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No evidence for goal priming or sensory specific satiety effects following exposure to ambient food odours

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ABSTRACT

Sensory-specific satiety describes a decline in hedonic value of the taste of a food as it is consumed, relative to a non-consumed food – the pudding tummy phenomenon. Incentive motivation towards consumed foods has also been shown to decline. Interestingly, several studies report that brief exposure to food odours can also produce a sensory-specific satiety effect, in the absence of consumption, selectively reducing hedonic ratings and subsequent high calorie food choices. Yet, other studies report goal-priming effects of ambient odours, in which brief implicit exposure increases the hedonic value of odour congruent food options. The present study aimed to determine whether exposure to ambient food odours would enhance or reduce incentive motivation for associated foods. Participants completed either an ambient odour ($N = 38$) or food consumption ($N = 40$) task. In both, participants were randomly assigned to an indulgent *(chocolate)* or non-indulgent *(orange)* food group and completed two blocks of a cross-modality matching grip-force task. One block was completed immediately before, the other immediately after, odour exposure/food consumption. A grip-force transducer measured effort exerted "to win" briefly presented (33 or 200ms) visual images of these foods, relative to control stimuli. In both studies, participants exerted greater effort to win the food items than control images. While neither satiety nor priming effects were found following ambient odour exposure, a classic sensory-specific satiety effect was found in the food consumption study. That is, force exerted for chocolate images declined significantly following chocolate consumption, in the absence of any decline in motivation for orange stimuli. While differences in odour exposure findings could be explained by factors such as concentration, timing, and nature of exposure, questions remain about the robustness of previously reported odour induced satiety and priming effects.

1. Introduction

Sensory-specific satiety refers to the reduced pleasantness of a food as it is eaten, relative to other uneaten foods which possess different sensory qualities (Andersen, Byrne, & Wang, 2023; Abeywickrema, Oey, & Peng, 2022; Rolls, Rolls, Rowe, & Sweeney, 1981). This phenomenon is thought to promote both the termination of an eating episode and the tendency to resume eating when different foods become available (Abeywickrema et al., 2022). For example, rats display reduced hedonic taste reactivity to foods after being pre-fed congruent diets (Myers, 2017; Reichelt, Morris, & Westbrook, 2014; Berridge, 1991), while humans consistently report reduced hedonic pleasure from, and demonstrate reduced selection of, consumed relative to unconsumed foods (Rolls et al., 1981; Hetherington & Rolls, 1996; Rolls & Rolls, 1997; Hendriks et al, 2019).

The term olfactory-specific satiety (OSS) was coined to describe the observation that the perceived pleasantness of the odour of foods eaten to satiety declines relative to the odours of other non-consumed foods (Rolls, Murzi, Yaxley, Thorpe, & Simpson, 1986). This reduction in hedonic ratings has been replicated with both ortho and retronasal exposure to food odour (Abeywickrema et al., 2022; Fernandez et al., 2013; Stafford, 2016). Neurally, OSS is reflected as reduced odour evoked responses in the orbitofrontal cortex, which in motivational terms is encoding the current value of the associated food (Gottfried, O'Doherty, & Dolan, 2003). Intriguingly, Rolls and Rolls (1997) also observed partial OSS following 5 min of chewing but not ingesting a food. Subsequently Fernandez, Bensafi, Rouby, and Giboreau (2013) have reported that retronasal exposure to a food associated odour while eating

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reduced the perceived pleasantness of the flavour of other foods containing that aroma when encountered later in the meal. Such findings have sparked interest in the potential of food odour exposure to modify food selection and consumption, and several studies have reported that non-conscious exposure to ambient odours associated with high calorie, indulgent foods can induce OSS effects, driving people to make more low calorie, healthy food choices (Biswas & Szocs, 2019; Chae et al., 2023). However, such reports stand in direct contrast to findings from a wide range of studies where exposure to ambient odours induce goal-priming effects, with brief implicit exposure leading to an increase in selection of odour congruent food options (Gaillet et al., 2013; Gaillet-Torrent et al., 2014; Proserpio et al., 2019; Smeets & Dijksterhuis, 2014).

Such mixed findings on the motivational effects of food odours may be explained by methodological variations in the nature and duration of odour exposure. For example, explicit retronasal exposure for 5 min has been shown to induce satiety effects (Rolls & Rolls, 1997), while explicit orthonasal exposure for 10 and 20 min resulted in increased appetite for odour congruent foods (Jansen et al., 2003; Ramaekers et al., 2013). Consistently, non-conscious exposure to ambient odours for 10 to 20 min has been reported to prime congruent food choice (Gaillet et al., 2013; Gaillet-Torrent et al., 2014; Proserpio et al., 2019), and enhance both appetite ratings (Ramaekers, 2013) and food cue reactivity (Mas et al., 2020). While, in contrast, Biswas and Szocs (2019) reported priming effects after only 30 s of implicit exposure to an ambient food odour, with exposure of 2 min or more reducing selection of odour congruent foods. Meanwhile, Morquecho-Campos et al. (2021) did not find any effect on appetite, preference, or intake after implicit exposure of 3 min. Taken together, reports that extended exposure to ambient food odours primes non congruent food choices (Biswas & Szocs, 2019; Chae et al., 2023) stand in contrast to the majority of the extant literature.

The incentive salience theory of motivation distinguishes neurally and psychologically between the motivational drive to obtain a reward (wanting) and the hedonic pleasure derived from its consumption (liking) (Robinson & Berridge, 2003). Operationally, liking is measured as an explicit affective response to reward during, or immediately after, consumption while wanting is a measured as motivation to obtain a future reward and can be either implicit or explicit (Berridge, Venier, & Robinson, 1989; Pool et al., 2016). Results from both animal and human studies demonstrate that sensory specific satiety effects are apparent, not just in affective measures of food liking (Berridge, 1991; Rolls et al., 1981) but also in motivational assessments of food wanting, manifested as a selective decrease in drive to obtain a consumed food (Balleine & Dickinson, 1998; Havermans, Janssen, Giesen, Roefs, & Jansen, 2009; Saelens & Epstein, 1996; Ziauddeen et al., 2014). In animals, wanting is typically measured in instrumental behavioural tasks such as progressive ratio-schedules, where motivation is assessed as the amount of effort expended to obtain food (Zepeda-Ruiz, 2022; Velázquez-Sánchez et al., 2015; Kendig et al., 2013). In equivalent tasks, human participants are asked to perform actions such as pressing a response key (Rogers & Hardman, 2015; Temple, 2016) or squeezing a grip-force dynamometer (Ziauddeen et al., 2014). Here, the goal is to assess the value of the food at the moment of the response. For example, Ziauddeen et al. (2014) found that participants exerted less effort to win a visually cued food after they had consumed it to satiety, while there was no change in effort exerted to obtain a food that hadn't been consumed. This sensory-specific decrease in incentive motivation was apparent whether the food images were presented at a conscious or non-conscious level, suggesting that modulations of effort for the consumed food occurred outside conscious awareness.

