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Olfactory notes in the mind space: A registered report

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ABSTRACT

Olfaction is an archaic sense but its central mechanisms are lesser known than those of other senses. Here we address a possible link between olfactory stimuli and mental spatial representations. Although olfactory percepts are not commonly related to space, perfumiers tend to describe scents in terms of top/head or base notes and arrange them vertically on olfactory pyramids, with the most volatile on top. We tested whether odors evoke in naïve participants a mental vertical representation dependent on odor quality, in the absence of explicit references to elevation. In a speeded choice classification task, 110 participants pressed one of two vertically aligned buttons in response to fruity or gourmand odors. A spatial stimulus-response compatibility (SRC) effect was expected to emerge from compatible versus incompatible mappings of stimuli to responses, due to the hypothesised dimensional overlap. However, the preregistered contrast on means of median correct responses neither confirmed the presence of a vertical SRC effect at the group level, nor provided conclusive evidence for its absence. An analogous exploratory test on means of restricted means supported the presence of the predicted effect but its Bayesian counterpart found the outcome inconclusive. Exploratory analyses revealed three distinct clusters of participants with regards to the vertical SRC effect for odors, with two (N = 61 and N = 19) showing a significant effect in the expected direction and one (N = 30) showing a significant effect in the opposite direction. These results call for replications that factor in potential sources of individual differences.

1. Introduction

Humans generally do not think of their sense of smell in spatial terms intuitively, unlike for vision, and much effort in past research on human olfaction has been directed to other core aspects such as odor pleasantness and quality (e.g., Gottfried, 2010; Yeshurun & Sobel, 2010). When considering animal behavior, however, the sense of smell plays a major role in extracting spatial information from the environment (Ackerman, 1991; Jacobs, 2012; Porter et al., 2005; Thesen et al., 1993). Although other mammals may be equipped with a more extensive range of olfactory receptors than humans, humans are able to perform more sophisticated cognitive processing due to larger central olfactory regions (Buck et al., 2021;

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Shepherd, 2004). Scientific evidence increasingly suggests that humans can assign spatial coordinates to incoming olfactory stimuli via modality-specific mechanisms sharing several features with those of the auditory domain (e.g., Porter et al., 2005; Porter et al., 2007; Von Békésy, 1964). Moreover, a strong relationship has emerged recently between olfaction and spatial memory in humans; in particular, the ability to identify odors has been found to covary with navigation abilities requiring the creation of cognitive maps (Dahmani et al., 2018). Since olfaction tends to be neglected and undervalued compared to other senses (Hansson, 2023; Shepherd, 2004), a more in-depth knowledge of its contribution to spatial cognition and mental representations of space allows for a re-evaluation of the role of olfaction and olfactory stimulation in higher functions and their potential use for improvement and rehabilitation (e.g., to improve or rehabilitate learning and memory, increase information processing without additional cognitive overload and reduce response times; Morrin & Ratneshwar, 2000; Vance et al., 2024; Washburn et al., 2003, Washburn and Jones, 2004). It could help promote the development of more effective tools to support or stimulate spatial memory in those with sight- and hearing-related disabilities or with cognitive decline (Pereira & Burnett, 2003; Silva & Martínez, 2023). It could also inform the creation of visual-to-olfactory sensory substitution devices for the blind that convert visual images into olfactory images (or odorscapes) by mapping visual features via olfactory cues, as previously done via auditory stimuli (see e.g., Bordeau et al., 2023; for visual-auditory substitution). Further, it could suggest new avenues for the integration of olfactory stimulation with other sensory modalities, in order to enhance users' quality of experience via mulsemedia – the forefront of multimedia. Indeed, to achieve optimum interaction, the various media sensory channels must be coordinated in a clear and informative way (MacLaverty & Defee, 1997). Synchronization of olfaction-enhanced multimedia is non-trivial and rests on the possibility of creating metadata and models of the relationship across different modalities, different stimuli and their combinations, with a specification of temporal, spatial and content relationships (e.g., Murray et al., 2016).

