquecho-Campos et al., 2022), we planned to recruit 60 participants. To determine their eligibility, all potential participants were required to complete an online screening questionnaire via EyeQuestion® (Version 3.11.1, Logic8 BV). The screening questionnaire included questions related to general lifestyle, medical information, and a color blindness test. In addition, the participants were asked to fill in the Dutch Eating Behavior Questionnaire (DEBQ, van Strien et al., 1986), Barratt Impulsiveness Scale (BIS-11, Patton et al., 1995), and the Behavioral Activation System scale (BAS, Carver & White, 1994). Exclusion criteria included the following: self-reported history of medical eye procedures; color blindness as assessed by the Ishihara color test; self-reported weight change (greater than5 kg) in the past two months; any food restriction, allergy to the food items used in this study; pregnancy. Participants were also required to have a self-reported normal weight (BMI: 18.5——25 kg/m2), be non-smokers, fluent in English, and have normal vision (with contact lenses).

A total of 63 participants (49 females and 14 males) met the requirements, provided their informed consent and participated in the study. Of those, ten participants were excluded from the final data analysis: one participant only completed one of the two test sessions, four participants had a low gaze quality and six participants did not pass the odor identification test after the two test sessions. Table 1 shows the main characteristics of the remaining 53 participants (42 females and 11 males). The study was conducted in accordance with the Declaration of Helsinki (revised in 2013) and participants received €20,- on study completion.

Dutch Eating Behavior Questionnaire scale: 1–5, higher scores indicating higher frequencies of engaging in behaviors that are associated with overeating (DEBQ, van Strien et al., 1986).

Barratt Impulsiveness scale: 1–4, higher scores indicating higher impulsiveness (BIS-11, Patton et al., 1995)).

Behavioral Activation System scale: 1–4, higher scores indicating a higher willingness to approach reward (BAS, Carver & White, 1994).

2.2. Study design and procedure

We used a within-subjects design to assess the effect of (sweet) food

Table 1
Characteristics of the participants.

	Mean	SD	Range
Age (years)	23.9	3.4	18——31
BMI (kg/m^2)	21.8	1.7	18.9 – 25.1
DEBQ			
Restrained eating	3.2	0.5	2.3 – 4.6
Emotional eating	3.7	0.5	2.2 – 4.7
External eating	2.7	0.4	1.8 – 3.7
BIS-11			
Attentional	2.2	0.5	1.5 – 3.3
Motor	2.0	0.3	1.5 – 3.0
Non-planning	2.2	0.3	1.5 – 3.1
BAS			
Drive	2.2	0.5	1.0 – 3.0
Fun seeking	2.0	0.4	1.0——3.0
Reward Responsiveness	1.5	0.4	1.0 – 2.6

odor exposure on visual attention and food choice. Participants were required to visit the test location twice, once for each odor condition (healthy or unhealthy odor exposure). They were exposed to only one odor per condition in a counterbalanced order. Two sessions of 40 min were scheduled at approximately the same time of day with 5 days in between. 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. In addition, they were instructed to refrain from using any heavy makeup around their eyes which could affect the eye-tracking measurement, and wearing any perfume which could affect odor perception. Two participants who had Covid-19 related symptoms were required to reschedule their appointment.

Fig. 1 shows the procedure of the experiment. Odors were dispersed in both testing rooms via vaporizers (Iscent, Zeewolde, The Netherlands) for 7 min prior to the participants entering the room. Upon arrival, the participants were taken into ROOM 1 where they were exposed to an odor for 10 min (similar to Morquecho-Campos et al., 2022). In this room, the eye-trackers were calibrated for each participant. During the calibration process, the participants were required to look at a calibration card which was held flat against a wall 1 m away from them for a few seconds. Once the calibration was complete, we asked the participants to look at our fingers or pens to verify the calibration results. Then they were instructed to fill out a questionnaire related to their general appetite and emotions (I-PANAS-SF; Thompson, 2007). Next, the participants performed a visual memory task ("Easter Memory" or "Memory game"; see website: https://www.improvememory.org/brain-games/memory-games/) and assessed the difficulty of the task and their stress levels. The memory tasks were set to distract participants from the real aim. Instead, participants were informed of an alternative aim: to investigate the effect of hunger state on memory performance. Subsequently, they were led to enter ROOM 2, which was also equipped with a vaporizer to disperse the same odor in ROOM 1. There, participants stood in front of a mini-refrigerator to (visually) explore a variety of food products, and they were instructed to choose one that they want to eat and consumed as much as they wanted in 5 min. Afterwards, the participant went back to ROOM 1 to (again) assess their general appetite, perform a (different) visual memory task, and assess the difficulty of the task and their stress level. At the end of the second session, participants were asked to guess the real aim of the study and assess the odors' and the food products' attributes. Moreover, an odor identification test was done to assess olfactory function (Hummel et al., 1997). After participants completed both sessions, they were debriefed.