According to incentive salience theory, at any given time, motivational drive (wanting) is determined by a combination of both internal and external factors, specifically an organism's internal physiological state (e.g. how hungry they are) and the presence of external stimuli encountered in the environment that are associated with reward (e.g. sight or smell of food) (Berridge et al., 1989; Pool et al., 2016). Thus, it would be predicted that encountering a food odour when hungry would result in a greater drive to obtain an associated food item than when the same odour was encountered when satiated. To our knowledge, behavioural measures of wanting have not so far been used to test the effects of ambient odour exposure on incentive motivation for associated foods. Thus, to further explore the psychological mechanisms underlying previously reported priming and satiety effects, the current study used grip force (Ziauddeen et al. 2012, 2014) to investigate the effect of implicit, ambient odour exposure on appetitive motivation. In addition, to confirm the sensitivity of this task to changes in motivation, a classic sensory specific satiety consumption study was conducted using an identical procedure and the same foods.

In-line with incentive models of motivation, consistent with previous reports of implicit odour priming (Gaillet-Torrent et al., 2014; Proserpio et al., 2019), and in contrast to the OSS effects reported by Biswas and Szocs (2019), it is hypothesised that a non-conscious, 5-min exposure to an ambient food odour will result in a priming effect, with participants displaying selective enhancement of motivation for congruent food images following odour exposure. In contrast, it is hypothesised, consistent with previous studies (e.g Ziauddeen et al., 2014), food consumption will result in a satiety effect, with participants showing a selective decrease in exerted effort for consumed but not unconsumed foods. In addition, participants will be asked to make an unobserved explicit food selection at the end of the study. It is hypothesised that, while odour exposure will increase selection of the primed over the non-primed food, food consumption will increase selection of the non-consumed food.

2. Materials and methods

2.1. Participants

Odour Exposure study: 38 participants, aged 18–60 years old (24 female*)* were quasi-randomly assigned to either Orange (N = 18, Mean age = 32.95, SD = 12.79) or Chocolate (N = 20, Mean age = 30.90, SD = 12.89) odour exposure groups. Age was not reported by one participant in the Orange group.

Food Consumption study: 40 participants, aged 18–60 years old (24 female), were quasi-randomly assigned to either Orange (N = 19, Mean age = 24.89, SD = 6.64) or Chocolate (N = 21, Mean age = 24.33, SD = 7.55) food consumption groups.

In both studies, participants were assigned to groups alternately.

Participants were recruited from the staff and student population at Liverpool John Moores University and from the wider public using the university's Psychology Research Participant Panel. Participants were excluded from taking part if they had any respiratory problems, food intolerances or allergies. The experimental protocol was approved by the Ethics Committee at Liverpool John Moores University (19/NSP/062). Participants received a £10 shopping voucher to thank them for their time. Participants were recruited for the odour exposure study between October 2019 and January 2021, with testing periods intermittently interrupted due to COVID-19 restrictions. Participants for the Food Consumption study were recruited between June 2021 and May 2022.

2.2. Materials

2.2.1. Odour stimuli

In line with a previous laboratory-based study reporting satiety effects of ambient food odour exposure (Biswas & Szocs, 2019), one indulgent (high-calorie) and one non-indulgent (low-calorie) food associated odour was selected for the study. The final selection of Double Chocolate and Seville Orange aroma oils (*AromaPrime.com)* was based on pilot testing (n = 13) which confirmed, during explicit exposure (odour presented on filter papers in glass jars), that both odours were identifiable and did not differ significantly in terms of ratings of perceived pleasantness, intensity, familiarity, or edibility.

2.2.2. Odour pilot

Diffusion times were based on pilot testing, which determined that both odours were recognisable when attention was directed towards them, but the intensity was not so strong as to capture attention upon entering the room. N = 19 faculty members at LJMU (11 Male) were asked (one-by-one) to enter each of the four rooms in any order they wished. One room contained the Seville Orange Odour, one room contained the Double Chocolate Odour, and two rooms were used as controls and contained no odour. Participants were asked whether they were able to identify the odour and to rate the intensity on 12 cm Visual analogue Scales (VAS).

For detection and concentration of the Seville Orange Odour, 100% of participants were able to detect an odour in the room, with 52.6% correctly identifying the odour as being either Orange or Citrus, with a mean intensity of 7.97 (SD = 2.59). For the Double Chocolate Odour, 84.2% (n = 16) of participants were able to detect an odour in the room, with 62.5% being able to correctly identify the odour as being either 'Chocolate' or 'Cocoa', with a mean intensity of 7.38 (SD = 3.53).

2.2.3. Odour dispenser

During the main testing sessions, 20 min prior to the participant entering the odour exposure room, 200 μl (4 drops from a Pasteur pipette) of the aroma oil were pipetted onto individual quarters of filter paper (GE Healthcare Whatman TM 55 mm diameter, Fisher Scientific), placed into the top of a mini scent diffuser (AromaPrime.com) and dispersed for 60 s. The diffuser was then removed from the room.

2.2.4. Visual images

Task Images were sourced from non-copyright online sources and prepared using Adobe Photoshop. They were formatted to 500 x 500 pixels and had the same luminance and opacity, with all edges being blurred to reduce any sharp contrast between the stimuli image and the masked background. In line with the task design used in Ziauddeen et al. (2012) study, in order to minimise direct motor specification effects different images were used for the long (200 ms) and short (33 ms) presentation trials (see Fig. 1A). All test images were randomly scrambled using MATLAB. A random combination of pixels from each image were then merged using MATLAB, in order to create ten composite mask images (see Fig. 1B). These were then randomly selected across all trials for both the pre and post-stimuli mask.

2.3. Measures

2.3.1. Food Preference Questionnaire

Prior to attending the laboratory, participants completed a Food Preference questionnaire presented online via Qualtrics survey software (Qualtrics.com). This asked whether they followed a particular diet (e.g. vegetarian/vegan), their snack preferences (e.g. for sweet or savoury foods), general eating habits and any food intolerances/allergies. Information gathered from this questionnaire was used to ensure participants were eligible to take part in the study and able to consume the foods being presented. These data were not used in any subsequent analysis.

2.3.2. Grip-force task

Experiment generator software E-prime 3.0 (v3.0.3.80) was used to create the task (modified from Ziauddeen et al., 2012). All images were presented on a 19-inch monitor (resolution: 1280 × 1024; refresh rate: 60Hz). The monitor was set up to be approximately 50 cm from the participants and at eye level. A pre-calibrated strain gauge-based isometric dynamometer with a linear response in the 0 to 800 N (N) range (MLT004/ST Grip Force Transducer, ADInstruments, Dunedin, New Zealand) and accuracy of ±5% of reading was used to measure hand-grip force at a sampling rate of 1000 Hz.

Prior to starting the task, all participants provided a measure of their maximum grip-force by applying as much effort as possible onto the transducer three times. The Maximum of these three trials was then taken as the participant's Maximal Volitional Contraction (MVC) (Ziauddeen et al., 2014). Whilst the response screen was only visible for 1000ms during each trial, to ensure the full responses were captured, exerted effort was measured for a total of 4500ms, which was then binned into 100ms intervals. Thus, providing a total of 45 data-points per trial.