The Nobel laureate Von Békésy (1964), based on the observation that binaural comparison enables sound localization in the horizontal plane (e.g., Yost & Dye, 1997), hypothesised that the existence of two nostrils could similarly enable odor localization. He observed that even a slight onset asynchrony of .3 msec was sufficient to move the perceived location to the side of the nostril that was stimulated first. When keeping onset and duration fixed, a change of 10% in concentration was sufficient to induce localization to the side of the nostril receiving the higher concentration. Von Békésy (1964) concluded that directional smelling is based on the combined analysis of temporal delay and concentration differences between the two nostrils, as the direction of a sound source can be determined binaurally from time and loudness differences. Centrally, neither olfactory nor auditory experiences are spatially structured in the same way as visual experiences are. The neurons within area V1 are retinotopically organized following a spatial polar coordinate system (Holmes, 1945; Horton & Hoyt, 1991). Along the horizontal direction in the primary visual cortex, the representation of the visual field shifts from the center (in the posterior part) to the periphery (in the anterior part) of the visual field, and in the vertical direction from the upper vertical meridian (in the lower lip of the calcarine cortex) to the lower vertical meridian (in the higher lip of the calcarine cortex; Engel, 1971). This reflects and preserves a characteristic of the sensory surface, as the location of a stimulus is directly mapped onto the retinal surface. In both the auditory and the olfactory systems, instead, some intrinsic characteristic of the stimulus, such as sound frequency or an odorant's physicochemical properties, but not its location, appears to be mapped onto the sensory surface (e.g., Guild et al., 1931; Ressler et al., 1993, 1994). Thus, spatial information in audition and olfaction needs to be reconstructed from inputs conveyed by binaural hearing and birhinal smelling up to a cortical representation (Stevens & Marks, 1965). A tonotopic organization is found at the receptor level of the auditory system, with low-frequency sounds mapped at the apex of the helicotrema and high-frequency sounds mapped at the base of the cochlea near the oval window (Pratt, 1930). Subsequently, the stimulus is processed in the primary auditory cortex and other subdivisions that are organized topographically with respect to frequency selectivity by strongly tuned neurons and respond selectively to pure tone frequencies over the narrow range of the audible spectrum (Adams et al., 1997; Head & Holmes, 1911; Mountcastle & Darian-Smith, 1968). Olfactory perception stems from the presence of volatile molecules ascending into the nasal cavity and reaching the epithelium in its upper part, where the olfactory receptors are located. The volatility of a substance impacts the total number of molecules that will be able to reach the olfactory epithelium, and can produce consequences at the perceptual-behavioral level. For example, in a study conducted in animal models, namely mice, it was observed that the higher the volatility of the substances to which they were pre-exposed in the retronasal conditioning phase, the more efficient they were at learning to recognize and discriminate the same substances by the orthonasal route, compared to substances with low volatility (He et al., 2021). Once the olfactory stimulus reaches the olfactory epithelium, based on its physicochemical properties it elicits activations that produce signals characterized by a temporal component, reflecting the more or less rapid binding of molecules and interactions with the receptors (Buck, 2000). Subsequently, this information is sent to the glomeruli located at the level of the bulb that form, from the input received from the olfactory receptors, spatiotemporal patterns that will be used in the following processing of the stimulus in the piriform cortex (Stevenson & Wilson, 2007). The piriform cortex is selectively involved in coding the structural characteristics (e.g., the functional group in the molecular structure) and the qualitative features of the olfactory stimulus (unique characteristics such as its perceptual character, e.g., mintiness, sweetness, as opposed to other perceptual characteristics, such as intensity or pleasantness; Gottfried et al., 2006; Gottfried, 2010; Scott et al., 2014; Sobel et al., 1999).

It has been demonstrated that the two nostrils, via active sniffing (Mainland & Sobel, 2006), inhale air from different, non-overlapping areas of space and at a different rate (Porter et al., 2007; see also Mainland & Sobel, 2006). The nostril with higher airflow is better tuned to odors with a higher rate of absorption (e.g., limonene; Scott et al., 2014), while the nostril with lower airflow is better tuned to odors with a lower rate of absorption (e.g., vanillin; Scott et al., 2014; Sobel et al., 1999). This reveals a strong similarity to the receptive fields in vision and audition, where, both eyes and ears provide a slightly offset image of the sensory content to help, in vision, to obtain depth perception, while in audition and, supposedly, in olfaction, to enable spatial localization (Zelano & Sobel, 2005). However, whereas in the visual system the location of a stimulus is mapped directly onto the sensory surface (i.e., the retina), in the auditory and in the olfactory system it is an intrinsic characteristic of the stimulus, such as sound frequency in the case of audition and physicochemical properties in the case of olfaction to be mapped onto the sensory surface (e.g., Guild et al., 1931; Ressler et al., 1993, 1994). Consequently, the localization of sound or odor sources, as tested in typical laboratory conditions where the head is kept still, is reliant on cues extracted from the interaction between a stimulus's intrinsic qualities and the external ears or nostrils (Porter et al., 2007; Wallach, 1940; Wightman & Kistler, 1999). Such cues must then be analyzed by central mechanisms and integrated in order to build a representation of the auditory and olfactory spaces (Bao et al., 2019). Interaural and birhinal differences in stimulus time and intensity can help localize sources on the horizontal axis but they are less informative regarding the possible location along the vertical axis (Oertel & Wang, 2021; Von Békésy, 1964; Yost & Dye, 1997). In auditory processing, fewer cues are available to identify spatial elevation, which under passive conditions is largely based on spectral shape cues (Middlebrooks, 2015; Wightman & Kistler, 1997; Yost, 2007). It is also well known that intrinsic qualities of the auditory stimulus, such as pitch height (corresponding to our perception of the fundamental frequency of a sound), are able to evoke a subjective experience of spatial elevation (Stumpf, 1883) - this, according to some authors, may reflect learned environmental regularities, although the issue is not yet settled (e.g., Parise et al., 2014; Pratt, 1930). Since Pratt's (1930) initial inroads (see also Mudd, 1963; Trimble, 1934), numerous studies have shown that high and low auditory pitches tend to be preferentially associated to high and low positions, respectively, in a way that may also influence behavioral performance and does not depend entirely on musical experience, on the explicit use of a localization task or spatial labels, or on the individual ability to read and write musical notes (Umiltà et al., 2018). This phenomenon has wide-ranging implications: from a natural enrichment of music listening and performance, to the employment of auditory cues for the rehabilitation of visuo-spatial attention deficits or for helping the visually impaired to navigate, to mention just a few (e.g., Ishihara et al., 2013; Lippman, 1963; Lloyd-Esenkaya et al., 2020). While a number of studies have investigated the localization of odors on the horizontal axis suggesting a strong analogy with the auditory system (Frasnelli et al., 2009, 2012; Porter et al., 2005, 2007), very little is known about whether intrinsic qualities of the olfactory stimulus can evoke representations of spatial elevation, similar to those documented with the fundamental frequency of sound for auditory stimuli. This study aims to throw light onto this aspect.