2.3. Odor stimuli

A pilot study was conducted to select (sweet) food odors and determine their concentration: six odors representing healthy (apple, honey melon, banana) and unhealthy (chocolate, caramel, blond almond) were dispersed via vaporizers in the testing rooms. Participants who did not take part in the main study were exposed to one of these odors per category in a counterbalanced order. They were asked if they noticed any odor in the room; and if so, to rate the odors' intensity on a 100-mm visual analogue scale (VAS, from 0 = "Not at all" to 100 = "Very"). To determine the stability of the odors, the participants were required to wait outside of the testing rooms for 10 min, then re-entered the room and were asked to again rate awareness and intensity, as well as familiarity, liking, and healthiness of the odor-associated products on a 100-mm VAS (see supplementary materials Table S1). They were also asked to write down at least one food product associated with the odor. The intensity of the odors was set to be noticeable but unidentifiable by the pilot participants. We aimed to achieve a perceived intensity of 40–60 mm on a visual analogue scale in 10 min. Based on these results, apple (healthy; Symrise 651343; 3.5% in propylene glycol (PG)); honey melon (healthy; Symrise 218299; 13% in PG); Chocolate (unhealthy; Symrise 651007; 18% in PG); Blond almond (unhealthy; Symrise 448023; 9.5% in PG) were selected. Most participants associated the blond almond odor with caramel, thus we refer to it as caramel here.

2.4. Food products

A separate pilot study was conducted to determine healthy and unhealthy snack products matching the odors. Eighteen participants who did not participate in the main study rated familiarity, liking, and healthiness of 4 apple-flavored, 4 honey melon-flavored, 5 chocolate-flavored, and 8 caramel-flavored food products on 100-mm VAS (see supplementary materials Table S2). Based on this, we selected eight food products (one healthy and one unhealthy food product per odor): apple, apple pie, honey melon, watermelon candy, chocolate granola bar, chocolate muffin, caramel granola bar, and caramel tompouce (a typical Dutch pastry). All of them were purchased from the local supermarket (Albert Heijn) and were packaged.

All products had similar sizes and were placed in 4 rows × 2 columns in a mini-refrigerator (88 L; 82.5 (h) × 43 (w) × 48 (d) cm, see Fig. 2). As