The trial design is shown in Fig. 2. Each trial consisted of a fixation cross which was presented for 200ms, followed by a mask screen presented for 200ms, a stimuli screen depicting either chocolate cake (indulgent), an orange (non-indulgent) or a teapot (control stimuli), was presented for either 33ms (short-presentation) or 200ms (long-presentation). A second mask screen was then presented for either 300ms (short-presentation) or 100ms (long-presentation), followed by a response screen, which cued participants to respond with the grip-force transducer. Lastly, a fluid level screen was presented for 3000ms, the purpose of this was to provide visual feedback that a response has been recorded, however, participants were made aware that the visual guides were not always accurate and should only be taken as an estimate of the exerted force. This fluid level was in-fact set at three randomised levels and was not directly associated with the participant's exerted effort. The purpose of the different timings of the second mask screen was to ensure the total trial time was consistent across long and short presentation trials (4700ms).

Participants first completed 6 practice trials, followed by two identical test blocks. Each block comprised 13 long-presentation and 13

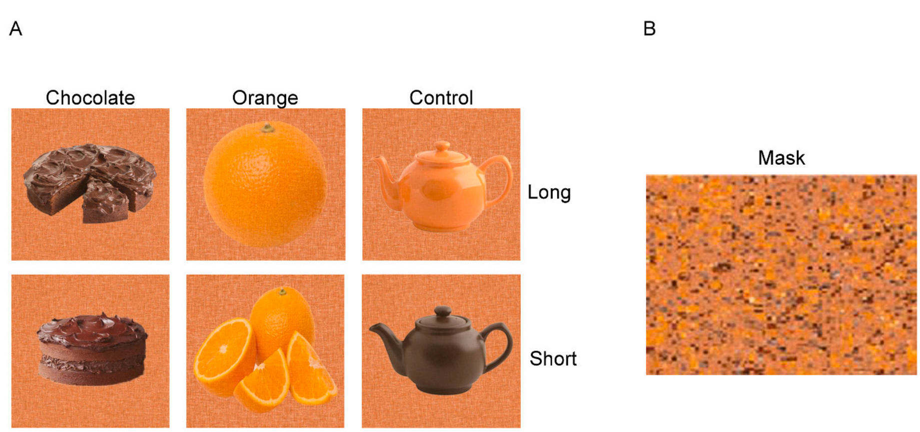

Fig. 1. (A) Visual Stimuli used in the Grip-Force Task; two images were used for each category (Chocolate, Orange, Control). The top three images were presented for the Long-duration trials (200msec) and bottom three images were used for the Short-duration trials (33 msec). (B) An examplar of one of the mask images used.

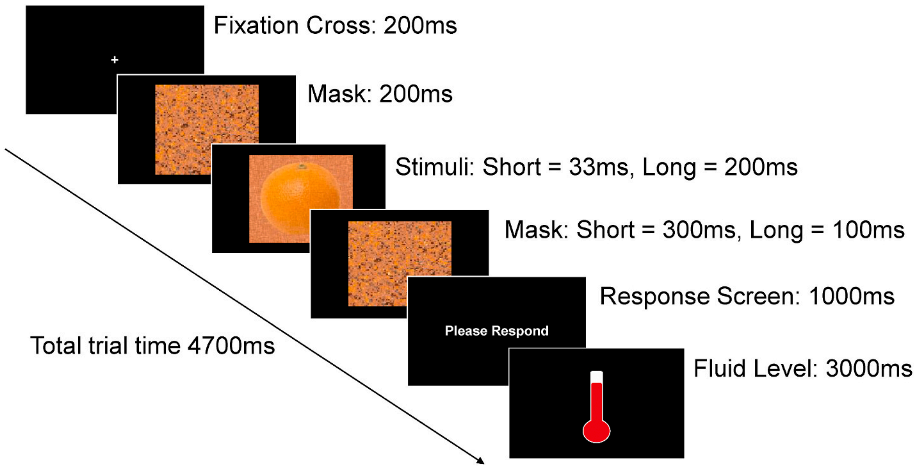

Fig. 2. Task Diagram showing order and duration of screens presented during each short-presentation (SP) and long-presentation (LP) trial. On each trial participants were presented with a fixation cross, followed by a mask, a stimulus was then displayed for either 33 or 200 msec, followed by a second mask, a response screen then cued the participant to respond on the grip-force transducer. Finally, a fluid level screen provided visual feedback to the participant that a response had been recorded.

short-presentation trials per stimulus (78 trials per block). Within each block, stimuli were presented in a randomised order for each participant. The images used during the practice trials were the same as those used during the main task. Participants were instructed *"In order to win the food items, you need to squeeze the handgrip in line with how much you want each item – so, the more you want the reward shown, the harder you squeeze"*.

2.3.3. *Odour exposure*

In the odour study, between blocks one and two of the grip force task, participants were taken to the test room where the odour had been diffused. Participants were not told about the odour. They spent 5 min there completing a reading comprehension task (taken from Ngllife.com) which consisted of a ~500-word piece of text and 8 multiple-choice questions related to the text. The piece was chosen as it was affectively neutral and contained no food related content. Data from this task was not intended for analysis and was merely used as a distractor during odour exposure.

2.3.4. *Food consumption*

In the Food study, between blocks one and two of the grip force task, participants were taken to a room where fixed portions of either ten fresh satsumas (ASDA Grower's Selection) or ten chocolate cake slices (Mr Kipling Chocolate Slice) were available. Participants were instructed "P*lease consume as much food as you wish during this 5-min period. Please do not leave the room until instructed to do so by the researcher*". Participants were unaware that portion size was recorded before and after consumption. The researcher recorded food intake by counting the number of missing items from the plate. In cases where a participant was part way through consuming an item of food when the researcher returned, they were allowed to finish it before returning to the grip-force testing room.

2.3.5. *Forced Choice Discrimination Task*

This task measured participant awareness of the images used in the Grip-Force task and comprised 30, 33ms masked presentations in a randomised order. The images used in this task were the same six images used in the main task, the presentation timings were the same as those used for the short-presentation trials in the main task. During each trial, participants were presented with a mask screen, followed by a stimulus screen and then a second mask screen. They were then shown a response screen which consisted of two images; the image just presented for that trial and a second randomly selected image. Using keys Z and M on the keyboard, they were required to indicate which of the two images was the one just presented. Position (left or right) of the correct image on this screen was counterbalanced across trials.

2.3.6. *Food choice*

At the end of the experiment, participants were asked to select a food item: either a fresh orange (ASDA Grower's Selection Satsumas) or a chocolate cake slice (Mr Kipling Chocolate Slice - Individually wrapped), which they were able to take away with them. Since prior research has found that participants are more likely to change their eating behaviour if they believe their food intake is being monitored, (Robinson et al., 2014), the food selection was completed in another room, out of sight of the experimenter. Participants were directed to the food choice room upon completion of the other tasks. Two dishes, one containing oranges and the other chocolate slices were available. All food selections were recorded after the participant had left the laboratory.

