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Orthonasal olfactory influences on consumer food behaviour

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A R T I C L E I N F O

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A B S T R A C T

It is often suggested in the popular press that food chains deliberately introduce enticing product aromas into (and in the immediate vicinity of) their premises in order to attract customers. However, despite the widespread use of odours in the field of sensory marketing, laboratory research suggests that their effectiveness in modulating people's food behaviours depends on a range of contextual factors. Given the evidence that has been published to date, only under a subset of conditions is there likely to be a measurable effect of the presence of ambient odours on people's food attitudes and choices. This narrative historical review summarizes the various ways in which food odours appear to bias people's food preferences (appetite) and food choices (food consumption and purchase). Emphasis is placed on those experimental studies that have been designed to investigate how the characteristics of the olfactory stimuli (e.g., the congruency between the olfactory cues and the foods, intensity and duration of exposure to odours, and taste properties of odours) modulate the effects of olfactory cues on food behaviour. The review also explores the moderating roles of individual differences, such as dietary restraint, Body Mass Index (BMI), genetic and cultural differences in odour sensitivity and perception. Ultimately, following a review of empirical studies on food-related olfaction, current approaches in scent marketing are discussed and a research agenda is proposed to help encourage further studies on the effective application of scents in promoting healthy foods.

1. Introduction

While retronasal olfaction constitutes an integral component of the multisensory perception of flavour during the consumption of food and drink (e.g., De Araujo, Rolls, Kringelbach, McGlone, & Phillips, 2003; Spence et al., 2015; Wilson, 2021), orthonasal olfaction plays an important pre-consumption role, signalling relevant sources of food, and helping to set people's expectations concerning the likely contents of those foods that may subsequently be consumed (Stevenson, 2009). As such, olfactory cues (both orthonasal and retronasal) play an important role in shaping an individuals' food preferences and their consumption behaviours (e.g., Boseveldt, 2017; McCrickerd & Forde, 2016).

There has been a marked recent growth of interest in the role of ambient olfactory food cues (perceived orthonasally by the consumer) in the world of gastronomy (see Spence, 2022c, for a review).[1] Many establishments have purportedly chosen to deliberately introduce appetizing food odours into their stores in order to entice potential customers to spend/consume more (e.g., Hari, 2015; Latina, Sordan, Calamba, & De Jesus, 2022; Leenders, Smidts, & El Haji, 2019). On the other hand, the laboratory research that has been published to date suggests that the effectiveness of orthonasal olfactory cues in modifying people's food-related behaviours may depend on the particular context in which they happen to be experienced (e.g., Ferriday & Brunstrom, 2011; Pangborn & Berggren, 1973; Tetley et al., 2009). While many merchants would appear to believe that odours serve as an almost magical lure for customers, academic researchers have questioned the magnitude of any effect of food odours on consumer behaviour.

Looking more closely at several laboratory-based studies that have investigated the impact of orthonasal olfactory food cues on participants' food behaviours, it soon becomes apparent that it is an over-simplification to assume that food odours will necessarily always result in people eating and/or drinking more than they otherwise might (i.e., if specific food odours were not present). For example, Fedoroff, Polivy, and Herman (2003) reported that restrained eaters (i.e., those individuals who intentionally restrict their food intake to prevent/control weight gain) consumed more cookies and pizza following their exposure

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[1] In this review, olfactory cues refer specifically to those odours that are experienced orthonasally, as opposed to retronasally (i.e., when food aromas reach the nasal receptors as we chew or swallow food/drink) while eating and drinking (see Debnath, Nath, Pervin, & Hossain, 2020, for a review on retronasal olfaction).

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to food odours than were unrestrained eaters. However, this only happened if the olfactory cues happened to match the food that was available to the participants. In other words, pre-consumption olfactory food cues may increase people's appetite for products related to those cues (i.e., those food products that are consistent with the expectations that happen to be set by the orthonasal odours) rather than incongruent products (see Yeomans, 2006, for a review). This phenomenon has been explained as a food-specific priming effect (Gaillet, Sulmont-Rossé, Issanchou, Chabanet, & Chambaron, 2013).

Marked individual differences have been documented in people's responses to orthonasally-presented food odours. In addition to dietary restraint (e.g., Coelho, Polivy, Herman, & Pliner, 2009; Fedoroff et al., 2003; Ferriday & Brunstrom, 2008), BMI (Body Mass Index, BMI; Cocchetto et al., 2022; Ferriday & Brunstrom, 2008, 2011; Tetley et al., 2009), impulsivity (Larsen, Hermans, & Engels, 2012), and olfactory sensitivity (e.g., Ginieis et al., 2021, 2022; Simchen et al., 2006), appear to moderate the effect of orthonasal food odours on people's appetite and subsequent food intake. Cultural differences may also play a role in the differential perception of, and responses to, olfactory stimuli. For instance, Chi (2019) recently highlighted the distinct perception and preference for 'stinky tofu' and 'smelly cheese' amongst multilingual couples with different languages and cultural backgrounds (in particular, Taiwanese nationals and their foreign partners living in England).

Designing environments that help to promote healthy purchases when food shopping constitutes an important focus of public health and research efforts aimed at reducing obesity and thus improving health outcomes. Accordingly, consumer psychologists and behavioural scientists have shifted their research focus in recent years towards the question of how to nudge consumers to purchase food products that are "better-for-you" (e.g., Cardello & Wolfson, 2011; Glanz, Bader, & Iyer, 2012; Kotler & Armstrong, 2010; see also Karpyn, McCallops, Wolgast, & Glanz, 2020, for a review). Given the popular use of odours (no matter whether they happen to be food-related or not) in a variety of food-related marketing contexts (e.g., Glazer, 2017; Klara, 2012; see Spence, 2017, for a review), it is important to investigate how the use of ambient scents can be integrated in the marketplace to enhance people's dietary well-being.

As this narrative historical review of the literature demonstrates, experimental studies on the impact of orthonasal olfactory cues exhibit mixed findings as far as their effects on consumers' food behaviours are concerned, depending on the properties of the food odours and the perceivers' traits. For example, there is evidence to suggest that the use of food odours associated with unhealthy foods may prompt consumers to be more likely to make unhealthy food choices (e.g., de Wijk et al., 2018; Gaillet-Torrent et al., 2013; Paakki et al., 2022). This would also seem to have been the intuition that the food marketers have been operating under for years (though often without publicly available support, or necessarily peer-reviewed evidence). At the same time, however, other researchers have found crossmodal sensory compensation effects, whereby olfactory stimuli can compensate/satisfy cravings for cued flavours and the desires to obtain or consume the food (Biswas & Szocs, 2019; Li & Lee, 2023). For instance, Biswas and Szocs demonstrated that the presence of indulgent[2] food-related ambient odours could potentially reduce the purchase of unhealthy foods. They argued that prolonged exposure to food scents induced pleasure in the brain's reward circuitry which then diminished the desire for actually consuming indulgent foods. The anticipation of future food intake may well increase people's appetite for cued foods through a process of olfactory priming (see Smeets & Dijksterhuis, 2014, for a review), whereas cueing, or believing, that food intake has already taken place (as a result of mental imagery, modified pseudo-feeding, or else actual intake) may decrease people's appetite for the foods that have been cued.

Due to people's rapid adaptation to ambient odours (Spence, 2020), the use of food-related olfactory cues as an effective strategy to nudge people toward healthier food choices is potentially complicated, as it appears to depend on the features of environmental olfactory cues (e.g., the sequence of exposure, exposure time, the perceived appeal) and individual characteristics (e.g., BMI, dietary restrains, and state of hunger).

1.1. Review outline

This narrative historical review (see Ferrari, 2015; Furley & Goldschmied, 2021, on the strengths of narrative-style reviews) summarizes the various ways in which food odours (i.e., those odours experienced primarily orthonasally) bias people's food preference (appetite) and food choice (intake), with a focus on studies that have experimentally investigated the moderation of olfactory features (e.g., the congruence, intensity, and valance of scents) on the effect of orthonasal olfactory cues on consumers' food behaviours. The phenomena of sensory specific appetite (SSA; Sørensen et al., 2003) and sensory specific satiety (SSS; Hetherington & Rolls, 1996; Larson, Redden, & Elder, 2014) are highlighted as far as they are relevant to understanding the appetizing effect of food odours. In addition, this review discusses the evidence concerning food odours' influences on people's (un)healthy food choices (e.g., Biswas & Szocs, 2019; de Wijk et al., 2018; Gaillet-Torrent et al., 2013). The role of individual differences, including those related to dietary restraint (e.g., Fedoroff et al., 2003; Rogers & Hill, 1989), BMI (e.g., Cecchetto, Pisanu, Schöpf, Rumiati, & Aiello, 2022), genetic differences in people's sensitivity to specific odours (Menashe, Man, Lancet, & Gilad, 2003), and cultural differences (Chrea et al., 2004), are also examined. From a practical point of view, the literature review presents the use of scents in the context of food marketing.

2. The impact of ambient odours on appetite

While retronasal olfaction is constitutively involved in multisensory flavour perception (see Spence et al., 2015), orthonasal olfaction is more relevant in terms of helping to set people's flavour expectations (Spence, 2023; Stevenson, 2010). Ambient odours detected orthonasally (i.e., via sniffing), play a critical role in an individual's ability to detect and identify food sources, which can then trigger a range of appetitive responses (e.g., Boesveldt & de Graaf, 2017; Morquecho-Campos, 2010; Stevenson, 2010). Familiar food odours, but not non-food odours (e.g., butanol or farnesol), activate the neural regions associated with the processing of food rewards (Camerer, Loewenstein, & Prelec, 2005; Small et al., 2005), thus suggesting the anticipatory role of orthonasal olfactory food cues on food wanting. Additionally, exposure to food odours has been shown to stimulate people's appetite by triggering the release of digestive enzymes and hormones that signal the brain to initiate hunger and prepare the body for the intake of food (Mattes, 1997). The results of structural equation modelling demonstrate that the odour of food is one of the key predictors that initially elicit expectations of food taste (Moore, 2014). Olfaction is crucial in terms of triggering the anticipation of gustatory enjoyment.

According to Stevenson (2010), the regulation of appetite is the primary function associated with human olfaction, signifying the role of olfactory cues in diverting people from their original behavioural intentions. For example, when wandering down a shopping street, pedestrians are likely to be drawn to a donut bakery and slow down when they encounter the sweet smell of pastries. Even though the effect of food odours on people's appetite is widely acknowledged, the studies that have been published to date are inconsistent with respect to the effectiveness of odour-induced SSA. That is, several studies have failed to observe a significant influence of food odours on food wanting (e.g., Morquecho-Campos, de Graaf, & Boesveldt, 2021; Szakál et al., 2022; Zoon et al., 2014). While the exposure to food-related aromas can

[2] Defined as those foods linked to high energy density products that are consumed for the primary purpose of immediate pleasure.

stimulate the desire to consume food, they may also elicit sensations of satiety. For instance, Coelho et al. (2009) demonstrated that the pre-consumption exposure to cookie odours substantially reduced participants' ad libitum intake of cookies. This effect was explained as an odour-induced SSS. Sections 2.1 and 2.2 therefore present an overview of the various ways in which food odours have been shown to influence food appetite and satiety, respectively.

2.1. Olfactory-induced SSA

Exposure to olfactory food cues for a short period of time prior to consumption has been shown to have mixed effects on people's appetite. For example, Jansen et al. (2003) reported that intensely smelling large amounts of either sweet or salty snacks, led to increased appetite ratings. Similarly, Tetley et al. (2009) measured participants' craving and desire for pizza both before and after exposing them to an authentic pizza smell (associated with a 300g slice of pizza). The ambient pizza scent significantly increased participants' self-reported craving and desire for pizza. That being said, despite the descriptions provided in studies such as Jansen et al. (2003) detailing the exposure procedure as "intensely smelled large amounts of food on dishes", the specific characterization of what constitutes 'intensely smelling' and whether larger quantities of food indeed produce stronger aromas remains ambiguous and unquantifiable.