To this effect, the literature on crossmodal correspondences between olfactory and auditory stimuli has been considered, in order to identify which property of the olfactory stimulus could entertain a relation with spatial elevation. Crossmodal correspondences are phenomena in which associations occur systematically and consistently between different dimensions or attributes in different sensory modalities, and reflect operating principles or heuristics that determine the patterns of activity and organization of our brain (Spence, 2011). Not all possible dimensions can give rise to crossmodal correspondences though, and to date four, non-mutually exclusive, explanations have been identified as their potential basis (structural, statistical, linguistic, emotional; Spence, 2011). The specific type of crossmodal correspondences we will refer to here might be an example of structural correspondence (Deroy et al., 2013). Interestingly, consistent crossmodal correspondences have been documented between certain odors that differ in quality (that is, their perceptual character, such as mintiness, sweetness; Gottfried, 2010; Howard et al., 2009) and the auditory dimension of pitch height (Belkin et al., 1997; Crisinel et al., 2013; Crisinel & Spence, 2012; Persson, 2011; Stevenson et al., 2012; Ward, Wuerger, & Marshall, 2022). However, it is still unclear which feature(s) or dimension(s) of the olfactory stimuli would generate such a match, and there is an open question as to what the mechanism underlying such a mapping might be. More recently, studies conducted through the use of an electronic nose have indicated the physicochemical composition of the olfactory stimulus as one significant factor in the generation of such crossmodal correspondences, and more relevant than temperature, pleasantness and intensity (e.g., Ward, Rahman, et al., 2022, 2023). With regard to the underlying potential mechanism, crossmodal correspondences between odors and sounds can hardly be rooted in the internalization of the statistical regularities of the environment, as it is unlikely that sounds and odors co-occur systematically in everyday life. Moreover, the use of shared linguistic terms to describe both sound pitch and odors, would seem unlikely as the primary cause of this crossmodal correspondence. Indeed, perfumery experts refer to the olfactory “notes” of a fragrance but this is not a common practice among non-experts, and yet the systematic association between odors and pitches appears to emerge in participants with no specific fragrance experience. Deroy et al. (2013) went so far as to suggest that the mapping between odors and pitch height can be better understood as a genuine case of structurally-based crossmodal correspondences. They proposed that odors and tones might share some structural features, such as the dimension of spatial elevation. While it is true that odors and tones do not share specific linguistic terms in common parlance, both odors and tones can be classified in terms relating to the dimension of spatial elevation: in the case of tones, we commonly refer to high tones and low tones, while in the case of odors, perfumery experts use the terms top/head notes and base notes to refer to odors (as

Fig. 1 – Example olfactory pyramid. Scents can be technically visualized via olfactory pyramids, with component odors classified, for example, as top or base notes depending on their position on the pyramid; they are positioned on the pyramid according to their relative volatility.

components of a complex perfume) with high and low volatility,[1] respectively. It is also noteworthy that both odors and tones are represented visually in an orderly manner along the vertical axis by the respective field professionals. Among perfumery experts, odors are mapped on an olfactory pyramid according to their volatility, whereby odors with the highest volatility occupy the highest position while odors with the lowest volatility occupy the lowest positions (a typical representation is shown in Fig. 1).[2] Similarly, in the musical notation system, the pitch of a sound is related to the position on the staff. The use of terms and graphical representations that express an intuitive recall to spatial elevation suggest that, as in the case of the widely demonstrated correspondence between pitch height and spatial elevation, even odors could induce a subjective experience of spatial elevation. Moreover, looking closely at the data in the literature on odor-pitch correspondences, a connection emerges between the position of odors in the olfactory pyramid and their crossmodal association with tones. Notes commonly placed at the top of the olfactory pyramid such as lemon, orange and bergamot, belonging to the citrus fruit olfactory category (Di Nicolantonio et al., 2022), are typically associated with higher tones, whereas base olfactory notes such as caramel, vanilla and coffee, grouped in the gourmand category, are typically associated with lower tones (Belkin et al., 1997; Crisinel et al., 2013; Crisinel & Spence, 2012; Speed et al., 2021; Stevenson et al., 2012; Ward, Wuerger, & Marshall, 2022). According to the structural hypothesis, crossmodal correspondences come from the presence of common or analogous neural substrates coding for the same specific dimension across sensory modalities. In fact, to date crossmodal plasticity phenomena are widely known, where indeed primary sensory cortices may respond to other sensory modalities or otherwise their functioning is shaped by stimuli presented in other sensory modalities (Teichert & Bolz, 2018). Thus, as an increase in stimulus intensity is normally related to an increase in neuronal firing rate regardless of the stimulus modality (Stevens, 1957) and this is thought to underpin the crossmodal association between auditory loudness and visual brightness (Stevens & Marks, 1965), it is plausible that in sound pitch and olfactory quality of odors their respective principal perceptual axes may be related to a vertical structural representation.