2.4. *Procedure*

Prospective participants for both studies were informed they were investigating motivation for food related images and food choices. Once a participant agreed to take part in the study, an e-mail containing a link to the Food Preference Questionnaire was forwarded for completion prior to attending the laboratory. On the scheduled test day, participants were asked not to eat or drink anything, apart from water, for at least 3hrs prior to arriving, and to refrain from smoking for 1hr prior to testing. Upon entering the laboratory, participants were asked to place their personal belongings, including their mobile phone, to one side They were then provided with a paper version of the information sheet and instructed to read it carefully prior to being verbally briefed and offered the opportunity to ask any questions. Once the participant was happy with the instructions, they were asked to sign a consent form. Participants then provided a measure of their MVC using the grip-force transducer, before completing the practice trials on the task. Once the participant was happy, they continued to complete block-one of the grip-force task.

Following completion of the first block, participants in the odour study were told that they were required to take a 5-min break in another room where they completed the reading comprehension task. The room had previously been diffused with either the Chocolate or Orange odour without the participant's knowledge, with separate rooms being used for each odour. For those in the Food study, participants spent 5-min in another room where they consumed either oranges or chocolate cake.

On returning to the test room, all participants completed block-two of the grip-force task followed by the Forced Choice Discrimination Task. Upon completion of the experimental tasks, participants in the odour study were asked if they had noticed anything unusual about the room during the task blocks, providing them an opportunity to report any perception of the odour. Additionally, in both the odour and food studies, participants were asked if they understood the aims of the study prior to the food choice task, however, no further information was provided at this point. Participants were then informed that they could collect a food item from the next room if they wished. Following this, participants were presented with a debrief sheet and were fully debriefed on the true aims of the study and the reasons for not disclosing the odour exposure beforehand.

2.5. Data analysis

A power analysis was conducted using G-Power (Faul, Erdfelder, Lang, & Buchner, 2007). Using the ANOVA: Repeated Measures, within-between interaction option with two groups and two measurements, a sample of 38 was required to detect a small-medium effect size (f = .25) with 85% power and an alpha level of .05.

Prior to analysis, data from 3 participants was removed. One participant in the odour study wore a face mask throughout testing. One participant in the satiety study did not eat any food between grip force blocks, (whilst all other participant consumed between 1 and 4 food items. 1–2 by the Orange food group and 2–4 by the Chocolate food group), and another acknowledged during debrief that they exerted more force for the teapots than the foods during both blocks, as they wanted a cup of tea (this was confirmed by inspection of their data). Thus, in the odour study 37 participants were included in the analysis, 18 in the orange and 19 in the chocolate group. In the food consumption study 38 participants were included in the analysis, 18 in the orange and 20 in the chocolate group. It was found that there was a significant difference in age between those in the Odour Exposure study and those in the Food Consumption study $t(73) = 20.38$, $p < .05$, $\eta p2 = -.65$, however, while previous research has shown that sensory perception, including olfactory and gustatory responses, can decline with age, these effects are typically more pronounced in elderly populations (Doty, Shaman, Kimmelman, & Dann, 1984), and here participants in both studies were primarily young adults. Since our participant groups are all within a range where sensory functions are generally stable, it is unlikely that the differences in mean age would lead to significant variations in how participants responded to the odour or food stimuli.

Grip-Force data were exported from LabChart to Microsoft Excel. Data from the Forced Choice Discrimination Task were exported using E-DataAid. All data was transferred to SPSS (IBM Corp. Released 2013. IBM SPSS Statistics for Mac, Version 23.0) for analyses. Upon checking each participant's data, it was clear that a number of participants did not exert any effort on some trials. However, due to the instructions given to the participant, this was expected, and no data were removed as a result. Following this, it was evident that, on some trials, where a participant had either not exerted any grip or failed to respond during the measurement period, the transducer recorded negative values, possibly due to the absence of force or a decrease in force from a previous state. Such negative values, resulting from non-responses, can distort the dataset. Therefore, a constant of 10 N was added to all data points, which meant any previously negative values became positive. The same transformation was applied to the Maximal Volitional Contraction (MVC) values.

To calculate each participant's MVC, the maximum force recorded during each 4500ms sampling period was extracted, and the maximum of these values over the three trials taken as their MVC.

For both studies, a mixed ANOVA with pairwise comparisons was conducted, with Block (One, Two), Image (Control, Chocolate, Orange) and Duration (Long, Short) as within subject factors and Group (Chocolate, Orange) as a between participant factors. Following the methods of Ziauddeen et al., (2011), all grip-force scores were then normalised based on each participant's MVC. The force exerted during the response period was measured as a percentage of the difference between the baseline and the MVC: (trial value/MVC value)*100.

Secondly, in both studies, to compare effort exerted for food stimuli, before and after odour exposure/food consumption, the second stage of the analysis focused on exerted effort for the food items only. Thus, again following the methods of Ziauddeen et al. (2011), the normalised scores obtained in the first analysis were standardised by subtracting category specific control trial responses from category specific food trial responses *(*e.g.'Block1_Control_Short, was subtracted from Block1_-Chocolate_Short*)*. A mixed ANOVA was then conducted with Block (One, Two), Image (Chocolate, Orange) and Duration (Long, Short) as within participant factors and Group (Chocolate, Orange) as a between participant factor.

The Forced Discrimination data was analysed using a Chi-Square test, between Image Condition and Response Accuracy.

To compare the proportions of 'Orange' food choices versus 'Chocolate' food choices, data were analysed using binomial logistic regression on the proportion of participants in each group selecting an orange.

All data fulfilled the assumptions for parametric analysis and there was homogeneity of variances for all conditions, as assessed by Levene's test. In cases where data did not meet the assumptions of sphericity, greenhouse geisser correction was applied.

3. Results

3.1. Exerted effort: main effect of image type

Initial analyses were conducted to determine whether exerted effort varied based on the presumed motivational value of the depicted food items. Specifically, we assessed how motivation influenced effort for food images, irrespective of the block (pre- or post-intervention) and presentation duration.

In the Odour study, a repeated measures ANOVA revealed a significant main effect of Image on exerted effort ($F(2, 74) = 12.26$, $p < .001$, $\eta_p^2 = .25$). As shown in Fig. 3A, participants applied significantly less force on Control trials compared to either Chocolate ($p < .001$) or Orange trials ($p < .01$). Effort did not significantly differ between Orange and Chocolate trials ($p = .06$).

Similarly, in the Food study, there was also a significant main effect of Image ($F(2, 72) = 13.72$, $p < .001$, $\eta_p^2 = .28$). As shown in Fig. 3B, participants applied significantly less force on Control trials compared to either Chocolate ($p < .001$) or Orange trials ($p < .001$). Effort did not differ significantly between Orange and Chocolate trials ($p = .41$).

Thus, in both studies, participants exerted significantly more effort to "*win*" the food items than the control stimuli.