Further to the previously mentioned two studies of orthonasal olfactory induced appetite, which were both conducted amongst young women, Sulmont-Rossé et al. (2018) investigated whether scenting a dining room with a meat odour before lunch might serve to increase the appetite of those patients suffering from Alzheimer's disease. In this study, the aroma was diffused in the dining room constantly to maintain a relatively stable physical intensity so that adults could clearly notice the odour.[3] In this case, the participants (all over 75 years of age) were found to pay significantly more attention to the meal and their consumption of meat and vegetables increased by 25% when they were exposed to the meaty odour in advance. However, no such appetizing effect was observed when the researchers reintroduced the meat odour two weeks later. The authors proposed that the disappearance of SSA was due to participants' olfactory habituation. However, a two-week interval between testing sessions should presumably have been long enough to prevent habituation. Additionally, there was a lack of information regarding the type of dishes that the participants consumed the day before their first and second exposure to meat odour, and a lack of control over their participants' hunger levels. Although there are many possible explanations for the null results in Sulmont-Rossé et al.'s repetition of odour exposure, their study suggests that future research should consider a procedure involving multiple repetitions of pre-consumption exposure to the odour. Such an experimental design may lead to the development of a theoretical framework liable to account for the habituation effect of olfactorily-induced SSA.

While the three studies described above confirmed the appetizing effect of pre-consumption odours, Massolt et al. (2010) found that the odour of dark chocolate elicited satiation rather than an appetitive response in participants. Massolt and colleagues had their participants smell chocolate for 5 min before they completed any outcome measure. These researchers observed that participants' self-reported appetite scores correlated inversely with their ghrelin levels, indicating a gradual loss of appetite when they actively smelled dark chocolate. Similar to the effects of sniffing dark chocolate, Kemps, Tiggemann, and Bettany (2012) had their participants sniff jasmine oil (which they classed as a non-food odorant) from an open opaque vial, significantly reducing their participants' chocolate craving, relative to both the food (green apple) and control (water) condition. Although jasmine is popularly used in both tea (e.g., Gao et al., 2009), and occasionally in food (Spence, Wang, & Youssef, 2017), the odour was nevertheless rated as the least food-related amongst the eight artificial fragrance oils (i.e., cinnamon, vanilla, green apple, banana, gardenia, sandalwood, jasmine, and lavender) in Kemps et al.'s (2012) pilot study. The study demonstrated that a commercially-available odorant (i.e., an artificial fragrance), jasmine (classified as non-food like by their participants), could potentially be used to help curb people's food cravings.

When appropriately presented, ambient olfactory cues can be used to increase people's appetite for related foods. This phenomenon, referred to as SSA, results in individuals reporting an increased appetite for the kinds of foods that are linked to the food odours that they have been exposed to (Boesveldt & de Graaf, 2017). Food odours indicate that something is suitable for ingestion and will likely prime previous knowledge of the immediate and delayed consequences of its consumption (e.g., Yeomans, 2006; Zafra et al., 2006). The anticipated enjoyment associated with subsequent food intake may then induce an appetitive effect for the specific food. Often this is measured via changes in appetite ratings.[4] SSA has been shown to activate specific metabolic pathways for the ingestion of the (macro-)nutrients associated with the odorous cues (Mattes, 1997; Smeets et al., 2009). These metabolic pathways for ingestion include myriad digestive, endocrinologic, thermogenic, cardiovascular, and renal responses that help prepare the body to absorb and use the ingested nutrients more efficiently (Mattes, 1997). Consequently, SSA can even lead to behavioural changes in subsequent food choices and food intake (e.g., Ferriday et al., 2011; Jansen et al., 2003).

Previous studies have aimed to elucidate the reasons behind the varying outcomes of SSA in different contexts. For instance, Ramaekers et al. (2014a, b) conducted a series of experiments to investigate the impact of various palatable food odours on appetite. In this case, five different food odours (banana, chocolate, meat, tomato soup, and bread) and two non-food odours (pine tree and 'fresh green') were presented to participants at levels above the threshold for olfactory perception. The participants were either instructed to smell the odorants actively (Ramaekers, Boesveldt, Gort, et al., 2014) or else the scents were diffused passively in the room (Ramaekers et al., 2014a). In both experimental setups, sweet odours (in this case, the artificial fragrances of banana and chocolate) enhanced participants' SSA for sweet foods, reducing the appetite of normal-weight women for savoury foods, and *vice versa*. At the same time, however, the non-food odours distributed in the testing room suppressed participants' general appetite for different types of food compared with no-odour control condition.

Based on the SSA effect that was observed both when participants were actively sniffing fragrances and when they were passively exposed to the environmental odours, Ramaekers et al. (2016) conducted a follow-up study to further explore the phenomenon of SSA. Instead of exposing individuals to a certain type of odour, this follow-up investigation was designed to investigate how switching between sweet and savoury food odours influenced the appetite for sweet and savoury products, respectively. To simulate exposure to a variety of food cues

[3] Note that we have refrained from providing a stand-alone discussion concerning whether the odour was perceived consciously vs. unconsciously as: 1) this information is not available in most studies included in most of the studies reviewed; 2) the quantification of consciousness is vague especially considering an individual's potential habituation and adaptation to ambient odours (Kelling et al., 2002; Peng, Coutts, Wang, & Cakmak, 2019), and individuals' allocated attention to the odours (Forster & Spence, 2018). Additionally, we have chosen not to delve into the differences in concentration. This decision stems from the fact that studies using fragrance oils have often selected oils from various suppliers, and the common approach is to maintain consistent scent intensities across different odours within the same study.

[4] Appetite questionnaires typically probe an individual's hunger levels and their desire to eat (Ramaekers et al., 2014a). For specific appetite towards certain foods, participants are normally asked to report "how large is your appetite for food X at this moment?"

that might be encountered in daily life, such as when individuals stroll through a supermarket, the study used a within-group experimental design, consisting of four different combinations: no odour/banana odour, no odour/meat odour, meat odour/banana odour, and banana odour/meat odour. The participants were presented with cups containing either a tablespoon of medium ripe mashed banana (banana odour), or a tablespoon of warm steamed Coertjens Stoofvlees (meat odour), or water (no odour). During the 5-min odour exposure (participants actively smelling the contents of cups with the resources of odours), the participants' appetite for the smelled food remained elevated while the pleasantness of the odour decreased over time (Ramaekers et al., 2016). Notably, this study's results not only confirmed the presence of the SSA effect, but also revealed that the SSA induced by food-related odours can be rapidly switched (i.e., within 1 min) from the previous odour to the one that is currently being smelled. Specifically, participants reported an increased appetite for savoury food when exposed to the meat odour. However, after the cue exposure switched from meat to banana odour for just 1 min, the participants reported a decreased appetite for savoury food and an increased appetite for sweet food instead. These findings not only suggest that olfactory cues can induce SSA irrespective of the way used to deliver food odours to individuals, but also highlight the rapid adaptability of SSA to ambient olfactory stimuli (Ramaekers et al., 2014a; 2014b; Ramaekers et al., 2016).

2.1.1. Food odours: implications for taste, appetite, and energy intake regulation

The SSA effect related to ambient food odours has been explored across various macronutrients, including carbohydrates, proteins, and fats. Morquecho-Campos et al. (2019) conducted a study in which the participants were exposed to odours typically associated with carbohydrates (honey odour), protein (chicken odour), fat (butter odour), and low-calorie foods (melon odour). The participants were instructed to sniff bottles containing different odours (pretested to determine a similar level of detectability) for 3 min and, at the same time, participants' saliva was collected.[5] However, the composition of saliva did not exhibit significant differences between the odours associated with distinct macronutrients. Although previous studies suggested an increase in salivary α-amylase in response to sham feeding of carbohydrate-related products (Froehlich, Pangborn, & Whitaker, 1987; Mackie & Pangborn, 1990), α-amylase and lingual lipase activity were not affected by specific odour exposure (honey odour) in this study. This raises the question of whether sensory stimulation through odour exposure alone is sufficiently robust to elicit a more pronounced impact on specific cephalic phase responses (Nederkoorn, Smulders, & Jansen, 2000). In a subsequent study using a similar procedure, Morquecho-Campos, de Graaf, and Boesveldt (2020) reported that only protein-related odours (i.e., the odours of duck or chicken) enhanced the appetite and liking for congruent foods (chicken, tuna, and meat) compared to incongruent (in terms of macronutrient content) food products such as bread, corn, and cucumber. However, the study did not find an SSA effect for the odours that were associated with other macronutrients. Other odour samples included corn and bread aromas signalling carbohydrates, butter and cream odours signalling fat, and cucumber and melon aromas signalling low-calorie foods. The authors suggested that the arbitrary classification of odours based on primary macronutrients might have weakened the link between orthonasal olfactory cues and foods, as the foods people typically encounter are complex mixtures of nutrients (Martin & Issanchou, 2019; van Langeveld et al., 2017).

It is worth bearing in mind that commonly consumed foods are usually rich in a diversity of nutrients, challenging the notion of classifying scents solely based on the dominant macronutrient. For example, consider Gouda cheese, which was classified as having a "fat odour" in Morquecho-Campos et al.'s (2020) study. This cheese also contains a significant amount of protein (Renner, 1993). Similarly, cherry tomatoes, although categorized as a low-calorie food, have a proteinaceous taste due to their high glutamate content. Despite being classified as vegetables, tomatoes exhibit elevated levels of glutamic acid, providing a robust umami taste/flavour more commonly associated with meat (Beullens et al., 2008). Taken together, therefore, these examples emphasize the complexity and richness of the sensory profile of various foods and challenge the effectiveness of simply categorizing food odours based on the dominant macronutrient of the cued foods.

Along with categorizing orthonasal olfactory cues based on the associated macronutrients, prior research has also investigated the SSA effect of odours with different taste qualities (sweet, sour, savoury, and bitter) (see e.g., Itoh et al., 2022; Lim, Fujimaru, & Linscott, 2014; Spence, 2022a). For example, in Morquecho-Campos et al.'s (2019) Study 1, the participants were exposed to odours signifying various tastes (i.e., vanilla odour for sweetness, beef odour for savoury, lime odour for sourness, and fresh green odour as the non-food control). The results showed that participants salivated significantly more following pre-consumption exposure to the odours associated with various tastes. However, the specific taste properties of the odours did not exert a significant impact over the composition or secretion of saliva (Carreira et al., 2020), suggesting that salivary responses to orthonasal olfactory cues may not be taste-specific. Similarly, Zang et al. (2019), conducted a study in which the participants sniffed the odours of bottled food items or fragrance oil, found no difference in the ratings of "appetitiveness" of odours representing different tastes. Concurrently, other studies indicated that smelling a sweet/savoury odour increased the appetite for sweet/savoury products, when compared to a no odour control and the odour of the other taste category (e.g., Frank & Byram, 1988; Ramaekers et al., 2014a; b; Ramaekers et al., 2016; Zoon et al., 2016). The SSA effect for a specific taste was also observed in the case of alcoholic beverages, with social drinkers who were not physically dependent on alcohol showing an increased desire for alcohol when presented with the odour of their favourite alcoholic beverage (Greeley, Swift, & Heather, 1993).