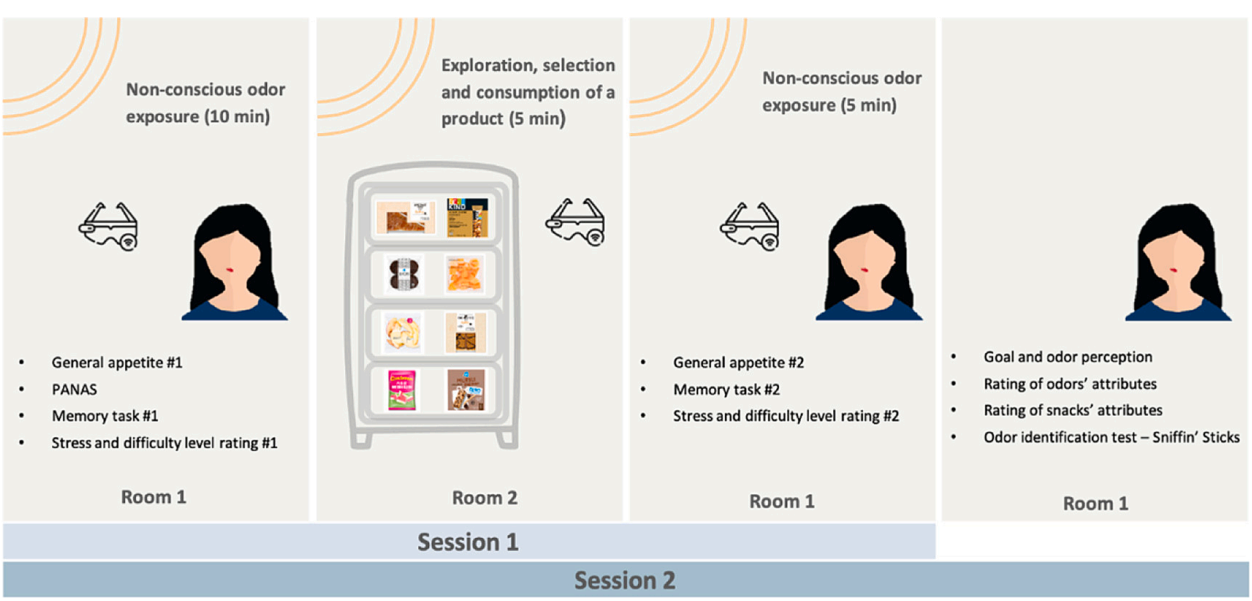

Fig. 1. Procedure for the test sessions. The waves in the figure indicate odor exposure.

Fig. 2. An example of the food products' placement in the mini-refrigerator.

product placement can influence choice and introduce bias (Dayan & Bar-Hillel, 2011), the first and the last product in the fridge differed in perceived healthiness. For example, if the first (top left) was a healthy food product, the last (bottom right) should be an unhealthy food product. Participants were assigned to different product arrangements in a counterbalanced order.

2.5. Measurements

The Dutch Eating Behavior Questionnaire (DEBQ, van Strien et al., 1986) was used to measure eating behaviors. It consists of 33 items, including 13 items for Emotional Eating, 10 items for External Eating, and 10 items for Restraint Eating. Responses were ranged on a 5-Likert scale from 1 = 'Never' to 5 = 'Very often'. Higher scores indicate a greater concern with dieting.

Barratt Impulsiveness Scale (BIS-11, Patton et al., 1995) was used to measure impulsiveness which can be associated with unhealthy eating (Jasinska et al., 2012). It has 30 items with a four-options Likert scale from 1 = 'Never'/'Rarely' to 4 = 'Almost always'/'Always' with 8 items assessing attentional impulsiveness, 11 items assessing motor impulsiveness, and 11 items assessing non-planning impulsiveness.

Behavioral Inhibition & Activation Scales (BIS/BAS, Carver & White, 1994) contains three BAS subscales and one BIS subscale, measuring reward sensitivity which is associated with food preferences (Davis et al., 2007). In this study, only the BAS subscales were used with 17 items with a four-options Likert scale from 1 = 'Very True for me' to 4 = 'Not at all true for me'. It includes 5 items for reward responsiveness, 4 items for fun-seeking, 4 items for the drive, and 4-filler items.

The international Positive and Negative Affect Schedule Short Form (I-PANAS-SF, Thompson, 2007) consists of 10 items assessing positive affect (PA; 5 items) and negative affect (NA; 5 items). All items were rated on a 5-point Likert scale from 1 = Never to 5 = Always. Emotion plays an important role in food intake (Patel & Schlundt, 2001). Negative affect can be an antecedent for disordered eating (Wildes et al., 2012).

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'. The general appetite score was computed by averaging the hungry state, satiated state (reverse-scored), desire for food, and prospective consumption scores.

In order to avoid a possible impact of perceived stress on food choices (Zellner et al., 2006), the difficulty level of the memory tasks and the stress level they felt under these tasks were measured by asking "How difficult was the task you just performed?'' and "How stressed do you feel at this moment?" on 100-mm VAS anchored from 'Not at all' to 'Very'.