3.2. Exerted effort –main effects of block and duration

In the Odour study, there were significant main effects of Block ($F(1, 36) = 4.39$, $p < .05$, $\eta_p^2 = .11$) and Duration ($F(1, 36) = 13.58$, $p < .001$, $\eta_p^2 = .27$) reflecting the fact participants exerted greater force in block-one compared to block-two, and for long compared to short duration images. There was no interaction between Block and Image ($F(2, 74) = .39$, $p = .68$, $\eta_p^2 = .01$), however, there was a significant interaction between Image and Duration ($F(2, 72) = 6.17$, $p = .004$, $\eta_p^2 = .14$), which reflects the fact duration only had an effect on force exerted for Chocolate ($p < .01$) and Orange Images ($p < .01$), effort for Control Images did not differ across long and short duration trials ($p = .73$). See Fig. 4A.

For the Food study, there was again, a significant main effect of Block ($F(1, 36) = 17.37$, $p < .001$, $\eta_p^2 = .33$) and Duration ($F(1, 36) = 5.97$, $p < .05$, $\eta_p^2 = .14$) reflecting the fact participants exerted greater force in block-one compared to block-two, and for long compared to short duration images. In addition, there was a significant Block × Image interaction ($F(2,72) = 3.83$, $p = .03$, $\eta_p^2 = .10$), reflecting a significant

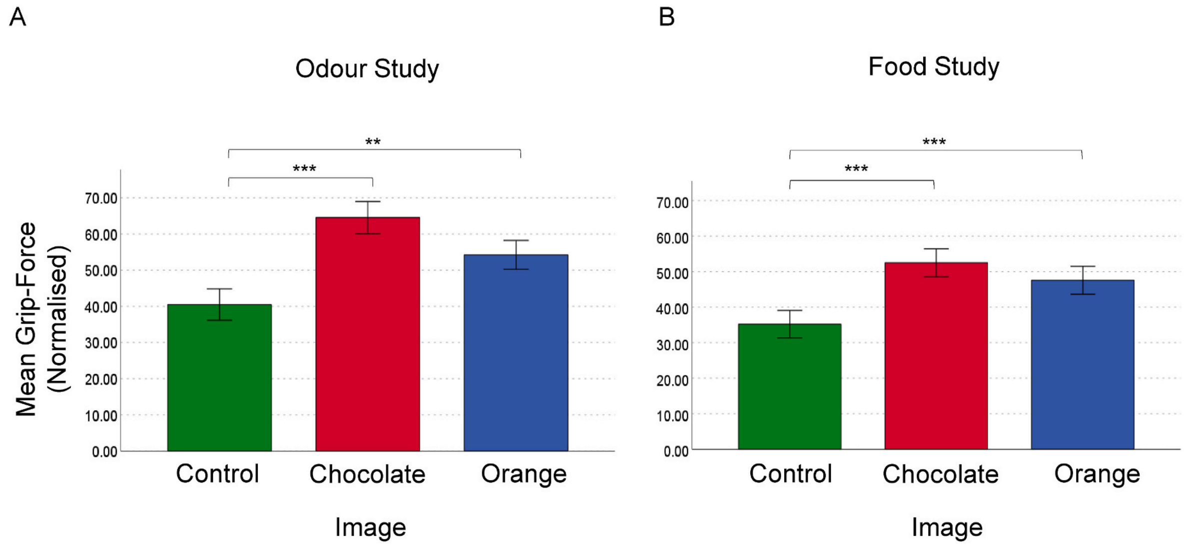

Fig. 3. Mean Grip-Force applied for each image type during the Odour Study (A) and the Food Study (B). Exerted effort was significantly greater for food images compared to control images in both studies. *** denotes sig level <.001, ** denotes sig level <.01. Error bars indicate 95% CI.

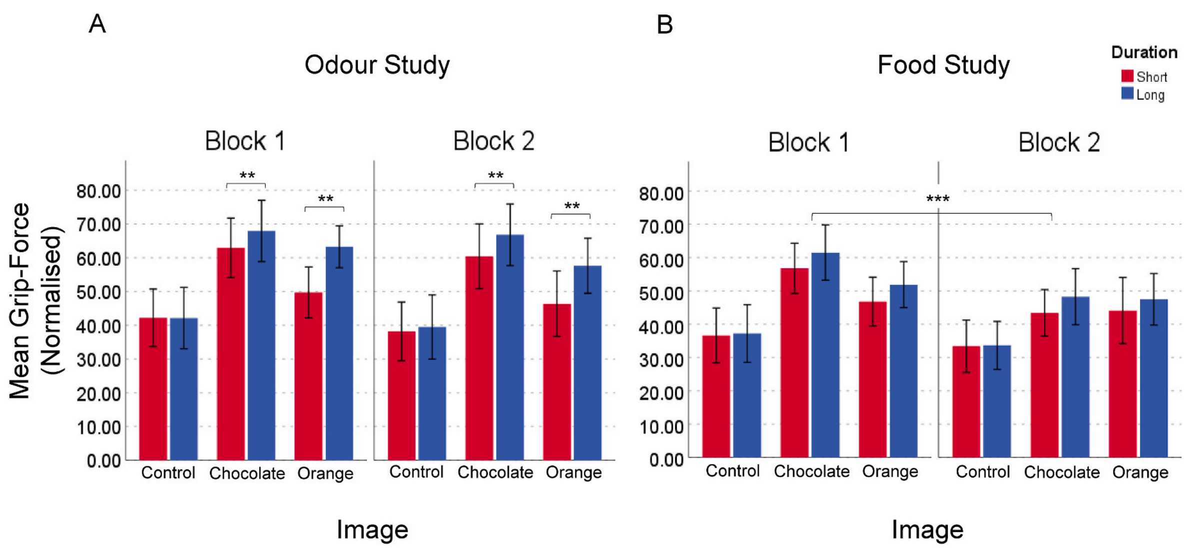

Fig. 4. Mean Grip-Force applied for each condition during the Odour Study (A) and the Food Study (B). Red bars represent Mean Grip-Force for Short Duration trials (33 msec) and blue bars represent Mean Grip-Force for Long Duration trials (200 msec). Block One is shown on the left of each figure and Block Two is shown on the right. In both studies there was a significant main effect of block and duration, with greater effort exerted in block one than block two and to long than short duration images. Error bars indicate 95% CI.

decrease in effort for chocolate images ($p < .001$) but not orange images ($p = .15$) or control images ($p = .26$), from block-one to block-two (Fig. 4B). In this study, the interaction between Image and Duration was not significant (F(2, 72) = 1.58, $p = .21$, $\eta_p^2 = .04$).

3.3. *Effect of food/odour exposure on exerted effort*

To determine whether there was any change in exerted effort for Food Images following Odour Exposure or Food Consumption, mixed ANOVAs were conducted using standardised scores of effort exerted for food images minus effort exerted for control images, thus accounting for the general decrease in effort observed in block 2 compared to block 1. Here, within participant factors were Block (Block 1 & 2) Image (Chocolate, Orange) and Duration (Long, Short) and the between participant factor was Group (Orange, Chocolate).