Beyond comparisons between food odours related to different macronutrients and specific taste qualities, researchers have also categorized food odours according to the energy density of the associated foods. For instance, Zoon et al. (2016) demonstrated that actively sniffing high-calorie foods (chocolate and beef; the odours were from bottled solutions that were rated to be of similar olfactory intensities) for 3 min increased their participants' appetite for high-calorie foods while reducing their appetite for low-calorie foods, and *vice versa*. Meanwhile, Proserpio, de Graaf, Laureati, Pagliarini, and Boesveldt (2017) reported that odours (vaporized in the room at a detectable but mild concentration) signalling high energy density food products significantly increased saliva production when compared to a no-odour control condition. Interestingly, while the odour of melon helped people to control their intake of high-energy dense foods, the odour of cucumber appeared to be more effective in controlling salivation, yielding significantly lower rates of salivation as compared to the beef and chocolate conditions (Proserpio et al., 2017). Although both cucumber and melon odours are typically associated with low-energy density foods, the latter may be more effective in terms of helping people to control their energy intake, while the former might be more effective at regulating people's appetite for high-energy foods. Proserpio et al. (2019) conducted another study on SSA (where odours were also dispersed in the test room at a detectable but mild level), finding that the odour of bread (rated as savoury and of high-energy density according to their pilot study) induced SSA for congruent food products in terms of taste and energy density (i.e., breaded veal cutlet, cheese, and French fries) but not for other foods (i.e., melon, apple, strawberries, ice-cream, cake, chocolate,

[5] Several classic, as well as more recent studies, have demonstrated an increase in salivation upon multisensory exposure to various foods (e.g., Ferriday & Brunstrom, 2011; Wooley & Wooley, 1973; see Spence, 2011, for a review).

tomato, zucchini, and raw carrot). There was also a significant increase in general appetite scores for those participants exposed to the smell of bread as compared to the control group without the smell.

Nearly all of the studies included in this review exposed participants to familiar food odours (e.g., the scent of baking pizza in Tetley et al., 2009; the scent of baking cookies in Larsen et al., 2012), and the SSA can be explained in terms of the classical conditioning between the olfactory stimulus and anticipated gustatory experiences (Matsumoto, Menzel, Sandoz, & Giurfa, 2012). A person's olfactory memory is related to their previous food experiences and may influence their experience of SSA. Previous studies have found that repeated associative learning of odour-taste mixtures can produce conditioned changes in perceived odour quality and provide examples of learned associative perception (e.g., Stevenson & Boakes, 2004; Stevenson & Case, 2003; Stevenson et al., 1998; Stevenson et al., 2000a; b). For example, Stevenson et al.'s (1998) study revealed that an odour conditionally paired with sucrose was later perceived to be sweeter than one that had been paired with water. Such evidence supports the notion that odour-induced taste expectation is dependent on people's prior experience and learned associations between taste and smell. Future studies should therefore consider including novel odours to examine how SSA effects works when participants gradually become accustomed to novel scents. For example, Stevenson and Mahmut (2011) exposed Australian participants to the scents of water chestnut and lychee to examine how odour-taste pairing influence participants' perceived taste and hedonic rating of the odours. Other factors, such as the circumstances under which consumers would prefer a familiar or novel scent, could also be potential areas of research interest.

To summarize, the exploration of the SSA effect related to ambient food odours across various macronutrient categories has challenged the simplistic classification of scents based solely on dominant macronutrients. Additionally, research involving participants being exposed to orthonasal olfactory cues, classified according to taste qualities (e.g., the odour of caramel signalling sweetness, and the odour of lime signalling sourness), has yielded mixed results, highlighting the non-specific nature of salivary responses and the seemingly more sensitive detection of specific appetitive responses to different odours with appetite scales. Investigations into the influence of food odours on appetite based on energy density have revealed nuanced relationships, suggesting that the impact of odours on the regulation of energy intake is multifaceted. Furthermore, the role of associative learning between odours and taste experiences has been documented, underscoring the importance of prior experiences, and learned associations in shaping the perception of food flavour and olfactory-induced appetite. A summary of findings of experimental studies on orthonasal olfactory cues and appetitive responses is provided in Table 1. As future research delves into novel odours (i.e., those odours that are unfamiliar to participants) and examines factors influencing preferences for familiar or novel scents, a more comprehensive understanding of the complex interplay between odour, taste, and appetite will likely be gained.

2.1.2. Understanding the dynamics of odour-induced sensory-specific appetite: duration of exposure, habituation, and rapid adaptation

Experimental studies on odour-induced SSA often account for the duration of exposure to the odours as a moderating factor. Repeated exposure to odours will create habituation (decreased behavioural response), referring to the organism's behavioural equilibrium achieved in response to alterations in environmental stimuli (Dalton, 2000; Pellegrino, Sinding, De Wijk, & Hummel, 2017). Initial explanatory models of human olfactory habituation pointed out that the phenomenon is directly proportional to the duration of exposure to the odorant (see Pellegrino et al., 2017 for a review). Usually, repeated, or prolonged exposure to an odorant leads to decreases in olfactory sensitivity towards that odorant (Ekman, Berglund, Berglund, & Lindvall, 1967; Wang et al., 2002). However, such olfactory habituation can be eliminated over time if there is no further exposure (Kelling, Ialenti, & Den Otter, 2002).

Odour-induced SSA appears to adapt rapidly. For instance, exposing people to the odour of freshly cooked pizza for just 60 s has been found to lead to a significant elevation in the desire for pizza, and a simultaneous decrease in the desire for sweet foods such as cake (Ferriday & Brunstrom, 2008). Moreover, food odours may become less pleasant as odour exposure is extended to the point of satiety (Rolls & Rolls, 1997). Such a process can occur even after just a relatively brief exposure to odours orthonasally (Jansen et al., 2003; Jansen & Vandenhout, 1991; Massolt et al., 2010; Rolls & Rolls, 1997; Smeets et al., 2009). For instance, Rolls and Rolls reported that 5-min of orthonasal exposure (via active sniffing foods in cups) to the odours of banana and chicken decreased the perceived pleasantness (a measure of SSS) associated with the idea of consuming the cued foods, but had no effect on other foods, such as satsuma and fish (Rolls & Rolls, 1997). Meanwhile, Ramaekers et al. (2016) presented a study demonstrating the rapid switch of odour induced SSA. These researchers exposed normal-weight women to the smell of bananas or meat in a randomized order and found that the appetite for specific food items shifted within 1 min from the previously smelled odour to the currently introduced one. Though some experimental studies on ambient food-related olfactory cues have extended the exposure time to investigate the moderating effect of the duration of odour exposure (e.g., Larsen et al., 2012 compared 1 vs. 15 min exposure), the effectiveness of such manipulations remains questionable as Ramaekers et al. (2016) suggested that odour preference could change within 1 min of exposure.

Future investigations into odour-induced SSA might consider presenting different odours associated with the same attribute. For example, researchers can identify several odours related to sweet/bitter/savoury/sour foods (various taste attributes) that are of similar likeability and familiarity to the participants. This approach would allow researchers to explore SSA responses for odours classified according to basic tastes, while mitigating any potential effects of olfactory adaptation to a specific smell.

2.1.3. Assessing appetite: questionnaires, biomarkers, and food intake

Appetite, being a subjective construct, poses a challenge for direct measurement. Consequently, studies on SSA necessitate the reliance on several indirect measurements. Three assessment methods are commonly used: questionnaires, biomarkers, and eating patterns/food intake (Blundell et al., 2010; de Graaf, Blom, Smeets, Stafleu, & Hendriks, 2004; Mattes, Hollis, Hayes, & Stunkard, 2005).

Questionnaires are popularly adopted as the self-report assessment of appetite, of which VAS and/or Likert scales are the most popular (see Table 1 for examples of these studies). VAS scales require participants to respond to a question by placing a mark on a straight horizontal line, anchoring at each end with opposing statements such as "not at all hungry" and "as hungry as I have ever felt". While these questions encompass various facets of appetitive sensations, such as hunger, the desire to eat (e.g., "how strong is your desire to eat right now?"), and the estimation of likely food consumption (e.g., "how strong is your desire to consume something savoury right now?"; Rogers & Blundell, 1979), it remains uncertain as to whether participants fully grasp the subtle distinctions between them. To establish a more quantitative technique to index perceived hunger and/or fullness, Cardello, Schutz, Lesher, and Merrill (2005) developed the satiety labelled intensity magnitude (SLIM) scale, which places labels of phrases along a vertical line scale at positions corresponding to their geometric mean magnitude estimates of hunger (fullness) (see Fig. 1). Compared to VAS scales, SLIM scale demonstrated greater sensitivity and displayed an average reliability coefficient of .90 (Cardello et al., 2005). Similarly, there is a generalized Labelled Magnitude Scale (gLMS) for measuring sensations of taste and smell (Bartoshuk et al., 2004; Green et al., 1996), with seven intensity anchor labels provided (i.e., strongest of any kin, very strong, strong, moderate, weak, barely detectable, no sensation). Despite the advantages of labelled magnitude scales (LMS), a major drawback is that such

Table 1
Chronological summary of studies that have investigated the impact of ambient odours on appetite in humans.

Study	Participants	Measures	Odours	Odour exposure	Key findings
Fedoroff, Polivy, and Herman (1997)	Restrained ($N = 49$) and unrestrained women ($N = 42$) *Mage* = 21 years Abstain from eating for 2h beforehand	VAS ratings of hunger, desire to eat, liking, and craving	Pizza†	10 min The pizza was baked in the next room and the door to the experimental room was kept ajar	Dietary restraint * Odour: Restrained participants in the smell cue condition rated their craving higher than did the unrestrained participants
Fedoroff et al. (2003)	Restrained ($N = 60$) and unrestrained women ($N = 72$) *Mage* = 21 years Abstain from eating for 2h beforehand	VAS ratings of hunger, desire to eat, liking, and craving	Pizza† Cookies†	10 min Foods were baked inside an oven that was positioned in the room, but out of sight	Dietary restraint * Odour: Self-reported desire to eat, liking, and craving for a particular food increased more for restrained eaters after exposure to the smell of that food
Jansen et al. (2003)	Overweight ($N = 16$) and normal-weight children ($N = 15$) *Mage* = 10 years Abstain from eating for 2h beforehand	9-point scales of hunger and appetite Saliva flow	Sweet and salty snacks†: M&M's, sugar peanuts, cake, Milky Way, crisps, and savoury nuts	10 min Intensely smelling the food	Odour: Exposure to food smells led to increased appetite in both groups, but did not influence salivary flow BMI: No evidence for differential cue reactivity (change of appetite and hunger level) between overweight and normal-weight children
Coelho et al. (2009)	Restrained ($N = 59$) and unrestrained women ($N = 57$) *Mage* = 22 years	7-point scales of hunger and satiety	Chocolate-chip cookies†	12 min Cookies were baked in the room adjacent to the testing room	No significant main effect or interactions for either hunger or satiety ratings
Tetley et al. (2009)	Normal-weight women ($N = 120$) *Mage* = 21 years Participants were satiated before cue exposure	VAS ratings of craving and desire Desired portion size of pizza	Pizza†	3 min Pizza was presented on the table directly in front of participants (sight and smell)	Odour: Pizza odour exposure significantly increased participants' craving for pizza, and their desire to eat this food, but did not stimulate the selection of a larger portion of pizza Everyday portion size and BMI did not predict odour reactivity
Massolt et al. (2010)	Normal-weight women ($N = 12$) *Mage* = 27 years Abstain from eating for 1h beforehand	VAS ratings of satiety, appetite, and hunger Ghrelin	Dark chocolate†	5 min Actively smelling dark chocolate Data was collected at 5/10/20/30/40/50/60 min	Odour: Smelling chocolate suppressed appetite (more satiation and fullness and less appetite and hunger); the correlation between VAS scores and ghrelin was positive before smelling chocolate and negative after smelling No VAS changes after chocolate smelling per time lag
Ferriday and Brunstrom (2011)	Overweight women ($N = 52$) and normal-weight women ($N = 52$) *Mage* = 35 years Abstain from eating for 3h beforehand	VAS ratings of hunger, desire to eat, and liking for the test foods Saliva flow Desired portion size of foods (scrambled egg, chips, baked beans, chicken tikka masala, pasta and tomato sauce, cake, chocolate buttons, pizza)	Pizza†	1 min Sight and smell of freshly cooked pizza	Odour: Food-cue exposure increased hunger and decreased fullness, increased desired portions of foods (except for cake and chocolate buttons) Odour * BMI: Overweight women had larger increase in desire to eat pizza, scrambled egg, chips and beans; overweight women produced more saliva after cue exposure
Larsen et al. (2012)	Normal-weight women ($N = 109$) *Mage* = 21 years Abstain from eating for 3h beforehand	Saliva flow	Cookies†	1 min or 15 min Cookies were baked in an oven in the testing room	Neither olfactory cue exposure, nor impulsivity, the duration of the exposure, or the interactions, were significantly related to saliva secretion
Kemps et al. (2012)	Normal-weight women ($N = 67$) *Mage* = 21 years Abstain from eating for 2h beforehand	VAS rating of craving for chocolate	Green apple* Jasmine* Water	The experimenter opened an opaque vial containing the oil (or water) and held it under the participant's nose	Odour Type: The non-food odorant (jasmine) significantly reduced chocolate cravings relative to both the food (green apple) and control (water) conditions
Ramaekers et al. (2014a)	Unrestrained normal-weight women ($N = 21$) Age range: 18–45 years Abstain from eating for 2.5h beforehand	VAS ratings of general appetite and SSA Food preference questionnaire Saliva flow	5 food odours: banana*, chocolate*, meat*, tomato soup*, and bread† 2 non-food odours: pine tree* and fresh green*	20 min Scents were distributed in the test room Data was collected at 0/5/10/15/20 min	Duration of exposure: Odour intensity ratings decreased by 16 mm on a 100 mm VAS on average for each odour in 18 min Odour: Food odours increased general appetite, non-food odours suppressed general appetite, compared with no odour control Odour signalling tastes: Odours signalling savoury and sweet foods elicited SSA for odour-specific foods, respectively; chocolate and banana odours increased the choice for