Numerous studies have investigated crossmodal correspondences between tonal pitch and spatial elevation at the behavioral level, highlighting how the common graphical and linguistic references to the spatial dimension may not be just metaphors (e.g., Evans & Treisman, 2010; Rusconi et al., 2006). The matter of correspondences between odors and spatial elevation, instead, appears to have been addressed so far only in one recent study (Caldana & Rusconi, 2023). The study was guided by the hypothesis of a dimensional overlap between odors and spatial elevation and adopted a behavioral approach (as opposed to self-report). It predicted that a preferential mapping could be found in the olfactory domain, between odors that are known to be crossmodally associated with pitch (high or low) and vertically aligned responses. Participants performed a two-choice odor categorization task by pressing one of two response buttons. Response buttons were aligned with the vertical meridian of the participant (one in a higher, one in a lower position) and the hand operating each button was balanced within participants across blocks of trials. No explicit reference to spatial elevation was introduced in the experiment. The results showed a preferential mapping of a category of stimuli (identified as "fruity"), that have been individually associated to high pitch in the literature on crossmodal correspondences, onto the higher response button, and a preferential mapping of a category of stimuli (identified as "gourmand"), that have been individually associated to low pitch in the literature on crossmodal correspondences, onto the lower response button. This vertical spatial stimulus-response compatibility effect (SRC) effect was not correlated with subjective ratings on pleasantness, intensity, lightness/heaviness of the stimuli. Thus, the authors concluded that the evidence is consistent with the existence of an internal spatial representation evoked by odor quality, inducing a preferential mapping between odor categories and spatial responses (Kornblum et al., 1990). They also suggested that a possible factor in connecting odors to vertical elevation may be volatility and judged unlikely a role of semantics instead. However, the authors highlight that the

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[1] Volatility is here used to indicate the tendency of a substance to evaporate or the speed at which it evaporates. Different odor molecules can diffuse into headspace, that is, they evaporate and reach the nasal cavity at different speed. Odors with lower volatility evaporate to a smaller degree and only a few of their molecules are carried away by the airstream (Brandstaetter et al., 2010).

[2] The idea of an olfactory pyramid was introduced in the industry by Aimè Guerlain in 1889, to describe the relative volatility of the component notes in his new perfume, Jicky (Martone, 2019).

Table 1 – Design table.

Question	Hypothesis	Sampling plan (e.g., power analysis)	Analysis plan	Interpretation given to different outcomes
EXPERIMENT 1 Will odors crossmodally associated to high pitch (lemon, orange, bergamot) and low pitch (coffee, caramel, vanilla) generate a vertical stimulus-response compatibility effect in a choice RT task requiring odor categorization?	COMPATIBLE condition (C) = fruity odors/top button OR gourmand odors/bottom button INCOMPATIBLE condition (I) = gourmand odors/top button OR fruity odors/bottom button H_1: Means of median RTs in I will be significantly slower than means of median RTs in C $H_{0(1)}$: No evidence for the predicted difference between means of median RTs in I versus C	Target sample size: 110 participants, after exclusion of those reporting professional experience or less than 50% correct responses. Study power = .90, $\alpha = .02$ (one-tailed) to detect an effect size $d_z = .321$ ($d_z = .329$ if non-parametric analysis is used)	Main, preregistered analysis: One-tailed *t*-test (if normal distribution according to Kolmogorov–Smirnov test) or Wilcoxon signed-rank test (if significant deviation from normality) on means of median correct RTs in I versus C Planned secondary analysis: Bayesian *t*-test (or Wilcoxon signed-rank test, if Kolmogorov–Smirnov test for deviations of normality is significant) with JZS prior between means of median correct RTs in I versus C: I > C	1. $H_{0(1)}$ rejected: Evidence for a preferential mapping between odors and spatial elevation 2. $H_{0(1)}$ not rejected: No evidence for the predicted preferential mapping between odors and spatial elevation $BF_{10} \geq 5$ Moderate evidence for a preferential mapping between odors and spatial elevation → study 2 will be initiated $1/5 \leq BF_{10} \leq 5$ Inconclusive evidence → study 2 will not be initiated $BF_{10} \leq 1/5$ Moderate evidence for the absence of a preferential mapping between odors and spatial elevation → study 2 will not be initiated
EXPERIMENT 2 (conditional to rejection of the null hypothesis in Experiment 1) Does the documented compatibility effect depend on relative odor volatility?	COMPATIBLE condition (C) = citrus odors/top button OR fruity odors/bottom button INCOMPATIBLE condition (I) = fruity odors/top button OR citrus odors/bottom button H_2: Means of median RTs in I will be significantly slower than means of median RTs in C $H_{0(2)}$: No evidence for the predicted difference between means of median RTs in I versus C	Target sample size: 110 participants after exclusion of those reporting professional experience or less than 50% correct responses. Study power = .90, $\alpha = .02$ (one-tailed) to detect an effect size $d_z = .321$ ($d_z = .329$ if non-parametric analysis is used)	One-tailed *t*-test (if normal distribution according to Kolmogorov–Smirnov test) or Wilcoxon signed-rank test (if significant deviation from normality) on means of median correct RTs in I versus C	1. $H_{0(2)}$ rejected: The preferential mapping between odors and spatial elevation may be related to relative volatility 2. $H_{0(2)}$ not rejected: No evidence for the predicted preferential mapping, in relation to relative volatility, between odors and spatial elevation

(*continued on next page*)

Table 1 – (continued)