After the participants completed the two test sessions, they were asked about their perceived aim of the study and whether they had noticed an odor at any point during the experiment. If the participant guessed the real aim (to investigate the effect of odor exposure on visual attention and food choice), they were excluded from the data analysis.

Participants were then presented with the same odors they had been exposed to from a 50 ml glass amber-brown bottle, and were asked to assess their liking, intensity, familiarity, desire to eat a product with this odor, mouthwatering sensation, healthy and unhealthy associations, sweet and savory associations on a 100-mm VAS anchored by 'Not at all' to 'Very'. Moreover, they had to identify the odor by choosing one food product from 7 options (Chocolate, Green apple, Caramel, Banana, Honey melon, Ice cream, and Odorless) and rate how well the odor matched that product on a 100-mm VAS scale. After the participants assessed the first odor, They waited for 30 s and then received another odor.

Participants were next presented with pictures of the food products in the mini-refrigerator and asked to assess their familiarity, liking, and health associations on a 100-mm VAS scale anchored by 'Not at all' to 'Very'. These attributes are thought to affect an individual's food choices (Chen & Antonelli, 2020).

Odor identification was measured by the identification subtest of the Sniffin' Sticks test (Hummel et al., 1997). Sixteen common odors were presented via pens to the participants who were required to choose one option that they thought would fit best with the odor from 4 options. An identification score ≥ 12 is regarded as normosmic (Oleszkiewicz et al., 2019). However, cultural and regional characteristics affect the result (Demir et al., 2021), Hence, in our international sample participants who obtained 11 points were also included in this study (n = 3) (Morquecho-Campos et al., 2022).

2.6. Statistical analysis

Data analysis was performed in Rstudio (version 4.1.0).

Eye movements were recorded with wearable Tobii Eye Tracker Glasses 2 (Tobii, Stockholm, Sweden). The time of interest (TOI) was determined from the time point before participants were exposed to the mini-refrigerator to the time point where their hand touched the food product that they chose. The areas of interest (AOI) were labeled as "Healthy" and "Unhealthy" according to the healthiness of the food products. Eye movements were initially processed by Tobii Pro Lab software. The data was mapped onto a Snapshot by the real-world mapping tool and filtered by the I-VT fixation filter with the velocity threshold parameter set to 100°/s. Three eye-tracking metrics were used to assess participants' visual attention to the food products: (1) fixation duration: the duration of all fixations inside an AOI; (2) fixation number: the number of fixations inside an AOI; (3) time to first fixation: the amount of time to the first fixation inside an AOI.

Eye-tracking data was analyzed using linear mixed models in lmerTest package. AOIs were defined as "congruent" and "incongruent" according to the healthiness of the products and the type of odors exposed. For example, healthy food products were defined as "congruent" and unhealthy food products were defined as "incongruent" after healthy odor exposure. The dependent variables in the model were the eye-tracking metrics: fixation duration, fixation number, and time to first fixation. The independent variables in the model were odor exposure (Healthy vs. Unhealthy) and congruency of the food product (Congruent vs. Incongruent). Both independent variables were dummy coded (odor exposure: 0 = "unhealthy odor", 1 = "healthy odor"; congruency: 0 = "incongruent", 1 = "congruent"). We conducted the analysis in two steps. In the first step, a model with only odor exposure and congruency of the food product was fitted. In the second step, a final model was obtained by a backward selection starting with covariates: gender, age, BMI, DEBQ subscales, BIS-11 subscales, BAS subscales, PA, NA, general appetite, stress, difficulty level, odor perception, odor attributes, and snack attributes, and removing non-significant covariates from the full model (alpha = 0.05). The model with covariates was important to assess the impact of individuals' characteristics on the eye-tracking metrics. Gender, age, BMI, BIS-fun seeking, food liking, and food healthiness were included in the final model as the covariates. Participants were regarded as a random effect (Example of a model: Fixation duration ~ Odor exposure*Healthy congruency + covariates + (1 | Participant)). A normality test was conducted, but the result showed that average scores were non-normally distributed. Thus, data were transformed to log (x + 1) into normal. The emmeans package in R was carried out to obtain estimated marginal means and detect the differences in visual attention between two odor conditions.