(continued on next page)

Table 1 (*continued*)

Study	Participants	Measures	Odours	Odour exposure	Key findings
					sweet foods, but decreased for savoury food, and *vice versa* Odours did not affect salivation
Ramaekers, Boesveldt, Gort, et al. (2014)	Normal-weight women (N = 61) Age range: 18–45 years Abstain from eating for 2.5h beforehand	VAS ratings of general appetite and SSA for 11 individual products Expected pleasantness	Banana†*	10 min Actively sniffing Data was collected at 1/5/9min	Odour * Odour Origin: Both artificial and natural banana odour increased SSA but did not change general appetite Odour signalling tastes: Banana odours, compared with no odour, increased the appetite for banana related products and other sweet products, whereas the appetite for savoury products decreased Banana odours increased the expected pleasantness scores for banana milkshake and decreased the scores for meat soup, compared with no odour Exposure time: Perceived odour intensity decreased over time
Ramaekers et al. (2016)	Normal-weight women (N = 30) Age range: 18–45 years Abstain from eating for 2.5h beforehand	VAS ratings of general appetite, SSA, odour intensity and pleasantness Food preference questionnaire	In combination, two successive odour exposures: banana†, meat*, and water	5 min/odour Sniffing cups containing either medium ripe mashed banana, or warm steamed meat, or water	Odour: Odour pleasantness adjusted within 1 min to the currently smelled odour after a switch Odour signalling tastes: Exposure to banana odour increased appetite for banana products, decreased appetite for meat and savoury products; exposure to meat odour increased the appetite for meat products, decreased appetite for banana and sweet products Exposure time: The perceived intensity of meat and banana odours decreased over time
Zoon et al. (2016)	Normal-weight women (N = 29) *Mage* = 27 years	VAS ratings of general appetite, SSA, and odour intensity	Sweet: chocolate*, melon* Savoury: cucumber*, beef* Non-food: fresh green*	3min Active smelling	Odour type: Non-food odour decreased general appetite Odour signalling tastes: Sweet odours increased SSA for sweet products than for savoury and neutral products, and savoury ones were significantly lower than neutral ones; the same pattern for savoury odour
Zoon et al. (2016)	Two sessions: hunger state and satieted state	VAS ratings of general appetite, SSA, and odour intensity	High energy-density: chocolate*, beef* Low energy-density: cucumber*, melon* Non-food: fresh green*	3min Active smelling	Odour signalling energy density: Smelling odours signally high-energy density foods increased appetite more than low-energy odours and no-odour control, and specifically for high-energy foods
Proserpio et al. (2017)	Normal-weight women (N = 32) *Mage* = 21 years Abstain from eating for 3h beforehand	VAS ratings of SSA Saliva flow	High-energy: chocolate* and beef* Low-energy: cucumber* and melon*	15 min for VAS ratings 10 min for saliva collection Scents were vaporized in the waiting room	Odour signalling energy density: Odours signalling high energy dense food products significantly increased saliva production compared to control condition Odour: Odour exposure did not induce SSA but increased general appetite
Sulmont-Rossé et al. (2018)	Alzheimer's disease residents (N = 32, 25 females) Age: >75 years	Attention assigned to the plates were coded as indication of appetite	Meat*	5 min Meat odour was diffused in the dining room	Odour: Participants paid significantly more attention to the main dish when primed with meat odour No such difference observed in the replication session
Proserpio et al. (2019)	Obese women (N = 30) *Mage* = 52 years	VAS ratings of general appetite and SSA	Bread*	10 min The odour was dispersed in the test room	Odour signalling energy density and tastes: The odour exposure induced SSA for congruent food products in term of taste and energy density, as well as a significant increase in general appetite scores
Zang et al. (2019)	Participants with olfactory dysfunction (N = 48), and normal participants (N = 41) Age range: 40–75 years	Ratings of pleasantness, intensity, and familiarity Saliva flow	Bitter: dark chocolate† Sour: lemon curd† Savoury: peanut butter† Sweet: caramel† Non-food: pea (rose-like flavour)*	45 s Active sniffing	Olfactory function * Odour: In comparison to controls, patients rated orthonasal food odours as less pleasant, intense, familiar, and less appetizing (chocolate, peanut, lemon)

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Table 1 (*continued*)

Study	Participants	Measures	Odours	Odour exposure	Key findings
					No significant difference in salivation
Morquecho-Campos et al. (2019) (Study1)	$N = 36$, 29 females *Mage* = 24 years Abstain from eating for 2h beforehand	VAS rating of mouth-watering, liking, intensity, familiarity, and intention to eat Saliva flow	Sweet: vanilla* Savoury: beef* Sour: lime* Non-food: fresh green*	3 min/odour Active sniffing	Odour signalling tastes: Saliva secretion rate significantly increase in the odour exposure conditions as compared to no-odour and non-food odour conditions No difference in saliva secretion rate between the taste-related odours
Morquecho-Campos et al. (2019) (Study 2)	$N = 60$, 47 females *Mage* = 27 years Abstain from eating for 2h beforehand	Saliva flow	Carbohydrates: honey* Protein: chicken* Fat: butter* Low-calorie: melon* Non-food: fresh green and wood	3 min/odour Active sniffing	Odour signalling macronutrients: Saliva secretion rate increased significantly in response to food odour exposure, but was not significantly different between the macronutrient-related odour categories
Morquecho-Campos et al. (2020)	Normal-weight women ($N = 32$) *Mage* = 22 years Abstain from eating for 2h beforehand	VAS ratings of mouth-watering sensation, general appetite and SSA Taste preference ranking task	Carbohydrates: corn*, bread* Protein: chicken*, duck* Fat: butter*, cream* Low-calorie: cucumber*, melon*	3 min Active sniffing	Odour type: there is main effect of odour congruency on SSA Odour signalling macronutrients: Exposure to congruent odours did not affect the subsequent preference ranking for corresponding macronutrients
Morquecho-Campos et al. (2021)	Normal-weight women ($N = 34$) *Mage* = 21 years	VAS ratings of general appetite and SSA Taste preference ranking task	Carbohydrate: bread* Fat: butter* Protein: duck* Low-calorie: cucumber*	3 min Odours were vaporized in air-conditioned room	Odour signalling macronutrients: A significant interaction between odour categories and congruency Odour did not influence liking or ranking of food
Cecchetto et al. (2022)	Normal-weight women ($N = 23$) *Mage* = 24 years 20 overweight women *Mage* = 26 years	Liking and wanting task Heart rate and skin conductance	Food related: pizza*, orange*, burger* Non-food: lavender*, rose*, leather*	Odours were presented using a computer-automated olfactometer to deliver odours in a temporally precise manner	Odour * BMI: Overweight participants liked food odours less than non-food odour, but no such difference was present in the normal-weight group No such interaction observed with heart rate and skin conductance Heart rate for non-food odours was lower than food odours with normal-weight group, but no difference in overweight group

Note. A scent marked with '*' indicates that it is synthetic (i.e., the flavour in mineral oil or fragrance). A scent marked with '†' indicates that it is the natural odour given off by food.

scales have no simple cognitive algebraic model underlying the responses (Schifferstein, 2012). Compared to more traditional category scales and magnitude estimation, LMS (including gLMS) has unequal quasi-logarithmic space intervals of the verbal descriptors, making it difficult to optimize statistical procedures and the explanation of data.

A shared problem of questionnaire-based assessment of appetite is that the validity of participants' responses in predicting subsequent food intake is inconsistent. Even in strictly controlled laboratory studies using standard questions, the correlation between pre-prandial appetite scores and subsequent food intake was only weak to moderate (e.g., Flint, Raben, Blundell, & Astrup, 2000; Sørensen et al., 2003). These observations caution against the interpretation of questionnaire-based measures of appetite. Although high appetite scores may indicate a strong interest in certain foods, they do not necessarily result in increased food intake.

Various physiological changes associated with food intake, such as an increase in the concentrations of gut peptide, can serve as potential biomarkers of appetite. One example is the gut peptide ghrelin, which has been identified as a potential biomarker for meal initiation. Indeed, there is a clear pre-prandial rise in ghrelin levels, which tends to be followed by a rapid post-prandial decline (Cummings et al., 2001, 2004). Massolt et al. (2010) measured participants' ghrelin levels as an indicator of gastrointestinal hormones related to appetite and found an inversion of the relationship between appetite and ghrelin after exposure to the smell of dark chocolate. Moreover, the effects of chocolate smelling and eating on appetite were similar according to the VAS scores, indicating a comparative cephalic response between smelling and tasting food. Though the olfactory effect with an inversion of the relationship between ghrelin and appetite self-reports was not observed in chocolate eating. Salivation is also a well-documented physiological measure of appetite (Wooley & Wooley, 1973). While recent studies have used saliva collection to measure appetite (e.g., Morquecho-Campos et al., 2019; Proserpio et al., 2017), its suitability as an unambiguous measure of appetite has long been questioned (Spitzer & Rodin, 1981). Salivation generally increases with food deprivation and palatability, but its relationship to food consumption has not been systematically investigated. Moreover, salivation can be induced by the sourness in food rather than solely by appetite or hunger (e.g., Wang et al., 2017). Consequently, the validity of using salivation as a biomarker for appetite studies is questionable.