Question	Hypothesis	Sampling plan (e.g., power analysis)	Analysis plan	Interpretation given to different outcomes
Manipulation check 1 Regardless of E1 and E2 primary outcomes: *E1: Will fruity odors be associated with higher pitch than gourmand odors?* *E2: Will citrus odors be associated with higher pitch than fruity odors?* *E1: Will the odor-pitch association (measured as the difference in mean pitch between fruity and gourmand odors) be correlated with the vertical SRC effect with odors (measured as the difference between means of median correct RTs in the I condition and means of median correct RTs in the C condition)?* *E2: Will the odor-pitch association (measured as the difference in mean pitch between citrus and fruity odors) be correlated with the vertical SRC effect with odors?*	E1 = Experiment 1 E2 = Experiment 2 $H_{1(M1a)}$: Mean pitch will be significantly higher for fruity than for gourmand odors (in E1) or for citrus than for fruity odors (in E2) $H_{0(M1a)}$: No evidence for a crossmodal association between odor quality and pitch $H_{1(M1b)}$: The odor-pitch association (measured as the difference in mean pitch between fruity and gourmand in E1 or citrus and fruity in E2) will be correlated with the vertical SRC effect with odors (measured as the difference between means of median correct RTs in the I condition and means of median correct RTs in the C condition) $H_{0(M1b)}$: no evidence of a correlation between odor-pitch crossmodal associations and the vertical SRC effect with odors	M1a and M1b Each test: Power = .90, $\alpha = .02$ (one-tailed), to detect an effect size $d_z = .321$ ($d_z = .329$, if non-parametric analysis is used)	One-tailed *t*-test (if normal distribution according to Kolmogorov–Smirnov test) or Wilcoxon signed-rank test (if significant deviation from normality) on means of median pitch selected for fruity versus gourmand (in E1) or for citrus versus fruity (in E2) Pearson (if normal distributions according to Kolmogorov–Smirnov test) or Spearman correlation (with Bonferroni-Holm correction) between crossmodal association and vertical SRC effect with odors	1. $H_{0(M1a)}$ rejected: The odors used in E1 and E2 are involved in crossmodal associations with pitch, as assumed 2. $H_{0(M1a)}$ not rejected: No evidence for the assumed crossmodal association between odors and pitch 3. $H_{0(M1b)}$ rejected: The vertical SRC effect with odors is related to odor-pitch crossmodal associations 4. $H_{0(M1b)}$ rejected: No evidence for a relation between the vertical SRC effect with odors and odor-pitch crossmodal associations
Manipulation checks 2, 3 and 4 (in the next columns, 'x' can be replaced with pleasantness, heaviness-lightness or intensity) Regardless of E1 and E2 primary outcomes: *E1: Are there systematic differences in x between fruity and gourmand odors?* *Is x (overall, for fruity or for gourmand odors) related with the vertical SRC effect (measured as for M1)?* *E2: Are there systematic differences in x between citrus and fruity odors?* *Is x (overall, for citrus or for fruity odors) related with the vertical SRC effect (measured as for M1)?*	E1 = Experiment 1 E2 = Experiment 2 $H_{1(M2\text{-}4a)}$: Median *x* will be significantly different for fruity versus gourmand odors (in E1) or for citrus versus fruity odors (in E2) $H_{0(M2\text{-}4a)}$: No evidence for a difference in *x* between fruity versus gourmand (in E1) or citrus versus fruity (in E2) $H_{1(M2-4b)}$: median *x* overall, for fruity or for gourmand (in E1) or overall, for fruity or for citrus (in E2) will be correlated to the respective vertical SRC effect $H_{0(M2-4b)}$: No evidence for a correlation between subjective judgments overall, or for fruity or for gourmand or for citrus and the respective vertical SRC effect	M2-4a and M2-4b Each test: Power = .90, $\alpha = .02$ (two-tailed) to detect an effect size $d_z = .357$	Two-tailed Wilcoxon signed-rank test on median *x* for fruity versus gourmand (in E1) or for citrus versus fruity (in E2) Three series of three Spearman correlations (with Bonferroni-Holm correction) per experiment between judgments and the vertical SRC effect with odors	1. $H_{0(M2\text{-}4a)}$ rejected: The odors used in E1 and E2 are differ in *x* 2. $H_{0(M2\text{-}4a)}$ not rejected: No evidence for a different in *x* for the odors used in E1 and E2 3. $H_{0(M2-4b)}$ rejected: The vertical SRC effect with odors (*overall or for a specific category*) is related to dimension *x* 4. $H_{0(M2-4b)}$ not rejected: No evidence for a relation between the vertical SRC effect with odors (*overall or for a specific category*) and dimension *x*

Manipulation check 5 Regardless of E1 and E2 primary outcomes: *E1: Is the vertical SRC effect (as measured for M1) related to correct odor identification (measured as the percentage of correctly identified odors)?* *E2: Is the vertical SRC effect (as measured for M1) related to correct odor identification (measured as the percentage of correctly identified odors)?*	Separately for Experiment 1 and Experiment 2 and in combination $H_{1(M5)}$: The percentage of correct odor identification correlates with the vertical SRC effect for odors $H_{0(M5)}$: No evidence for a correlation between the percentage of correct odor identification and the vertical SRC effect for odors	M5 Power = .90, α = .02 (two-tailed) to detect an effect size d_z = .357	Spearman correlations (one for E1, one for E2; with Bonferroni-Holm correction) between overall correct identification rates and the vertical SRC effect for odors	For each correlation the following interpretation will apply: 1. $H_{0(M5)}$ rejected: The vertical SRC effect with odors is related to the rates of correct odor identification 2. $H_{0(M5)}$ not rejected: No evidence for a relation between the vertical SRC effect with odors and the rates of correct odor identification

study was conducted on a sample size of convenience and with a restricted design. We therefore consider it as indicative preliminary evidence.