Food choice data were analyzed using generalized linear mixed models (GLMM) performed in the MASS package to investigate the effect of odor exposure on the healthiness of food choice. The dependent variable in the model was the category of the chosen food products (Healthy vs. Unhealthy). The independent variable in the model was odor exposure (Healthy vs. Unhealthy). The independent variable was dummy coded (odor exposure: 0 = "unhealthy odor", 1 = "healthy odor"). Same as the previous LMM, we analyzed two steps: with and without covariates. However, as there are fewer data points for food choice than for the eye-tracking data, we were not able to include all the covariates simultaneously as in the previous LMM. Instead, we conducted a forward selection and selected all the covariates with $p < 0.05$. Gender, age, BMI, BIS- non-planning impulsivity and negative affect were included in the final model. Participants were regarded as a random effect (Healthiness of the chosen food products ~ Odor exposure + covariates + (1 | Participant)). To further examine the difference between the proportion of healthy food and unhealthy food choice, a binomial test was carried out. Moreover, an exploratory analysis using GLMM was performed to determine the effect of odor exposure on flavor congruent food choice. The dependent variable in the model was the flavor congruency of the chosen food products (e.g., a chosen chocolate product after exposure to chocolate odor; Flavor congruency vs. Flavor incongruency). The independent variable in the model was the specific odor used (1 = "Apple", 2 = "Honey-melon", 3 = "Chocolate", 4 = "Caramel"). Similar to the analyses described above, a forward selection was used to include relevant covariates (leaving the odor attribute rating 'savoriness' in the final model).To explore the relationship between visual attention and food choice, binomial logistic regressions were performed. The dependent variable in the model was food choice (dummy coded as 0 = "Unchosen", 1 = "Chosen"). The independent variables in the model were the eye-tracking metrics: fixation duration and fixation number (Example of a model: Food choice ~ Fixation duration).

3. Results

3.1. The effect of odor exposure on food choice

A generalized linear mixed model without covariates showed that odor exposure did not affect the choice of healthy or unhealthy food products ($\chi^2 = 0.49$, $p = 0.49$). A generalized linear mixed model including covariates showed a similar result ($\chi^2 = 0.51$, $p = 0.47$). More specifically, participants chose healthy food products more frequently than unhealthy food products regardless of the healthiness of the odor exposure (probability = 0.69, 95% CI = [0.59, 0.78], $p < 0.001$, Fig. 3). The exploratory analysis showed there was no 'flavor congruency' effect of odor exposure on food choice (without covariates: $\chi^2 = 5.47$, $p = 0.14$; with covariates: $\chi^2 = 4.31$, $p = 0.23$).

3.2. The effect of odor exposure on visual attention

3.2.1. Fixation duration

A log-transformed linear mixed model without covariates showed a significant main effect of odor exposure on fixation duration ($\chi^2 = 14.58$, $p < 0.001$, Fig. 4a). Participants who were exposed to healthy odors fixed on food products for 0.11 s longer time than exposed to unhealthy odors. However, fixation duration on congruent food products was similar to that on incongruent food products ($\chi^2 = 0.24$, $p = 0.62$), and there was no interaction effect on fixation duration between odor exposure and healthy congruency ($\chi^2 = 0.56$, $p = 0.46$). The final model including covariates showed a significant main effect of odor exposure on fixation duration ($\chi^2 = 15.69$, $p < 0.001$) with the same effect of odor exposure.