Food intake is often considered as being closely linked to appetite and is sometimes used as a proxy for it. However, oftentimes this relationship can be disrupted. For instance, the lack of availability of certain food choices or social context may cause an individual to refrain from eating when they feel hungry or interested in certain foods. Alternatively, people may consume food in the absence of hunger due to boredom or simply when they are offered palatable food (Yeomans et al., 2004). Therefore, food intake, representing a direct food behaviour rather than mere intention, warrants separate examination in relation to the influence of orthonasal olfactory cues.

2.2. Olfactory-induced SSS

Rolls (1986) discovered the phenomenon of SSS, which initially

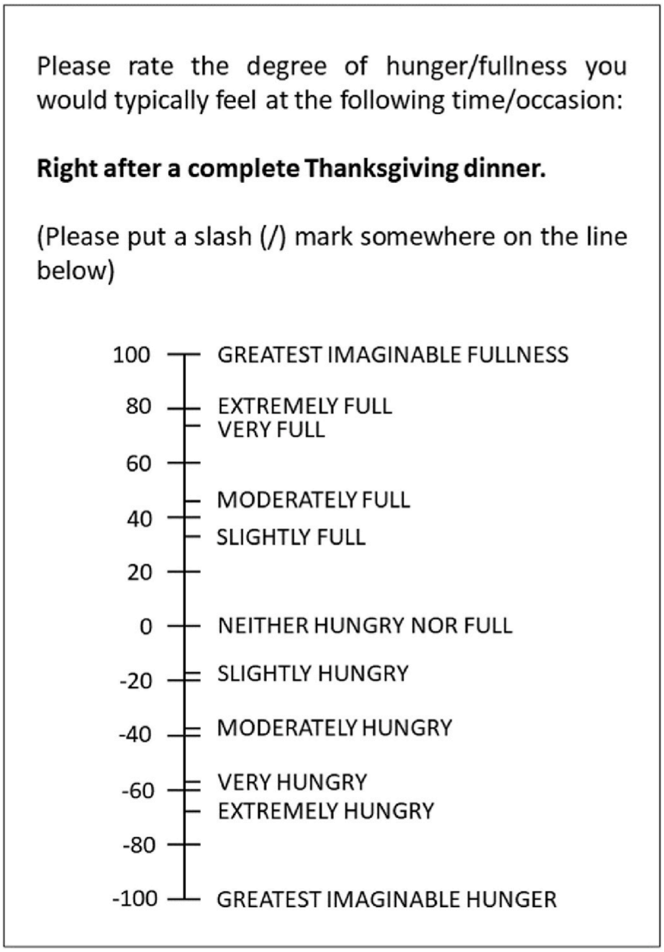

Fig. 1. The SLIM (Satiety Labelled Intensity Magnitude) scale.
Note. Adapted from "Development and testing of a labeled magnitude scale of perceived satiety", by Cardello, A. V., Schutz, H. G., Lesher, L. L., & Merrill, E. (2005). *Obesity Reviews, 44*(1), 1–13.

referred to the reduced pleasantness for a food that had been consumed to satiety, in comparison to uneaten foods. Over time, SSS has also been extended to encompass crossmodal sensory experiences. So, for example, exposure to orthonasally perceived smells can also elicit SSS, without the necessity of food entering the gastrointestinal system (Chaaban & Andersen, 2021; Rolls & Rolls, 1997). Contrary to the previously summarized SSA effect, the existence of an olfactory SSS effect suggests that exposure to odours may actually decrease, rather than increase, the interest and desire for cued foods (Abeywickrema, Oey, & Peng, 2022; McCrickerd & Forde, 2016).

According to Morewedge, Huh, and Vosgerau (2010), there is a significant overlap in neural machinery between the perception of food during actual and imagined consumption (see also, Djordjevic, Zatorre, & Jones-Gotman, 2004). Their research demonstrated that repeatedly imagining eating M&M's (Mars) or cheese cubes, led to a subsequent reduction in the intake of those foods that had been imagined as compared to other foods. Interestingly, they also found that repeatedly imagining moving M&M's from one place to another, increased the subsequent intake of the confectionary item (Morewedge et al., 2010). This suggests that it is the anticipatory process of food consumption, rather than random imaginative interactions with the food that contributes to SSS. In terms of measurement, while SSA is typically assessed by changes in appetite ratings or salivation, SSS is generally measured through changes in pleasantness ratings. Thus, SSS refers to a temporary decline in pleasure, characterized as decreases in both food liking and food wanting, following exposure to the taste and/or smell of certain foods.

Similar to the SSA, the SSS effect induced by orthonasal olfaction is specific to basic taste properties. For instance, Jansen et al. (2003) found that a 10-min exposure to the smell of sweet and savoury snacks significantly decreased the intake of those snacks amongst normal-weight children, as compared to a no smelling condition. Similarly, Coelho et al. (2009) observed that SSS appeared to be specific to the exact olfactory cue, such that only the chocolate-chip-cookie intake of their restrained participants was affected by the chocolate-chip-cookie odour but not the intake of other flavours of cookies. Additionally, Rolls and Rolls (1997) reported that smelling bananas or chicken for 5 min decreased the pleasantness of those smells relative to the pleasantness of other foods that were not smelled. The SSS effect elicited by the specific taste attribute of orthonasal olfaction is consistent with the findings demonstrated for the food intake process. As established by Griffioen-Roose, Hogenkamp, Mars, Finlayson, and de Graaf (2012), a 24-h fully controlled dietary intervention, where participants consumed diets that were either predominantly sweet tasting, savoury tasting, or a mixture of both tasting, significantly altered participants' food preferences. Specifically, after the sweet diet, the intake of sweet foods was higher than of savoury foods, and *vice versa* for the savoury-diet intervention.

Biswas and Szocs (2019) proposed that humans become satiated with the perceived reward associated with the experience of prolonged smelling. In their study, exposure to an indulgent food-related odour (i.e., cookie scent) for more than 2 min resulted in a lower purchase of unhealthy foods in a cafeteria setting, as compared to a no-odour control or a non-indulgent food-related ambient scent (i.e., strawberry and apple) conditions. They further demonstrated that the mere 2 min of exposure to indulgent food-related scents induced SSS whereas an exposure of less than 30 s induced SSA. The authors suggested that this effect may have been driven by crossmodal sensory compensation, whereby prolonged exposure to a rewarding food scent induces pleasure which, in turn, diminishes the desire for the actual consumption of indulgent foods.

The mechanisms underlying the differential responses to food-related odours, leading to either sensory-specific satiety (SSS) or sensory-specific appetite (SSA), continue to pose unresolved questions despite ongoing research interest in the field (e.g., Boesveldt & de Graaf, 2017; Chambers et al., 2015). Ramaekers et al. (2014a) postulated that the duration of sensory exposure may be the key factor but fail to establish a clear correlation between exposure time and the resulting appetizing effect. Several other studies suggest that the sensory input from orthonasal odours can be satiating after a long exposure time (Biswas & Szocs, 2019; Jansen et al., 2003; Jansen & Vandenhout, 1991; Rolls & Rolls, 1997; Smeets et al., 2009). However, contrasting evidence also exists: On the one hand, Federoff et al. (2003) detected SSA even with 10–30 min of orthonasal smell exposure, where participants were doing tasks in a room with oven baking either pizza or cookies; on the other hand, Biswas and Szocs (2019) found that a mere 2-min exposure to food-related ambient scents (i.e., cookie odour), where the odour was given out by scent nebulizers that were placed near the entrance of the cafeteria (for more details, see Table 2), could give rise to SSS. Thus, further empirical investigations are warranted in order to elucidate the role of exposure duration as a key moderator underpinning the sensory-specific effects of orthonasal olfactory cues.

When measuring SSS, it is essential to question whether the decline in pleasantness ratings is solely attributable to satiation with specific attributes of the food (i.e., SSS) or also influenced by a diminished desire to repeatedly consume a particular food (i.e., boredom with the concept) (see Piqueras-Fiszman & Spence, 2014, for a review). Zandstra et al. (2004) defined SSS as a decrease in liking resulting from a consumer's satiation with specific attributes of the consumed food. While exposure to food-related odours can elicit hedonic wanting for associated foods, prolonged exposure may eliminate any such hedonic impulse by creating satiation with attributes of the food, such as associated flavour

Table 2
Chronological summary of studies that have investigated the impact of ambient odours on food intake/consumption.

Study	Participants	Measure	Odours	Odour exposure	Key findings
Jansen and van den Hout (1991)	Restrained ($N = 19$) and unrestrained women ($N = 17$) Abstain from eating 1–3h beforehand	Eat as much as they wanted to	Dutch licorice†, English licorice†, cake†, smarties†, nuts†, spiced biscuits†, shortbreads† and soft sweets†	12 min Participants were asked to hold the dishes with the food directly under their noses and to concentrate on the smell of the food	Dietary restraint * Odour: Restrained women ate significantly more after smelling a "preload" than they were not exposed to food smell, while unrestrained women ate marginally less after smelling a "preload" than they did in a no-preload condition
Fedoroff et al. (1997)	Restrained ($N = 49$) and unrestrained women ($N = 42$) *Mage* = 21 years Abstain from eating for 2h beforehand	Taste test (eat as much pizza as liked to evaluate the pizza)	Pizza†	10 min The pizza was baked in the next room and the door to the experimental room was kept ajar	Odour: Intake was higher when participants smelled pizza Dietary restraint * Odour: Restrained eaters ate significantly more than did the unrestrained eaters after exposure to the smell of pizza
Fedoroff et al. (2003)	Restrained ($N = 60$) and unrestrained women ($N = 72$) *Mage* = 21 years Abstain from eating for 3h beforehand	Food intake of pizza or cookies until satisfied	Pizza† Cookies†	10 min The oven baking the pizza/cookies was positioned in the room, out of sight	Odour: Cued conditions led to greater food intake as compared to the no-cue condition Dietary restraint * Odour: restrained eaters showed cue specificity, eating more only when they had previously been cued with that food
Jansen et al. (2003)	Overweight ($N = 16$) and normal-weight ($N = 15$) children *Mage* = 10 years Abstain from eating for 2h beforehand	Taste test (eat as much as wanted)	Sweet and salty snacks: M&M's sugar peanuts†, cake†, Milky Way†, crisps†, and savoury nuts†	10 min Intensely smelling the food	BMI * Odour: Overweight children ate more after smelling tasty foods, whereas normal-weight children reduced food intake significantly after exposure to the same smell of tasty food
Coelho et al. (2009)	Restrained ($N = 59$) and unrestrained women ($N = 57$) M_{age} = 22 years	Intake of cookies (Gourmet chocolate-chip flavour, oatmeal-raisin flavour, and double-chocolate flavour)	Cookies†	12 min, chocolate-chip cookies were baked in a toaster-oven in the room immediately adjacent to testing room	Dietary restraint * Odour: Restrained eaters in the smell cue condition ate fewer chocolate-chip cookies (but not other cookies) than did restrained eaters in the no-cue condition. The chocolate-chip cookie intake of the unrestrained eaters in the cue condition did not differ from no-cue condition
Ferriday and Brunstrom (2011)	Overweight ($N = 52$) and normal-weight women ($N = 52$) M_{age} = 35 years Abstain from eating for 3h beforehand	Pizza intake (ad libitum meal)	Pizza†	1 min Sight and smell of freshly cooked pizza	No observed difference between cue condition and control condition
Larsen et al. (2012)	Normal-weight women M_{age} = 21 years ($N = 109$) Abstain from eating for 3h beforehand	Intake of cookies (3 flavours available: cardamom, ginger, and cinnamon)	Cookies†	1 min or 15 min Cookies were baked in an oven in the testing room	Impulsivity * Odour: Participants with low impulsivity scores ate more when exposed to the odour of baked cookies
de Wijk & Zijlstra (2012)	$N = 22$, 13 females M_{age} = 32 years ("young" group) M_{age} = 51 years ("middle-aged" group)	Food choice test: citrus-congruent (mandarin orange segments and orange juice); vanilla-congruent (vanilla cookies and milk); neutral (cubes of cheese and mineral water)	Citrus* Vanilla*	45 min The scents were vaporized in test rooms	Odour type: only exposure to ambient citrus aroma reduce selection of cheese; exposure to ambient vanilla odour did not affect food choice
Galliet et al. (2013) (Study 1)	$N = 58$, 38 females *Mage* = 27 years	Lexical decision task Menu-based choice task on a restaurant menu card	Melon*	10 min The scent was diffused in the waiting room	Odour: Melon-scented condition led to faster reaction speed for the word "melon" than the control condition; participants primed with melon odour tended to choose starters with vegetables more often than the control group
Galliet et al. (2013) (Study 2)	$N = 70$, 42 females *Mage* = 28 years	Lexical decision task Menu-based choice task on a restaurant menu card Choice of a snack (brownie and apple compote)	Pear*	10 min The scent was diffused in the waiting room	No significant increase in reaction speed to word "pear" in the pear-scented condition Odour: Participants primed with pear odour chose desserts with fruits more often