The present study aims primarily to establish in a preregistered and adequately powered experimentation the existence of a vertical SRC effect in the olfactory domain, and provide a first test of the possible sources of dimensional overlap between olfaction and spatial elevation. Preregistration concerns these two main objectives and includes two experiments. This study also improves on the rationale of Caldana and Rusconi (2023) by directly assessing the relation of the olfactory spatial SRC effect with crossmodal correspondences between odors and tonal pitch, both measured in the same participants, along with odor intensity, heaviness/lightness and pleasantness judgments. In line with the available evidence (Caldana & Rusconi, 2023), in the first experiment we expect that the relevant attribute to induce the SRC effect is odor quality, and that fruity odors (selected among those that are typically associated with high pitch; e.g., Crisinel et al., 2013) would be preferentially mapped onto a high response position, and gourmand odors (selected among those that are typically associated with low pitch (e.g., Belkin et al., 1997) will be preferentially mapped onto a low response position. When dimensional overlap occurs, reaction times (RTs) are a sensitive variable to stimulus-response mapping manipulations and they are typically faster with a compatible mapping between stimulus and response than with an incompatible mapping (Kornblum et al., 1984, 1990). Thus, it is predicted that (see also Table 1):

H1. the compatible stimulus-response mapping (fruity odors on the higher response button; gourmand odors on the lower response button) leads to faster RTs than the incompatible stimulus-response mapping (fruity odors on the lower response button; gourmand odors on the higher response button), the alternative frequentist scenario being that:

H0$_1$. no evidence for a difference in RTs is found between the compatible and the incompatible stimulus-response mappings.

Conditional on rejection of the null hypothesis and to finding moderate evidence in favor of H1, a second experiment would be conducted, in order to contrast the role of odor quality (in relation to its volatility) with that of the specific label related to the semantic category. Since fruity and gourmand odors are generally classified into top notes and base notes according to their volatility on the olfactory pyramid, a different categorization of odors would be proposed, such that the semantic label “fruity” is predicted to generate an opposite spatial compatibility effect, by being preferentially associated to the lower key. In order to achieve this, lower-volatility odorants would be used for the fruity category than in the first experiment, and the categorization task would be performed by choosing between “citrus” and “fruity” odors. Stimuli falling under the citrus category would be the same as those proposed in the first experiment (in that case, under the fruity category), namely: lemon, bergamot, orange, while the fruity category would include the following stimuli: coconut, strawberry and peach. The latter were chosen for their significantly lower degree of volatility than those falling under the citrus category (see Methods for details). It is predicted that (see also Table 1):

H2. the compatible stimulus-response mapping (citrus odors on the higher response button; fruity odors on the lower response button) leads to faster RTs than the incompatible stimulus-response mapping (citrus odors on the lower response button; fruity odors on the higher response button), the alternative frequentist scenario being that:

H0$_2$. no evidence for a difference in RTs is found between the compatible and the incompatible stimulus-response mappings.

A series of exploratory analysis has also been planned on the entire database, including Bayesian statistics.

2. Methods

2.1. Sampling plan and design

2.1.1. Power analysis

The power analysis was conducted in G*Power 3.1.9.7 (Faul et al., 2007) using the smallest effect size of interest (SESOI from critical *t*: $d_z = .334$; Lakens, 2022) in Caldana and Rusconi (2023), for the significant difference (paired samples *t*-test) between means of median correct RTs in the compatible versus incompatible mapping, in a two-choice odor categorization task. The size of the reported effect was $d_z = .381$, with a vertical SRC effect in the range of a hundred milliseconds. Our registered hypotheses would be evaluated in two separate experiments with a paired-samples *t*-test each (or a Wilcoxon signed-rank test, if the data are not normally distributed). To obtain a power of .90 and an alpha of .020 (one-tailed), a sample size of 102 (of 107, if a Wilcoxon signed-rank test is performed) would be required. No correction for multiple comparisons is required as a single registered test would be performed for each database. We thus aimed for a sample size of 110 participants per experiment, after exclusion of participants reaching less than 50% overall accuracy and participants with previous professional perfumery experience. The checks on professional experience and overall accuracy would be performed during data collection, to identify participants needing replacement. A sensitivity analysis indicates that a sample of 110 participants enables the detection of a $d_z = .321$ (90% power, alpha .020, one-tailed; $d_z = .329$, if a Wilcoxon signed-rank test is used).

The decision rule for proceeding to Study 2 took into account the outcome of confirmatory Bayesian tests, with a JZS prior with the default scale parameter of sqrt(2)/2 (Schönbrodt & Wagenmakers, 2018), to control for potentially misleading evidence. The experimental manipulation implemented in Study 2 for theoretical refinement crucially depends on whether Study 1 provides robust enough evidence in favour of the alternative hypothesis. Therefore, a positive outcome of the frequentist *t*-test in Study 1 would trigger Study 2, provided that the outcome of a confirmatory Bayesian *t*-test does not return a Bayes Factor (BF) lower than 5 (i.e., in the moderate evidence range; Lee and Wagenmakers, 2014). According to a Bayes Factor Design Analysis (BFDA) with 10000 repetitions (default Cauchy distribution, scale: sqrt(2)/2), conducted with the *BFDA package* for *R* (Schönbrodt & Stefan, 2018), a BF equal or higher than 5 would occur with a chance of about 82% under the alternative hypothesis and of .5% under the null hypothesis, whereas a BF lower than 5 would occur with a chance of about 99.5% under the null hypothesis and 18% under the alternative hypothesis. Thus, if $p_{\text{Study1}} \leq .02$ and BF $_{\text{Study1}} \geq 5$, we would initiate also Study 2. In all the other cases we would not proceed, as stronger relative evidence in favour of the alternative would be required to justify use of resources for the theoretical refinement envisaged in Study 2, in the case of $1/5 < BF_{10} < 5$, or because moderate evidence for the null is found, in the case of $BF_{10} \leq 1/5$.