3.2.2. Fixation number

A log-transformed linear mixed model without covariates showed a significant main effect of odor exposure on fixation number ($\chi^2 = 15.43$, $p < 0.001$, Fig. 4b). Participants who were exposed to healthy odors fixed on food products for 0.15 times more than exposed to unhealthy odors. However, there was no main effect of health congruency ($\chi^2 = 0.04$, $p = 0.83$) nor an interaction effect between odor exposure and

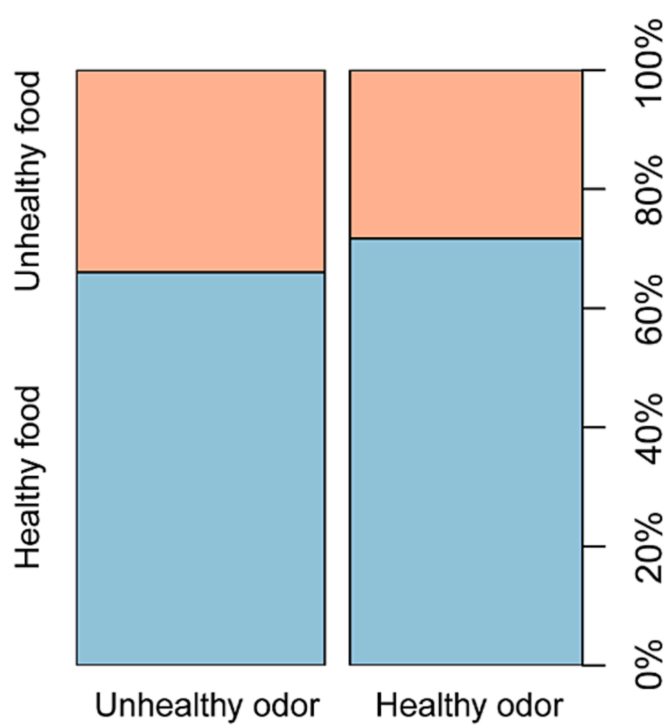

Fig. 3. Proportion of food choices after healthy and unhealthy odor exposure.

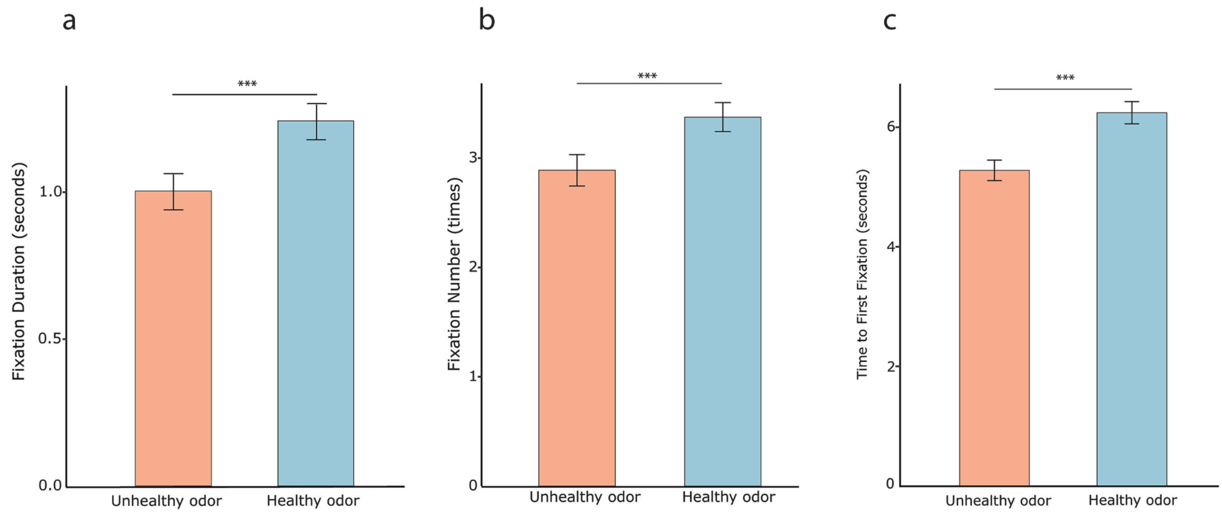

Fig. 4. The back-transformed mean of (a) fixation duration, (b) fixation number, and (c) time to the first fixation for unhealthy odor exposure compared with healthy odor exposure. Error bars represent the standard error of the means.

health congruency ($\chi^2 = 0.26$, $p = 0.61$). The final model including covariates demonstrated a significant main effect of odor exposure on fixation number ($\chi^2 = 16.29$, $p < 0.001$) with the same effect of odor exposure.