(*continued on next page*)

Table 2 (*continued*)

Study	Participants	Measure	Odours	Odour exposure	Key findings
Gaillet-Torrent et al. (2014)	*N* = 115, 84 females *Mage* = 26 years	Menu-based choice task on a restaurant menu card	Pear*	15min The scent was diffused in the waiting room	Odour: Participants in the scented condition chose to consume the 'fruity' dessert (apple compote) more frequently than those in the control condition, who chose the dessert without fruit (brownie) more frequently
Ramaekers, Boesveldt, Gort, et al. (2014)	Normal-weight women (*N* = 61) Age range: 18–45 years Abstain from eating for 2.5h beforehand	Ad libitum lunch (3 bread rolls with chosen topping of strawberry jam or chocolate spread, and banana milk shake)	Banana†*	10 min Actively sniffing	Exposure to banana odours did not affect ad libitum intake of banana milkshake
Zoon et al. (2014)	Over-weight (*N* = 25) and normal-weight women (*N* = 25) *Mage* = 33 years	Bogus Taste Test (choices: chocolate paste, peanut butter, strawberry jam, grated cucumber salad, cream crackers)	High-energy: chocolate*, peanut* Low-energy: strawberry*, cucumber* Non-food: fresh green*, wood*	20 min The scents were vaporized in the room	Neither energy intake nor food preference was influenced by ambient exposure to odours signalling different categories
Chambaron et al. (2015)	*N* = 75, 59 females Age range: 18–50 years	Buffet-style lunch food choices	Pain au chocolat†	15 min The pastry was baked in an oven	Odour: participants primed with the odour tended to choose more desserts with high energy density (i.e., a waffle) than those in the control condition
Proserpio et al. (2017)	Normal-weight women (*N* = 32) *Mage* = 21 years Abstain from eating for 3h beforehand	Ad libitum food intake of chocolate rice	High-energy: chocolate* and beef* Low-energy: cucumber* and melon*	30 min The scents were vaporized in the room	Odour: Exposure to beef and chocolate odours increased food intake, compared to control and melon conditions Energy dense * odour: Odours signalling high energy dense food products increased food intake more than the other conditions
de Wijk et al. (2018)	Normal-weight women (*N* = 28) *Mage* = 22 years	Food choice task (white bread/brown bread images) Leeds Food Preference Questionnaire with liking and wanting ratings of food images	Bread* Wood*	Aromas were vaporized with olfactometers while participants doing 3 blocks of rating tasks	Odour: The choice of brown bread images decreased in the presence of bread aroma and increased in the presence of wood aroma; Wanting and liking ratings were not significantly different across conditions
de Wijk et al. (2018)		fMRI			Bread aroma tended to activate the right amygdala and was associated with greater activation in reward regions, compared with wood aroma and control conditions Image types * Odour: Bread aroma induced greater activation for cookies in areas related to reward anticipation; neural differences between bread and wood odours were not reflected in behavioural measures
Ouyang et al. (2018)	*N* = 192, 98 females Age: most <50 years	Food purchases in the restaurant	Basil* Bacon* Hickory smoke*	Participants made their food purchases in the scented environment	Odour type: Basil and bacon aromas did not affect matching food item purchases, but hickory smoke a roma significantly decreased sales of the smoked beef sandwich
Sulmont-Rossé et al. (2018)	Residents with Alzheimer's Disease (*N* = 32) Age range: >75 years	Lunch intake	Meat*	15 min The odour was diffused in the dining room	Odour: Exposure to odours induced a 25% increase in food consumption compared to the control condition, but this effect was not replicated two weeks later with the same priming odour and the same menu
Biswas and Szocs (2019) (Study 1a: field experiment at middle school cafeteria; 1b: lab setting)	1a: Data was based on school (student enrolment of about 900) cafeteria sales 1b: *N* = 216, 109 females *Mage* = 22 years	1a: Lunch food purchase 1b: Food choice of unhealthy (cookies)/ healthy items (strawberry)	1a: Apple*, pizza* 1b: Cookie (indulgent)*, strawberry (non-indulgent)*	>2 min 1a: The odour was vaporized in at the entrance of cafeteria 1b: The odour was vaporized in the test room	Odour *(Un)healthy food choices: 1a: A lower percentage of unhealthy items were purchased when the pizza scent was diffused in the cafeteria, compared to apple or no scent conditions 1b: Cookie scent led to greater preference for healthy food option
Biswas and Szocs (2019) (Study 2)	*N* = 128, field experiment	Food purchase of unhealthy/healthy/ neutral/non-food items	Cookie (indulgent)*, strawberry (non-indulgent)*	>2 min	Odour *(Un)healthy food choices: Exposure to indulgent (vs. non-indulgent) ambient scent led to lower (higher) degree of unhealthy food purchases
Biswas and Szocs (2019) (Study 3)	3a: *N* = 78, 38 females, field experiment	Preference for healthy items and perceived reward	Cookie (indulgent)*, strawberry (non-indulgent)*	>2 min 3a: The odour was vaporized at the	Odour *(Un)healthy food choices: Indulgent (vs. non-indulgent) food scent reduces preference for the

(*continued on next page*)

Table 2 (*continued*)

Study	Participants	Measure	Odours	Odour exposure	Key findings
	Mage = 13 years 3b: *N* = 117, 48 females, lab experiment *Mage* = 22 years			entrance of cafeteria 3b: The odour was vaporized in the test room	unhealthy item, mediated by perceived reward associated with the experience
Biswas and Szocs (2019) (Study 4)	N = 257, 139 females, lab experiment *Mage* = 22 years	Food choice of unhealthy (cookies)/healthy items (strawberry)	Cookie (indulgent)*, strawberry (non-indulgent)*	>2 min (high duration) or < 30s (low duration) The odour was vaporized in the test room	Odour *(Un)healthy food choices* Exposure time: High duration of exposure to an indulgent (vs. non-indulgent) food–related ambient scent decreased choice for unhealthy items Low duration of exposure to an indulgent (vs. non-indulgent) food–related ambient scent increased choice for unhealthy items
Proserpio et al. (2019)	Obese women (*N* = 30) *Mage* = 51 years	Ad libitum intake of low energy dense food products (carrot soup and potato soup)	Bread*	15 min The odour was vaporized in the test room	Odour: The "scented" condition significantly increased the amount of soup eaten compared to the "unscented" condition
Morquecho-Campos et al. (2020)	Normal-weight women (*N* = 32) *Mage* = 22 years Abstain from eating for 3h beforehand	Ad libitum lunch at a salad bar, with 2 options per macronutrient	Carbohydrate: corn*, bread* Protein: duck*, chicken* Fat: butter*, cream* Low-calorie: cucumber*, melon*	3 min Active smelling	Total food intake did not significantly differ between conditions
Morquecho-Campos et al. (2021)	Normal-weight women (*N* = 34) *Mage* = 21 years	Ad libitum lunch at a salad bar, with 2 options per macronutrient	Carbohydrate: bread* Fat: butter* Protein: duck* Low-calorie: cucumber*	3 min Aromas were vaporized in air-conditioned room	Odour priming did not influence the amount of related food eaten in a self-selection from salad bar
Li and Lee (2023) (Study3)	*N* = 161, 70 females *Mage* = 23 years	A taste test with a bowl of M&Ms	Chocolate*	Length of exposure was the same as a video of consuming M&Ms for 33 times A cotton bud with chocolate scented aromatic oil was affixed to the front of the participant's head mounted display	Odour: Participants in the scent present condition consumed significantly fewer M&Ms than those in the scent absent condition

Note. A scent marked with '*' indicates that it is synthetic (i.e., the flavour in mineral oil or fragrance). A scent marked with '†' indicates that it is the natural aroma given off by the food concerned.

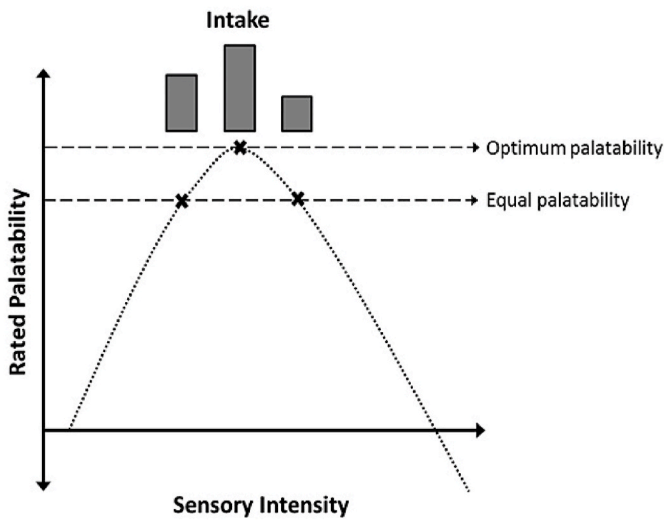

Fig. 2. An illustration of the reported relationship between sensory intensity of taste, rated palatability, and food intake by McCrickerd and Forde (2016).
Note. Adapted from "Sensory influences on food intake control: Moving beyond palatability", by McCrickerd, K., & Forde, C. G. (2016). *Obesity Reviews, 17* (1), 18-29.

properties (Piqueras-Fiszman & Spence, 2014).

The intensity of sensory stimuli can also modulate the effect of SSS. For instance, Vickers, Holton, and Wang (1998) directly compared SSS effects using high-versus low-sweetness yoghurt and observed a more pronounced reduction in liking and sweet food intake in response to high-sweetness yogurt. Meanwhile, McCrickerd and Forde (2016) suggested that taste intensity plays a role in suppressing the intake of foods by modifying changes in food palatability within a meal. Such changes can be assessed through subjective preference for specific foods and the perceived pleasantness of consuming them. As sensory intensity increases, palatability gradually increases to an optimum level, beyond which further increases in intensity become less palatable. This inverted U-shaped relationship, known as the Wundt Curve (see Fig. 2, adapted from McCrickerd & Forde, 2016), suggests that individuals tend to evaluate foods as most palatable when they contain their most preferred sensory concentration (Monneuse, Bellisle, & Louis-Sylvestre, 1991). Once the sensory input becomes excessively intense, it becomes less palatable, thereby reducing the likelihood of food intake (McCrickerd & Forde, 2016).