2.1.2. Participants

Participants were recruited aged 18–60 via advertisements across social media among the student and alumni population of the University of Trento. To be included in the study, participants were required not to be anosmic (as assessed with the Sniffin' Sticks Screening 12, Odofin™), and to have normal or corrected to normal vision (as assessed via self-report). Participants would be excluded from the analysis if they reported having previous experience in the perfumery industry/ retail, or did not complete the experiment according to the approved protocol, either because they interrupted or due to technical/human faults such as: a sudden electrical power cut; a mistake in administering the order of tasks and questionnaires; possible malfunction of the valves, loss of pressure from the jars that impacts proper delivery of stimulation; perception of any discomfort related to flow rate or type of olfactory stimulus; presence of any extraneous interference that could lead to incorrect recording of the data; lack of compliance with the instructions related to finger placement on the buttons and response assignment of the categories; failure to respond accurately to at least 50% of the total trials. Data was regularly checked for overall accuracy, and recruitment was stopped after data from 110 participants that did not fulfil any of the exclusion criteria had been collected. Data collection and analysis was not performed blind to the conditions of the experiments. The study was approved by the local Ethics Committee and all participants provided informed written consent.

2.1.3. Apparatus and stimuli

A copy of the handedness questionnaire and of the ad hoc screening questionnaire used to assess basic demographic information, professional experience and health status has been made available at the following link: https://osf.io/8tr3c.

In order to obtain precise temporal control of the administration of olfactory stimuli during the experimental task, an olfactometer with the basic specifications described by Lundström et al. (2010) was used. The olfactometer flowrates were set at a total airflow of 6 l/min. Specifically, each odorized air-channel and the odorless control channel was set at

5 l/min, while the continuous flow line was set at 1l/min.[3] The olfactometer was connected to a Dell Latitude 3480 laptop computer, on whose display (14″, 1366 × 768 pixels, 60 Hz) task instructions were presented, using a program written in *Python* on a *Spyder* development environment. The display was positioned 57-cm away from the mouth and chin rest. The computer was also used to record responses and response times, and to communicate to the olfactometer when to deliver odors via serial communication between *Spyder* and *Arduino* (Arduino MEGA 2560 Rev3). Manual responses were collected via a purpose-built, vertically attached push-button box with two response keys. In order to avoid the use of any reference to spatial locations, the top button and the bottom button were marked with an asterisk (*) and a hash mark (#) both centered on the respective button (for half of the participants the asterisk was assigned to the top button, the hash mark to the bottom button, for the other half the assignment was reversed).[4] The hand control and response keys were centered on the midline of the experimental station, as was the aerosol ampoule from which the air and olfactory stimuli flow and the computer screen on which the instructions for performing the task and the signal for breathing appear.

Odorants. A total of six odorants was used in the first experiment: bergamot, lemon, orange, caramel, coffee, vanilla from Mystic Moments. This brand was chosen because it has been already used in the relevant literature on crossmodal correspondences (Caldana & Rusconi, 2023; Ward, Rahman, et al., 2022; Ward et al., 2022, 2023). The odorant selection was based on previous studies, where each odorant was reported as being consistently associated with high or low pitches. Specifically, three odorants tend to be associated with high pitches: lemon (Speed et al., 2021; Stevenson et al., 2012) bergamot (Belkin et al., 1997), orange (Crisinel et al., 2013) (these were categorized as "fruity" in the experimental task) and three with low pitches: caramel, coffee (Belkin et al., 1997; Ward, Rahman, et al., 2022; Ward et al., 2022, 2023), vanilla (Brianza et al., 2019) (these were categorized as "gourmand" in the experimental task). In the second experiment, lower-volatility odorants would be used for the "fruity" category, whereas the original odorants categorized as "fruity" would be categorized as "citrus". The stimuli falling under the "citrus" category would thus be: lemon, bergamot, orange, and those falling under the "fruity" category would be: coconut (aldehyde c18), strawberry (aldehyde c16; crossmodally corresponding with low pitch; see Belkin et al., 1997), peach (aldehyde c14). These new odorants were chosen for their lower degree of volatility, based on their estimated vapor pressure values (according to www.echemportal.org), than those falling under the citrus category. The odorants were diluted in diethyl phthalate (SCCNFP/0411/01; widely employed as solvent for fragrances and essential oils) as done in previous studies (Belkin et al., 1997; Caldana & Rusconi, 2023; Demattè et al., 2006), with concentrations of 3% and a total of 3 ml of each odor was placed in dark glass cosmetic jars, with a capacity of 30 ml each. These jars were used as odor reservoirs in the olfactometer.