3.2.3. *Time to first fixation*

A log-transformed linear mixed model without covariates showed a significant main effect of odor exposure on fixation number ($\chi^2 = 18.87$, $p < 0.001$, Fig. 4c). Participants who were exposed to healthy odors spent 0.08 s longer for the first fixation inside an AOI than exposed to unhealthy odors. However, there was no significant main effect of health congruency ($\chi^2 = 1.92$, $p = 0.17$), nor an interaction effect between odor exposure and health congruency ($\chi^2 = 0.60$, $p = 0.44$). The final model including covariates indicated a significant main effect of odor exposure on time to first fixation ($\chi^2 = 18.87$, $p < 0.001$) with the same effect of odor exposure.

3.3. *The association between visual attention and food choice*

The result indicated that the eye-tracking metrics, both fixation duration and fixation number significantly contributed to predicting the choice for a food product (Table 2). More specifically, participants were more likely to choose a food product that they fixated on for a longer time (OR = 2.63, $p < 0.001$) and for more times (OR = 1.53, $p < 0.001$).

4. Discussion

The aim of this study was to examine how sweet ambient odors affect healthy food choices and visual attention. Overall, we found that healthy food products were chosen more frequently compared with unhealthy food products, regardless of odor exposure. Furthermore, healthy sweet odor exposure led to longer fixation, more fixations, and longer duration of the first fixation on food products, regardless of their healthiness. In addition, we found that visual attention (both fixation duration and frequency) was positively associated with the final food choice.

Table 2
Binomial logistic regressions for food choice.

Relationship	Coefficient	SE	OR	95% CI
A. Food choice: Fixation duration				
Intercept	−3.40***	0.20		
Fixation duration	0.97***	0.10	2.63	[2.19, 3.20]
B. Food choice: Fixation Number				
Intercept	−3.70***	0.23		
Fixation Number	0.43***	0.04	1.53	[1.42, 1.67]

Olfactory stimuli are assumed to be able to 'grab' an individual's attention and affect food choices by activating the mental representations that underpin those decisions (Gaillet et al., 2013; Gaillet-Torrent et al., 2014; Mas et al., 2019). For example, Gaillet et al. (2013) reported that participants reacted to the word 'melon' faster and were more likely to choose healthy starters during a melon odor exposure than in the control condition (Gaillet et al., 2013). However, the current study did not observe any effect of odor exposure on food choice: healthy food products were chosen more frequently compared with unhealthy food products regardless of the perceived healthiness of the odor exposure. In addition, we did not find any specific 'flavor congruency' effect of odors on food choice in the exploratory analysis. It may be explained by that the participants did not perceive the low concentrated odor at all. However, we did find the effect of odor exposure on visual attention. A possible explanation is that the potential effects of ambient odors on food choice are time-dependent. A recent study illustrated that participants exposed to cookie odor for more than 2 min chose less unhealthy products than those exposed to the odor for<30 s (Biswas & Szocs, 2019). In the current study, the participants were exposed to the odor for a timeframe of 10 min, which may have been too long to exert a priming effect on food choice. Other studies (e.g. Gaillet et al., 2013; Ramaekers et al., 2014) found effects of odor exposure on eating behavior measures (appetite, choice) with a duration of up to 20 min, consequently it would be interesting for future research to systematically explore and identify the boundaries of the time frame that will be beneficial for ambient odors to steer consumers towards healthy choices.

In addition, an alternative scenario should be considered, that perhaps our null results are in fact, true results, showcasing a lack of impact of odor priming on (food) choice behavior. MacGiolla et al. recently showed that ninety-four percent of replication studies on social priming had effect sizes smaller than the original effect and that the *meta*-analytic average of the replication effect was virtually zero (Mac Giolla et al., 2022). This suggests that the priming effects of environmental cues, in general, may be suspect, and that there could be publication bias towards positive results. Considerably more work will need to be done (and replicated) to verify if any impact of non-conscious (olfactory) cues on food choices.