For the Odour Study, there was no main effect of Group (F(1, 35) = 2.34, $p = .14$, $\eta_p^2 = .06$) or Block (F(1, 36) = .01, $p = .94$, $\eta_p^2 = .00$). There was, however, a significant main effect of Image (F(1, 36) = 5.78, $p = .001$, $\eta_p^2 = .14$). As shown in Fig. 5A, participants applied greater force for Chocolate compared to Orange images. There was also a significant effect of Duration (F(1, 36) = 13.81, $p < .001$, $\eta_p^2 = .28$), with greater force applied for Long compared to Short-Duration images. Contrary to the initial hypothesis, that odour exposure would influence effort for incongruent food images, there were no interaction effects with respect of the Groups ($ps > .05$), indicating that exerted effort for chocolate/orange images, did not differ between Groups following Odour Exposure.

For the Food Study, there was no main effect of Group (F(1, 35) = 2.34, p = .14, $\eta_p^2 = .06$), Block (F(1, 35) = 2.75, $p = .11$, $\eta_p^2 = .07$) or Image (F(1, 35) = 2.33, $p = .14$, $\eta_p^2 = .06$). However, there was a significant three-way interaction between Group, Block and Image (F (1,35) = 7.47, $p = .01$, $\eta p2 = .18$). In support of the hypothesis, the chocolate group displayed a significant decrease in force applied for chocolate images from block one to block two ($p = .001$), in the absence

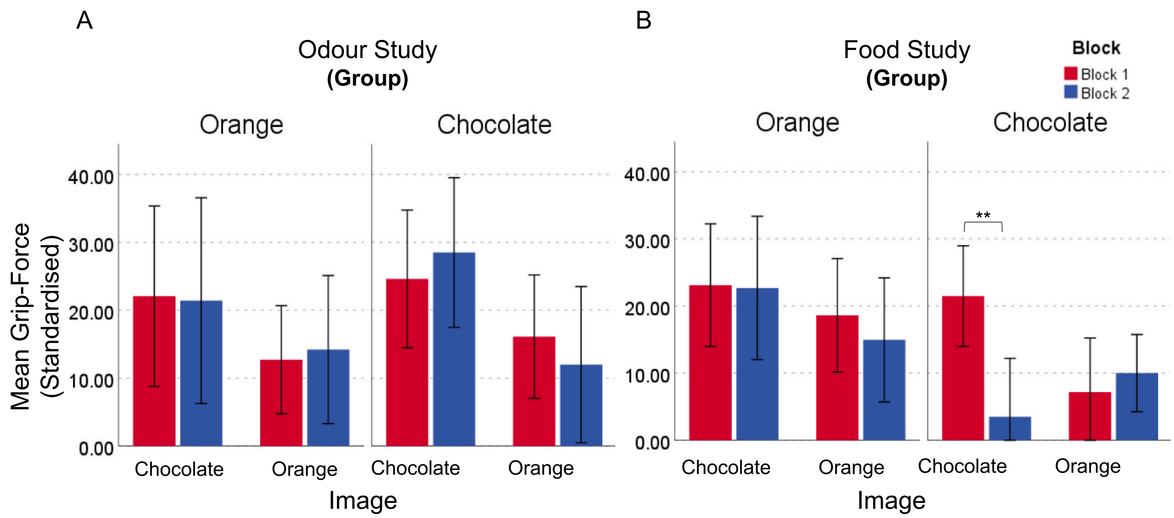

Fig. 5. Standardised Grip-Force applied for each condition for (A) the Odour Study and (B) the Food study. Red bars represent Mean Grip-Force for block-one trials and blue bars represent Mean Grip-Force for block-two trials. Exerted effort did not change from block one to block two in the odour study. However, in the Food Study, the chocolate group showed a selective decrease in effort exerted to chocolate images from block one to block two, in the absence of any change in effort exerted towards orange images. The orange group showed no change in effort across blocks to either image type. ** denotes sig level <.01. Error bars indicate 95% CI.

of any decrease in effort exerted for orange images ($p = .31$), indicative of a sensory specific satiety effect (Fig. 5B). The orange group showed no change in exerted effort from block-one to block-two for either Orange ($p = .32$) or Chocolate ($p = 27$) images.

3.4. Forced-choice discrimination

To determine whether images presented at the short-duration were at a subliminal level, a Chi-Squared test was conducted between Image Condition and Response Accuracy for both the Odour Study and the Food Study. For the Odour Study, the association between Image Condition and Response Accuracy was not significant, $\chi 2(2) = 4.31, p = .12$. Images were correctly identified 95.9% of the time (Control images 95.7%, Chocolate images 97.6%, Orange images 94.6% accuracy). Similarly, for the Food study, the association between Image Condition and Response Accuracy was not significant, $\chi 2(2) = 3.96$, $p = .14$. Overall, images were correctly identified 96.1% of the time (Control images 95.9%, Chocolate images 97.6%, Orange images with 94.7).

3.5. Food choice

In determining whether there was an effect of Odour Exposure or Food Consumption on food choice, data were analysed separately for the Odour Study and the Food Study. For the Odour study (Fig. 6A), it was found that overall, 41.2% of participants chose Orange as their gift, whilst 58.8% chose Chocolate as their gift. Contrary to the hypothesis, there was no significant effect of Group on these selections (Wald $\chi 2(1) = 2.26, p = .13$). For the Food Study, 59.5% of participants chose Orange as their gift, whilst 40.5% chose chocolate as their gift. In line with the hypothesis, there was a significant effect of Group on these selections