3. The influence of ambient olfactory cues on food intake

Orthonasal food odours play a significant role in influencing food selection. The valence of these aromas, ranging from unpleasant to pleasant, is considered a crucial dimension in human responses to olfactory cues (Bosmans, 2006; Engen, 1987; Kaeppler & Mueller, 2013). Olfactory signals from ambient scents can induce different food attitudes, activating approach or avoidance behaviours (Bellisle, 2003; Boesveldt & de Graaf, 2017; King, 2013). The sensory properties of foods, particularly their visual and olfactory aspects, have been found to regulate both the choice and quantity of food consumed (de Graaf & Kok, 2010; Sørensen et al., 2003). However, despite the anticipated appetizing effect of food cues, actual consumption behaviours may not always align with individuals' appetites due to factors such as price, shelf life, and dietary restrictions (Bryant, 2023). The discrepancy between anticipatory appetizing effect and actual consumption behaviours highlights the limitations of relying solely on self-reports to assess subsequent food behaviours (Mattes et al., 2005).

While it may be expected that odours with appetite-enhancing effects would influence consumer choice and intake behaviours, the translation of appetite scores to actual consumption is more intricate than initially thought. Conflicting findings exist regarding the impact of olfactory cues on tangible measures of eating behaviour, such as food choices and intake (e.g., de Wijk & Zijlstra, 2012; Zoon et al., 2014). Self-reported attitudes towards foods can differ from an individuals' food choices. Questionnaires may reflect consumers' thoughts but may not reliably predict how individuals will respond behaviourally to orthonasal olfactory cues. For example, de Wijk et al. (2018) embedded their participants in the ambient scents of either wood aroma or bread aroma and found that the smell of bread did not affect participants' liking or wanting for bread. Rather, odours biased the results of the food choice task, where images of brown bread (i.e., whole grain bread) were more often preferred in the presence of non-food odour (i.e., wood aroma), and images of cookies were more often preferred in the presence of a bread odour. Remarkably, de Wijk et al. (2018) also probed participants' brain activity through fMRI when exposed to different aromas. The neuroimaging data suggested that bread odour induced greater activation for cookies images in reward anticipation related areas. Such nuanced distinctions would have been overlooked if only questionnaires were used, highlighting the potential value of integrating neural and behavioural measures when researching odour-induced food behaviours. Similarly, in Morquecho-Campos et al. (2020), participants received a bottle containing an odour stimulus and were instructed to hold the bottle under their nose and breathe normally for 3 min. Odour stimuli encompass a selection of eight odours representing foods of various macronutrient composition (i.e., high in carbohydrates, protein, fat, or low-calorie). The study observed a significant main effect of odour-food congruency on SSA scores (measured with VAS), but no such effect was found when it comes to ad libitum lunch task. Therefore, it is necessary to observe actual food choices and eating behaviours to further examine the influence of orthonasal food-related odours (Köster, 2009; Mors, Polet, Vingerhoeds, Perez-Cueto, & De Wijk, 2018).

3.1. Do aromas elicit sensory specific effects on subsequent food intake?

Orthonasal olfaction can not only influence appetitive responses, but also plays a role in shaping subsequent food choices (see Table 2 for a summary). Many studies have supported the idea that individuals are more likely to choose those foods associated with aromas that they have been exposed to. For instance, Gaillet et al. (2013) investigated the link between the perception of a fruity odour (either melon or pear odour) and subsequent food-relate behaviour. For the first experiment, a melon odorant was chosen as the olfactory prime, which was diffused at a very low intensity that participants did not consciously notice. For the second experiment, a pear odorant was chosen as a representation of a fruit that is mainly consumed as a dessert. Results showed that the group exposed to melon odours increased the selection of fruit and vegetable starters, while pear aromas led to a preference for fruity desserts (Gaillet et al., 2013). These findings can be explained by the concept of odour-induced priming, whereby specific food aromas prime individuals towards the liking and wanting of corresponding food choices. Similarly, Gaillet--Torrent, Sulmont-Rossé, Issanchou, Chabanet, and Chambaron (2014) found that pre-consumption exposure to a pear scent led to an increase in the choice of a fruity dessert (i.e., compote), compared to individuals in the no-odour control group, who chose the brownie option more frequently. Another relevant study by Abeywickrema et al. (2022), although investigating retronasally introduced odour cues rather than orthonasal olfactory cues, reported contradictory results: A high-intensity vanilla odour was associated with increased sensory-incongruent (i.e., sweet) and decreased sensory-congruent (i.e., non-sweet) snack intake, compared to the low-intensity condition. Considering the limited research that has been conducted on the sensory-specific effects of odours on consequential food intake, this study (using retronasal odours) also offered valuable insights into the moderating role of odour intensity in shaping food choices.

There is, however, also evidence to suggest that the link between orthonasal olfactory cues and subsequent food intake may be unreliable. Tetley et al. (2009) exposed their participants to the smell and sight of pizza, which did not result in a larger desired portion size of pizza, even though olfactory perception was found to benefit substantially from visual cues (Gottfried & Dolan, 2003). Another study that also used the odour of pizza as an olfactory stimulus found that it led to greater intake of pizza compared to no-cue condition (Fedoroff et al., 1997, 2003). Notably, Fedoroff et al. specially mentioned in their articles that the odour was coming from pizza that was baked in the next room, while this information regarding the freshness and temperature of pizza was lacking in Tetley et al.'s article. As the smell of fresh hot and cold old pizza is by no means the same (nor equally appealing), it is likely that the null result in Tetley et al. (2009) might have been due to the difference in the pizza's temperature. Future studies that intend to use natural foods as the source of odours should be careful in manipulating the temperature of the foods and should make such information available. More importantly, the participants in Tetley et al.'s study were satiated prior to pizza-cue exposure, while in the other two studies mentioned above participants were asked to abstain from eating for a 2/3h period. There is a high chance that the hunger level moderates participants' cue reactivity to odours.

Additional examples are provided by Ouyang, Behnke, Almanza, and Ghiselli (2018) and Morquecho-Campos et al. (2020) who did not find a significant connection between ambient scents (such as basil, bacon, hickory smoke, and bread) and participants' food choices. In contrast, a study comparing the effects of citrus and vanilla scents revealed that exposure to citrus odour led to elevated mood, increased physical activity, and reduced selection of cheese, while vanilla scent did not affect food choices (de Wijk & Zijlstra, 2012). Even though the two ambient odours, vanilla and citrus, were similar in terms of their appeal and intensity, they produced different physiological, psychological and behavioural effects. Taken together, fruity scents appear to be more effective than other types of food odours in biasing people's food choices. For example, citrus odours were found to decrease the choice of cheese (de Wijk & Zijlstra, 2012). Similarly, the odour of pear increased the tendency of participants to choose fruity desserts over brownies, while brownie, perhaps unsurprisingly, was found to be more popular in the no-odour control condition (Gaillet-Torrent et al., 2014). Additionally, Proserpio et al. (2017) found that melon odour decreased their participants' intake of high-energy dense food (i.e., chocolate rice). Non-food odours were found to supress the appetite of participants (e.g., Kemps et al., 2012; Ramaekers et al., 2014). After exposure to non-food odours (i.e., jasmine, pine tree, and green, which were classified as non-food odours in pilot studies), participants reported a decrease in their appetite compared to the no-odour control condition (see Table 1 for more details). These findings align with the clusters of odour profiles proposed by Castro, Ramanathan, and Chennubhotla (2013), where citrus odours share a chemical profile with lemon, grapefruit, and orange. Wood and leaf odours belong to another cluster consisting of different compounds. Previous experimental results show that individuals are more likely to respond strongly to specific compounds within the "citrus" cluster, leading to a more pronounced appetizing effect (Hewson, Hollowood, Chandra, & Hort, 2008), while compounds in the "woody" category appear to inhibit appetitive responses.

3.2. Nudging healthy and unhealthy food choices with odours

There is a growing concern about unhealthy patterns of eating behaviour and rising obesity rates worldwide. Previous authors have sought to investigate the relationship between the senses and unhealthy eating, looking at what leads to unhealthy food choices and those factors that may help to curb the intake of unhealthy foods (e.g., Biswas & Szocs, 2019; Chambaron, Chisin, Chabanet, Issanchou, & Brand, 2015; Joyner, Kim, & Gearhardt, 2017; Li & Lee, 2023; Paakki et al., 2022). Biswas and Szocs (2019) proposed the cross-modal sensory compensation effects of ambient scent on food purchases, suggesting that humans can become satiated by prolonged sniffing which in turn diminish the craving for unhealthy foods (please see more detailed discussion in section 2.2). These findings highlight the possibility of employing scents to encourage healthier diet.

As summarized in Section 3.1, the current review highlights the potential role of fruity and woody odours in encouraging the choice of healthy foods and in regulating people's food intake. Notably, studies have demonstrated the effectiveness of fruity odours, such as citrus and pear, in influencing choices towards taste-related properties, while the odour of melon has shown potential in controlling the consumption of high-energy dense food products, as exemplified by the findings of Proserpio et al. (2017). These discoveries hold promising implications for the food industry, inspiring the incorporation of fruity odours to promote healthier product choices.

4. Individual differences in the perception food-related odours

4.1. Dietary restraint and BMI

Previous experimental studies on odour-induced SSA, SSS, and subsequent food choices have tended to group the participants according to their diets and/or BMI in order to investigate how dietary differences, specifically dietary restraint, and BMI moderated the perception of orthonasal olfactory cues. Restrained eaters (or overweight individuals) exhibit a heightened appetite and intake response when explicitly exposed to food cues compared to unrestrained eaters (or individuals with normal weight; see e.g., Cecchetto et al., 2022; Coelho et al., 2009 Fedoroff et al., 1997, 2003; Ferriday & Brunstrom, 2011). Restrained eaters demonstrate particular responsiveness to food cues, as evidenced by increased salivation in response to visually and olfactorily attractive food cues (Klajner, Herman, Polivy, & Chhabra, 1981; Legoff & Spigelman, 1987). Both a 5-min and a 10-min exposure to orthonasal olfactory food cues before eating stimulated increased consumption in dieters than in non-dieters (Jansen & van den Hout, 1991). A similar SSA effect was also observed with 10-min exposure to the odour of cookies amongst restrained eaters but not unrestrained eaters (Coelho et al., 2009).

Researchers have also explored the associations between obesity and cue reactivity, assessing changes in appetite, hunger, and salivation responses to food-related odours. For odour thresholds, meta-analysis suggests a trend of declining olfactory detection ability with increasing weight (Peng et al., 2018). Inspection of the results from individual studies similarly suggested that the overweight group generally had higher threshold scores (i.e., poorer sensitivity) compared with the healthy-weight group. For instance, Simchen et al. (2006) observed that, normal weight individuals showed higher olfactory sensitivity as detected by the European Test of Olfactory Capabilities based on 16 food-related odorants as compared to overweight participants. Experimental results showed that normal-weight children, but not obese children, demonstrated reduced intake of palatable sweet and savoury snacks after a 10-min exposure to the corresponding food odours compared to a no-odour condition (Jansen et al., 2003). Furthermore, a subsequent study investigating the effect of pizza odour found that exposure to the scent associated with pizza increased wanting for pizza and other savoury foods (e.g., scrambled eggs, chips, beans) among overweight participants, while concurrently decreasing desire for sweet foods (e.g., cake, chocolate buttons; Ferriday & Brunstrom, 2011). Interestingly, Cecchetto et al. (2022) used a liking and wanting task as an explicit measurement of appetitive response and used heart rate and skin conductance as implicit measures. They found that individuals who were overweight/obese explicitly rated food odours as less likeable than non-food odour but paradoxically expressed comparatively higher level of liking implicitly compared to explicit report.