Odor exposure affects visual attention toward objects is in line with results that have been reported in previous studies (Peng-Li et al., 2020; Seo et al., 2010). However, contrary to previous studies which have suggested that congruent information increases individuals' visual attention during odor exposure (Seo et al., 2010; Wada et al., 2012), we did not find a health-congruent effect of sweet odor exposure on visual attention in the current study. Our result showed that participants were more likely to fixate on all food products longer and more frequently, and spent more time on their first fixation on a food product after healthy odor exposure compared with unhealthy odor exposure. Fixation duration and fixation number are the most commonly used eye tracking metrics to study cognition and attention (Lai et al., 2013). The number of fixations and their durations reflect how visual information is processed (Motoki et al., 2021). Longer fixation duration is associated with deeper cognitive processing, such as deliberate consideration of information (Glöckner & Herbold, 2011), and suggests complexity, interest, or engagement (Wang et al., 2014). Together, our findings suggest that the participants processed visual food information slower and more deliberately, and were perhaps more consciously aware of their decision-making when in a 'healthy state of mind' due to the healthy odor exposure. Conversely, this may mean that the participants were more impulsive during unhealthy odor exposure. Indeed, individuals tend to be more impulsive when they were facing high energy-dense food cues than low energy-dense food cues (Mas et al., 2020).

Visual attention is able to help individuals process information selectively and then assist to make a choice (Van Loo et al., 2018). However, in the current study, we only found an effect of odor exposure/priming on visual attention and not on food choice. This inconsistency may be due to other cognitive factors that exert an effect on the final choice. Previous studies indicated that individual consumption habits, experience, and motivational state play an important role in food selection or intake (Mors et al., 2018; Pieters & Wedel, 2004). It has been proposed that individuals who have specific health goals are more likely to choose healthy food products (van Herpen & Trijp, 2011) and that nutrition knowledge was strongly associated with the consumption of fruit and vegetables (Wardle et al., 2000). Indeed, we found that participants mainly chose healthy foods, regardless of the healthiness of the odor exposure. Although we did not measure participants' attitudes towards health nor their nutritional knowledge, they were all highly educated and from a food/health-oriented university, which may have resulted in consistent healthy food choices.

It is not surprising that we found visual attention was positively associated with food choice. According to the attentional bias theory, visual bias towards a food product can increase the probability of choosing this product (Peng et al., 2021). We found that the fixation duration and fixation number of the food products were positively related to the final food choice in the current study which is in line with previous eye-tracking studies (Bialkova et al., 2014; Manippa et al., 2019; Smith & Krajbich, 2018). For example, van der Laan et al. (2015) reported that product choices were linked to longer fixation durations (van der Laan et al., 2015), indicating that fixation duration would be a good parameter to reflect food preference and the likelihood of being chosen. Indeed, it has been proposed that individuals are able to process detailed information during fixation contributes to downstream effects on behaviors like learning (memory), preference formation, choice, and buying behavior. (Motoki et al., 2021; Wedel & Pieters, 2008).It is worth mentioning that a strength of the study was that, instead of selecting from food images in most other studies, we used real food products which are familiar to participants in the Netherlands, making our results more applicable to real-life situations. Moreover, unlike previous studies, a wearable eye-tracker was used to measure visual attention. As a limitation, we did not include an odorless control condition in this study, making it impossible to infer any directionality of the effect of odors. For example, we found that visual attention varies according to the odor exposure condition (healthy/unhealthy), but we cannot infer whether healthy odor exposure increases the fixation duration or unhealthy odors decrease the fixation duration. In addition, the gender ratio is not balanced in our study. We try to address this problem by including gender as a covariate in our analysis, and it did not affect the results in either eye-tracking or food choice data.

5. Conclusion

Overall, the current study is one of the first to examine the impact of odors on healthy food choices specifically. It enhances our understanding of the effect of sweet odors on food choices. Our findings show that healthy sweet odors can prime visual attention and orientation towards both healthy and unhealthy foods. However, this priming does not necessarily lead to congruent food choices, and other cognitive factors likely play a role in the final food decision-making. Future research is required in order to establish which concepts of foods (healthy or sensory) can be primed by ambient odors to better understand how and under which circumstances odors can impact food choice behaviors.

CRediT authorship contribution statement

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

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2023.104922.

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