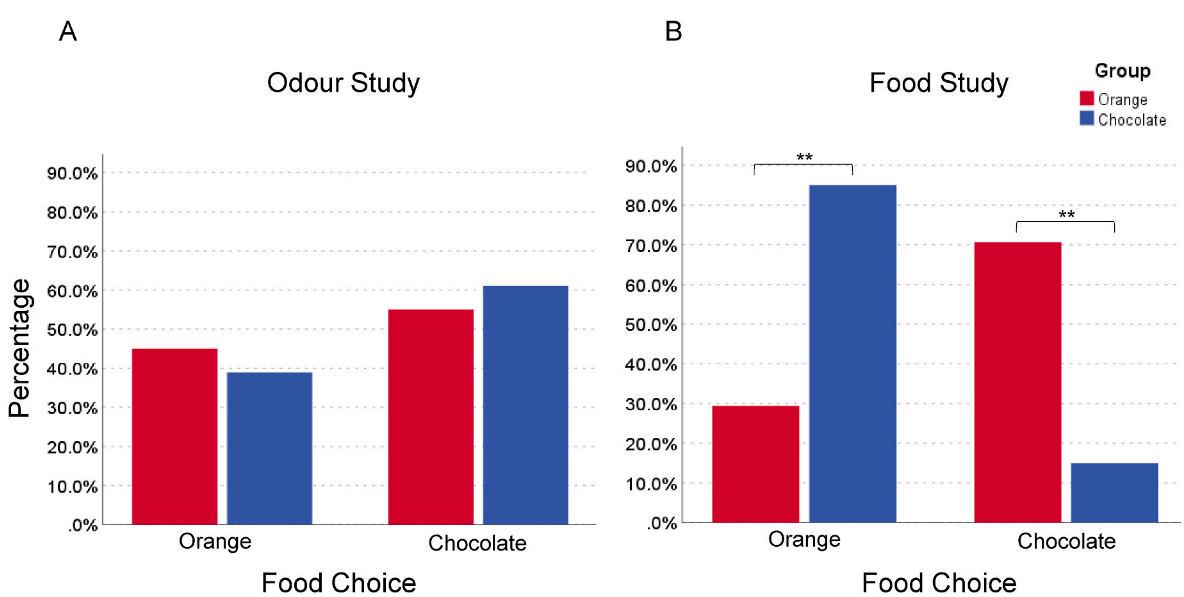

Fig. 6. Food selections for the Odour Study (left) and Food Study (right). Red bars represent Orange food selection and blue bars represent Chocolate food selection. As shown on the right, in the Food Study, there was a significant association between Food group and Food selection, in that, those in the Chocolate Group tended to choose Orange as their gift, whilst those in the Orange Group, tended to choose Chocolate as their gift. *** denotes sig level <.001.

(Wald $\chi2(1) = 14.90$, $p < .001$), with 85% of participants in the Chocolate group, choosing Orange as their gift and 70.6% of participants in the Orange group, choosing Chocolate as their gift, indicative of a satiety effect (Fig. 6B).

4. Discussion

The aim of this study was to determine whether implicit exposure to ambient food odours influenced motivation for congruent foods, using grip-force as a measure of incentive motivation. While no significant satiety or priming effect was found following ambient odour exposure, a classic sensory specific satiety effect was observed in the food consumption experiment. That is, grip-force exerted for chocolate images declined significantly following chocolate consumption, in the absence of any decline in that exerted for orange images. Behaviourally, while odour exposure also had no impact on explicit food selection, a satiety effect was seen following food consumption, with most participants selecting the food item they hadn't consumed.

The lack of any effect of ambient odour exposure on motivation for congruent foods contrasts with previous reports of both odour priming and olfactory-specific satiety (OSS) (eg Biswas & Szocs, 2019; Gaillet et al., 2013). In terms of odour priming, while non-conscious, ambient odour exposure lasting between 10 and 20 min has been reported to influence food choice (Gaillet et al., 2013; Proserpio et al., 2019), explicit exposure for 10 min has been reported to enhance appetite ratings (Jansen et al., 2003; Ramaekers et al., 2013), and increase food cue reactivity (Mas et al., 2020). While the short ambient odour exposure duration of just 5 min in the present study could potentially explain the null result, several recent studies have suggested that ambient odours can induce priming effects after exposure of just 1 min or less (Chae et al., 2023; Biswas & Szocs., 2019), while satiety effects on food selection have been reported following 2 min (Biswas & Szocs; 2019) and 5 min or more of implicit ambient odour exposure, in both laboratory and real-world settings (Chae et al., 2023). However, our findings align with other research indicating that moderate durations of implicit ambient odour exposure may not produce changes in reported food preferences or selection (Morquecho-Campos et al., 2021). Taken together, while explicit odour exposure paradigms using retronasal exposure of up to 5 min, appear to reliably induce OSS effects (Fernandez et al., 2014; Rolls & Rolls, 1997), explicit orthonasal exposure for ten to 20 min appears to enhance appetite for odour-congruent foods (Jansen et al., 2003; Ramaekers et al., 2013). In contrast, findings regarding the effects of non-conscious ambient odour exposure on both goal priming and satiety appear to be more equivocal, underscoring the need for further research.

Previous studies exploring the effects of odour exposure on eating behaviour have utilised a range of outcome measures, including consumption behaviours, food choices, and subjective rating scales (Chae et al., 2023; Morquecho-Campos et al., 2021; Biswas & Szocs, 2019; Proserpio et al., 2019; Ramaekers, 2013; Gaillet et al., 2013; O'Doherty et al., 2000; Rolls & Rolls, 1997). In contrast, the present study used an objective measure of incentive motivation (Pool et al., 2016; Berridge & Robinson, 1998) which has been established to be sensitive to the detection of classic sensory-specific satiety effects (Arumae, 2019; Ziauddeen et al., 2012), as shown again here in the food consumption study. Whilst similar satiety effects were not evident following odour exposure, consistent with previous literature (Ziauddeen et al., 2012), fasted participants in both of the present studies did display a greater level of motivation, indexed by greater expended grip-force, when they were presented with food images, compared to control images, and toward long-duration compared to short-duration food images. Thus, participants did modulate the grip-force applied depending on the motivational salience of the visual cue presented.

The fact that, in the consumption study, grip-force was only affected by chocolate and not by orange consumption likely reflects the smaller number of calories consumed in this condition. Participants in the chocolate condition consumed an average of 274 kcal, whereas those in the orange condition consumed an average of only 53.44 kcal per person. In addition to the calorific differences, two foods consumed in equal amounts may have distinct effects on satiety if their macronutrient compositions differ, with high-protein, high-fibre and high-fat foods delivering greater satiety effects than energy matched foods with lower levels of protein, fibre, and fat (Astbury et al., 2019; Berridge, Venier, & Robinson, 1989; Buckland et al, 2015). The decision to use non-macronutrient matched food options was based on the primary goal of partially replicating and extending the work of Biswas and Szocs (2019), that directly compared indulgent (high calorie) and non-indulgent (low-calorie) items. This contrasts with classic sensory-specific satiety studies which typically use two high-calorie foods such as full-fat chocolate milk (Pirc, Cad, Jager & Smeets, 2019), pizzas and cheesecake (Ziauddeen et al., 2012).

In contrast to previous grip-force studies which have reported visual stimulus presentations times of 50ms or less as subliminal (Pessiglione et al., 2006; Ziauddeen et al., 2012), participants in the present study were able to accurately identify all test stimuli when presented for 33ms in a forced-choice discrimination task. This is consistent with the wider visual processing literature which indicates that for stimuli to be considered subliminal, presentation times should not exceed 16.66ms (Ionescu, 2016; Potter et al., 2013). This perceptual threshold however can be dependent on a number of factors, such as the type (picture/texture) and direction (forward/backward/sandwich) of masking technique used (Wernicke & Mattler, 2019; Potter et al., 2013), as well as the temporal delay (Nakamura & Murakami, 2021; Harris, Wu, & Woldorff, 2011; Bacon-Macé et al., 2005) and contrast (Wernicke & Mattler, 2019; Harris et al., 2011; Haynes & Rees, 2010) between stimulus and mask. In the present study we replicated the stimulus presentation, masking timings and techniques previously reported by Ziauddeen et al. (2012) whose participants performed at chance level on the forced choice discrimination test of awareness. Differences in monitor refresh rates and visual stimuli used could potentially explain this difference. While monitors with a refresh rate of 60Hz, as used here, have been used for subliminal stimulus presentation, a higher refresh rate and shorter presentation time may have been necessary with the present stimuli (Baumgarten et al., 2017).