The heightened reactivity to olfactory cues in those individuals with a higher BMI aligns with Schachter's (1968, 1971) "externality-theory". Originally proposed to explain the eating behaviours of obese individuals, the theory suggests that the obese are more susceptible to environmental, food-related cues, influencing their attitude toward foods, leading to increased craving for foods, and making them prone to overeat. Consequently, it has been proposed that individuals characterized with a higher BMI are associated with a lower responsiveness to internal stimuli (e.g., the physiological responses of hunger and satiety) and a higher sensitivity to external stimuli (e.g., food-related smells). From this perspective, cue reactivity to external food stimuli could be a potential predisposing factor for overeating. It has also been suggested that for obese individuals, external sensory cues such as orthonasal smell of food (here referred to as the hedonic appeal of food) can override the internal/physiological signals of hunger and satiety (see e.g., Herman & Polivy, 2008; Hirsch & Gomez, 1995; Stafford & Whittle, 2015).

4.2. Trait differences

Individual traits, such as hunger state, impulsivity, olfactory functionality, and sex may influence the response to food cues (e.g., Cecchetto et al., 2022; Coelho et al., 2009; Fedoroff et al., 1997, 2003; Ferriday & Brunstrom, 2011; Jansen et al., 2003; Larsen et al., 2012; Ramaekers et al., 2014a; Rogers & Hill, 1989). While hunger state was assumed to moderate the relationship between olfactory cues and subsequent food-related behaviours, Zoon et al. (2016) indicated that for the 29 healthy-weight females in their study, hunger state was not a significant moderator of the sensory-specific appetizing effect. Surprisingly, though previous researchers assumed that people with high impulsivity should be taking in more food when they are cued with food odours, experimental results showed that low-impulsive females actually consumed more, though they did not salivate any more, when confronted with an olfactory food cue than no-aroma control.

Genetic differences have also been found to contribute to individual differences in odour perception, potentially impacting participants' sensitivity to food cues and subsequent food choices. Zang et al. (2019) compared participants with olfactory dysfunction to heathy controls and found that individuals with olfactory dysfunction rated food odours (chocolate, peanut, and lemon) as less pleasant, intense, and less appetizing. In addition, the sex of individuals plays an important part in determining their olfactory abilities. Although there are conflicting findings, most studies suggest that females generally outperform males in tasks related to odour detection, identification, discrimination, and memory (Brand & Millot, 2001; Doty & Cameron, 2009; Hummel, Kobal, Gudziol, & Mackay-Sim, 2007; Spence, 2019). Considering this difference, most studies have primarily included female participants (e.g., Cecchetto et al., 2022; Morquecho-Campos et al., 2020, 2021; Proserpio et al., 2019), resulting in an underrepresentation of males in the experimental results, which limits the generalizability to the overall population.

4.3. Cultural differences

The effects of odours, both psychological and physiological, are not fixed but rather vary depending on previous experiences and cultural contexts. For example, the aroma of Limburger cheese is initially disliked but appreciated with repeated exposure, and while the odour of wintergreen is generally liked in the United States of America, it tends to be disliked in Europe (Herz, 2009). Odour perception is highly dependent on previous experience, to the extent that the same sensory stimuli can evoke distinctive hedonic responses across different cultures. Ayabe-Kanamura et al. (1998) conducted a study on odour perception of natural everyday odours, involving two populations, Japanese and German. The results revealed significant differences between Japanese and German participants in their ability to provide descriptors, familiarity ratings, and pleasantness judgements of diverse odours, especially soy sauce, dried fish, soybeans, beer, pine wood, Japanese tea, anise, and almond.

Food preferences are learned behaviours, shaped by prior food experience that are highly related to cultural backgrounds. Fish-eating cultures (Japanese, Eskimo's) have completely different priorities in what they like and dislike from cassava eating cultures (Brazilian Indians) or French citizens (cf. Youssef et al., 2019). Therefore, whether olfactory cues will lead to expected food behaviours depend on the (learned) relation to the expected post-ingestion intestinal satisfaction, rather than the nature of the sensory stimulation itself. As an example, Proserpio et al. (2019) found that pre-consumption exposure to the odour of bread (vaporized in the testing room) increased the amount of vegetable soup consumed by the participants. According to the authors, in Italy, where the study took place, vegetable soups usually go together with bread, and this combination is regarded favourably. However, such a relationship may not be observed in other cultures where the bread-soup match is absent in the food culture. Hence, it is crucial for food industries to consider the taste-smell expectations that is embedded within specific cultural backgrounds.

5. Implications: the power of food odours in scent marketing

The use of scents in sensory marketing, known as "scent marketing," has been widely adopted by retail companies' marketers to enhance product perception, purchasing behaviours, and consumer responses (Herz et al., 2022; Lawrence, Salles, Septier, Busch, & Thomas-Danguin, 2009; Salles, 2006; Shiner, 2020; Spence, 2022b, 2022d). Food odours have been a popular tool in sensory marketing for over four decades (Wysocki, 1979). Nassauer's (2014) article in *The Wall Street Journal* highlighted various cases where companies intentionally used scents as marketing tools. Food marketing companies invest substantial efforts in creating lingering food odours. For example, Cinnabon, the bakery restaurant known for cinnamon rolls, strategically places ovens near the store entrance to entice customers with the smell of warm cinnamon rolls as the doors open. The company prefers locations on the ground floor near stairwells in malls, allowing the odour to waft to upper floors Besides location, Cinnabon acknowledges the importance of regularly releasing scents. They bake rolls every 30 min and heat additional brown sugar and cinnamon to keep the odour in the air. The company's R&D manager also avoids strong-smelling ingredients such as garlic and onion to prevent overpowering the smell of rolls. These tactics can be considered as methods used by food companies to reduce consumers' control over their food behaviours, enticing them to visit their stores and pay for the experiences associated with the pleasant scent. However, it is worth noting that odours that have come to be associated with high-energy density foods may not always be desirable. In 2008, Starbucks temporarily ceased selling paninis due to the strong odour of grilled and occasionally burnt cheese interfering with customers' enjoyment of their coffee. After six months of adjustments, including the use of leaner bacon, higher-quality ingredients, and a lower cooking temperature, the paninis were reintroduced to their stores, but now with a less intrusive odour.

In addition to retail stores, previous studies have explored the positive effects of ambient scents in restaurants on customers' dining experiences, including perceived food quality (e.g., Ouyang et al., 2018) and the amount of money spent (e.g., Guéguen & Petr, 2006). Another interesting research investigated the impact of food-related scents applied to wait staff as body odours scents on wait staff as body odours (Singh et al., 2019). Singh and colleagues conducted an experiment in a mock restaurant where wait staff wore fabric aprons scented with either smoky barbecue scent, perfume, or no scent. The results showed that scented conditions did not influence consumers' menu choices or flavour perception of chicken meat items. However, female participants rated their overall liking and meal satisfaction higher when the wait staff wore perfume as compared to the no-scent condition. These female participants, however, gave larger tips to wait staff with smoky chicken scent compared to the no-scent control group and perfume group. This study demonstrated that wait staff scents can lead to different outcomes, and restaurants can choose scents for their staff based on the desired behavioural responses from customers. Such findings provide new avenues for restaurants to gain attention in the highly competitive food industry. These findings open up new possibilities for restaurants to gain attention in the highly competitive food industry. Even if food odours do not have the desired effect in terms of attracting or pleasing customers to the extent researchers and merchants hope, the application of ambient food scents in restaurants, or even on staff, can still serve as a potential media marketing strategy.

In recent years, olfactory marketing campaigns have been implemented in various forms of public transportation. A notable instance of olfactory marketing took place on Highway 150 in Mooresville, North Carolina, where a billboard for Bloom, a division of Food Lion grocery store, emitted a scent resembling black pepper and BBQ through a fan positioned at its base. This scent was dispersed during peak commuter traffic hours, with the intention of eliciting associations of hickory-smoked barbecue and steak among passing motorists (Aronoff, 2010). Similarly, in Seoul, South Korea, scent dispensers installed on city buses responded to the Dunkin' Donuts jingle on the radio by releasing a coffee aroma. The "Flavour Radio" campaign aimed to prime passengers to visit Dunkin' Donuts stores after disembarking from the bus, resulting in increased coffee sales and footfall at nearby branches (Garber, 2012). Other examples include ambiently scenting parts of the Glasgow subway with a sweet lemon odour to promote Tennent Caledonian's Lemon T. drink (McEleny, 2016; Sutton, 2018, pp. 132–139). However, the success of such campaigns has varied markedly. For example, an olfactory marketing campaign for Amaretto di Saronno liqueur in the London Underground aimed to release the drink's almond odour into the ventilation system. Unfortunately, the campaign coincided with a newspaper article warning commuters about recognizing almond-like smells as they are associated with cyanide, resulting in the campaign being discontinued after a day (Jury, 2002; Lim, 2014).

Overall, the impact of food odours on consumption behaviours, as demonstrated through scent marketing, highlights the importance of creating a multisensory experience that goes beyond taste and visual cues (Barwich, 2019). The presence of an olfactory cue has been found to positively influence purchase behaviour, leading to increased product and product-category sales. Retailers are encouraged to consider implementing scents at the point of purchase as a sales promotion tool, with a focus on targeting a product category rather than a single product (Bonini, Graffeo, Hadjichristidis, & Perrotta, 2015; Kivioja, 2017). This approach suggests that the scent used in the store should be congruent with the overall product category, maximizing its effectiveness in terms of attracting and engaging customers. By harnessing the power of scent marketing, retailers can create a memorable and immersive shopping experience that drives consumer satisfaction and increases sales. Recent advancements in virtual reality tools have emerged new possibilities for incorporating the sense of smell in this field (Pizzoli, Monzani, Mazzocco, Maggioni, & Pravettoni, 2022).

6. Conclusions

Food marketers have long operated under the assumption that orthonasal food-related olfactory cues increase appetite and food intake. However, as presented in this review, such intuitive relationships have failed to stand up to experimental scrutiny in more than half of the published studies. Though olfaction-induced SSA and SSS have been investigated for more than two decades, researchers continue to repeatedly examine those factors that have been shown to exert no clear modulatory effect, such as the means of scent exposure (either through active sniffing or passive environmental exposure). Additionally, researchers have tended to focus on examining the effect of a small number of olfactory cues (cookie and pizza odours appear to be very popular) with the rationale that such odours are common in daily life. But, as the review shows, certain categories of food-related aromas are more consistent in their ability to modulate individuals' food-related behaviours. Examples of such odours include fruity aromas and woody smells. Future study should therefore consider following a more systematic categorization of food-related scents when designing experimental conditions rather than sticking to one or two frequently used ones.

Due to the scarcity of evidence of the role of orthonasal olfactory influences on consumers' food behaviours, it should be questioned whether environmental food odours have demonstrated the effects food marketers hope for. The smells may even be counterproductive. Further research is invited to examine the effect size of orthonasal olfaction induced SSA and SSS, and the relative percentage explained by ambient olfactory cues and other factors (e.g., the price of foods and dietary preferences of participants). At this juncture, the results in the field of orthonasal olfactory research are too inconsistent to provide clear guidance for food marketers to translate ambient odours into taste expectations, and thus proceed to purchase decisions.

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Author contributions

All parts of the manuscript were written by T.Z. & C.S.

Ethical Statement

Hereby, I, Tianyi Zhang, consciously assure that for the manuscript Orthonasal Olfactory Influences on Consumer Food Behaviour the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

The violation of the Ethical Statement rules may result in severe consequences.

To verify originality, your article may be checked by the originality detection software iThenticate. See also http://www.elsevier.com/editors/plagdetect.

I agree with the above statements and declare that this submission follows the policies of Solid State Ionics as outlined in the Guide for Authors and in the Ethical Statement.

Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

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