While the primary outcome measure was incentive motivation, to be consistent with previous odour priming studies, we also included a secondary food choice measure. In line with the grip force findings, whilst odour exposure did not influence subsequent food reward choice, food consumption did induce a satiety effect, in that participants were more likely to choose a food item different to the item they had consumed during the task. The lack of effect of ambient odour on food selection in the present study contrasts with previous research reporting that implicit odour exposure influences food choice and intake (Chambaron et al., 2015, Gaillet et al., 2013; Gaillet-Torrent et al., 2014, Proserpio et al., 2017). The method of food choice in the current study was two-alternative forced-choice while previous studies have used buffets (Morquecho-Campos, de Graaf, & Boesveldt, 2021), menus (Proserpio et al., 2017; Proserpio et al., 2019), as well as supermarket and cafeteria settings (Biswas & Szocs, 2019), where participants have a wider range of items to choose from. Forced-choice procedures are thought to offer insight into the immediate motivation behind selecting a specific food product over others (Finlayson, King, & Blundell, 2008), whereas selections from a wider array of choices may more strongly reflect dietary habits and goals (Appelhans et al., 2017). One possible explanation for the lack of effect of odour priming on food selection in the present study is timing. Here, approximately 30 min elapsed between odour exposure and food-choice selection, whilst participants in other studies selected food options either during or immediately following odour exposure (Biswas & Szocs, 2019; Gaillet et al., 2013; Proserpio et al., 2019). Also, though participants were instructed not to consume food for 3 h prior to attending the testing session, and we verbally confirmed their adherence to this rule, no measurements of subjective hunger were taken during the study. Given physiological state is a significant determinant of expended motivational effort (Pirc et al., 2019) and food selection (Köster, 2009), this should be addressed in future priming studies. However, the fact participants in both studies exerted greater effort for food stimuli compared to control stimuli during block one indicates that lack of motivational drive does not underlie our failure to observe an odour priming effect.

One of the biggest challenges in olfactory priming studies is control of stimulus concentration (Smeets & Dijksterhuis, 2014). For priming effects to occur the intensity of the odour should not be high enough to be consciously perceived, though not so low that it cannot be detected at all (Loersch & Payne, 2011; Morquecho-Campos et al., 2021). Whilst some studies do attempt to quantify the intensity of the odour e.g., below 50 on a 0–100 VAS (Morquecho-Campos et al., 2021; Proserpio et al., 2019), others merely state that intensity was low (Chae et al., 2023; Coelho et al., 2009; Gaillet et al., 2013; Gaillet-Torrent et al., 2014; Mas et al., 2020). In preparation for the present study, two pilot tests were conducted. The protocol used resulted in intensity ratings of approximately 7.68, on a 0–10 VAS, when dispersed in the test rooms, while odours were not reliably detected when attention was not directed towards them. In the study itself, only two participants reported noticing an odour prior to debriefing. Taken together, it seems unlikely our stimuli were too low in intensity to have a priming effect or so high that the aims of the study were obvious to participants. Future, cross-laboratory collaborations that determine best practice guidelines for odour dispersal, quantification and reporting would be beneficial to the field. For example, room size, air temperature as well as air flow and air exchange rates will impact odour concentration making precise replication of protocols challenging.

The present study does come with limitations, for example, the decision to expose participants to the ambient odour for a duration of 5 min was based on varying effects reported in previous studies, in which 5 min of retronasal exposure induces satiety effects (Rolls & Rolls, 1997), while ten to 20 min of orthonasal exposure increases appetite (Jansen et al., 2003; Ramaekers et al., 2013) and primes food choices (Gaillet-Torrent et al., 2014; Proserpio et al., 2019). Biswas and Szocs (2019) found priming effects with 30 s but reduced food selection with 2 min, whereas Morquecho-Campos et al. (2021) saw no effects with 3 min. Thus, our study explored an intermediate 5-min exposure duration that has revealed both priming and satiety effects (Biswas & Szocs, 2019; Rolls & Rolls, 1997). Due to the null findings following odour exposure, future research should incorporate both long and short exposure times in order to determine any differing effects. The use of indulgent (Chocolate) and non-indulgent (Orange) odours were again, chosen for replication of Biswas and Szocs (2019), with the specific matching of odours to images, replicating the methods of Ziauddeen et al. (2012), where foods consumed matched those used within the grip-force task. Much previous research (Mas et al., 2020; Proserpio et al., 2019; Chambaron et al., 2015; Gaillet-Torrent et al., 2014; Ramaekers, 2013; Zoon et al., 2016), though not all (Chae et al., 2023; Coelho et al., 2009), has opted for food categories matched for nutritional content (high/low energy) or food groups (sweet/savoury), as opposed to odours being directly congruent to images. In order to try and replicate previous priming effects, odours and images could be separated into these categories (for example, multiple savoury food images could be used alongside a savoury odour) in order to determine the impact of (sweet/savoury) odours on motivation for congruent foods. While the present study was powered to detect small-medium effects with 85% power, it could be that it was underpowered to detect what are likely to be small effects of odour exposure on incentive motivation. Therefore, future studies should utilise larger samples.

In conclusion, this study successfully replicated previous reports of sensory specific satiety effects on incentive motivation as measured using grip-force. These effects were accompanied by changes in food selection behaviour. In contrast, there was no effect of ambient odour exposure on incentive motivation nor on food selection. This contrasts with previous reports of odour priming following ambient odour exposure (Morquecho-Campos et al., 2021; Proserpio et al., 2019; Gaillet-Torrent et al., 2014) and recent reports of sensory specific satiety effects on food selection, in both real world and laboratory settings (Biswas & Szocs, 2019). Further research is needed to determine whether stimulus level factors, such as timing, intensity or character of the food odours differentially affect behaviour (Abeywickrema et al., 2022; Smeets & Dijksterhuis, 2014). However, inconsistent findings, along with other null effects (Morquecho-Campos et al., 2021; Zoon et al., 2016) highlight issues of reproducibility of the odour priming literature (Cesario, 2014) and reinforce the need for detailed methodological reporting and replication.

CRediT authorship contribution statement

Rachel Hagan: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ralph Pawling:** Writing – review & editing, Supervision, Methodology, Data curation. **Francis McGlone:** Writing – review & editing, Funding acquisition. **Susannah C. Walker:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Ethics statement

The research was conducted following the ethical principles stated in the Declaration of Helsinki. Participants gave informed consent before taking part and all data was collected anonymously. The experimental protocol was approved by the Ethics Committee at Liverpool John Moores University (19/NSP/062).

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Declaration of competing interest

RH.'s PhD studentship was partly funded by GlaxoSmithKline (G.S.K). G.S.K had no role in the design, analysis, or decision to publish this study.

Data availability

Data will be made available on request.

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