Crossmodal correspondences between each odor and sound pitch were probed with pure tones having a range of frequencies from 65 Hz to 1,046 Hz. To mirror the procedure of relevant work in the literature on crossmodal correspondences, participants were able to play and evaluate tones by moving the cursor on a slider, where pitch increases in a horizontal direction, and pressing the "listen" button with a mouse click (Crisinel et al., 2013; Crisinel & Spence, 2012; Ward, Rahman, et al., 2022; Ward et al., 2022, 2023). The slider was centered on the PC screen and subtended 26° degrees of visual angle in width. The direction of pitch increase was pseudorandomized so that for half of the participants the direction was from right to left, while for the other half of the participants it was from left to right. Once the tone was selected, participants had to press with a mouse click the "confirm" button on the PC screen (Crisinel et al., 2013; Crisinel & Spence, 2012). The sounds were edited to last for 1,500 msec and presented over closed-ear headphones (HP, gaming OMEN blast) at a loudness of 70 dB (Crisinel et al., 2013; Crisinel & Spence, 2012).

Seven-point Likert scales, presented on the PC screen, were used for ratings of individual odors on the dimensions of odor heaviness/lightness (from 1, extremely heavy, to 7, extremely light), pleasantness (from 1, extremely unpleasant, to 7 extremely pleasant) and intensity (from 1, extremely weak, to 7, extremely strong). Participants were required to provide the response by writing in a text box presented on the screen the selected rating and to press the confirmation button to confirm their answer.

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[3] According to Lötsch et al. (1998), a total airflow of up to 5 l/min within each nostril is considered as not generating any painful sensation; the use of a mask rather than inserts permits the use of a flow up to 8 L/min before any discomfort is reported (Lundström et al., 2010). Since instead of nasal inserts, an aerosol ampoule was used for this study, we maintained a total flow of 6 L/min.

[4] Such symbols have been previously used by (Caldana & Rusconi, 2023) Caldana and Rusconi (2023) in consideration of the literature on crossmodal correspondences between odors and visual forms in relation to the main hypothesis. Indeed, it has been reported that lemon-like odors, or odors that may be associated with sour flavours, crossmodally correspond to angular shapes, whereas caramel, coffee and vanilla odors, which are associated with sweet flavours, crossmodally correspond to rounded shapes (Hanson-Vaux et al., 2013; Ward, Rahman et al., 2022a, Ward, Wuerger et al., 2022b, 2023). It should be noted that no curve line is present in either of the symbols. However, in case the symbols were interpreted as more angular (#) versus more rounded (*), since a preferential mapping for fruity odors on the top response position and for gourmand odors on the bottom response position was predicted, Caldana and Rusconi (2023) chose to place the symbols in such a way that the predicted SRC effect, if present, could not be easily ascribed to crossmodal correspondences between visual shapes and qualitative odor categories. To this purpose, the hash mark was associated to the bottom button and the asterisk was associated to the top button. In the presence of a preferential mapping emerging from odor-shape crossmodal correspondences (rather than from a vertical spatial representation evoked by odor quality, as hypothesised), a SRC effect in the opposite direction than the predicted one would have been detected. In other words, the symbol-key assignment was fixed and, if anything, it could have worked against the expected effect. In the current study, the assignment of shapes to response buttons was counterbalanced between participants as this enabled to control for potential, no matter how unlikely, confounds.

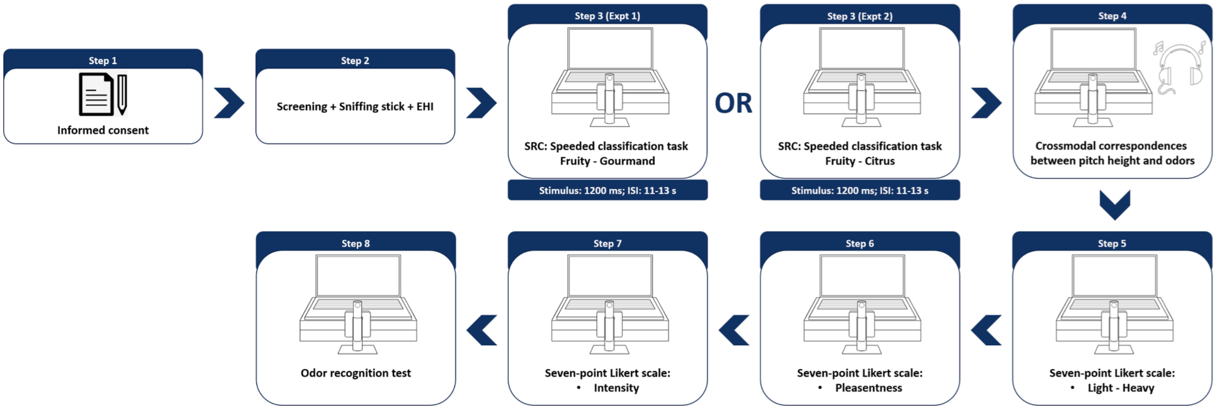

Fig. 2 – Task sequence. Sequence of the tasks included in a testing session. The order of tasks was kept fixed across participants.

A precompiled list of 12 odor sources (lemon, pine, orange, cherry, green apple, bergamot, caramel, musk, coffee, lavender, banana, vanilla, for the first experiment; lemon, pine, orange, strawberry, bergamot, caramel, coconut, peach, lavender, vanilla, coffee, cherry for the second experiment) was used for the identification of individual odors. As in previous studies (Caldana & Rusconi, 2023; Ward, Rahman, et al., 2022; Ward et al., 2022, 2023), a recognition test was preferred here, as opposed to a free naming test, in order to make the task more feasible, given that the ability to spontaneously identify and name olfactory stimuli is generally very poor (Yeshurun & Sobel, 2010).

2.1.4. *Procedure*

The structure of the experimental session is summarised in Fig. 2. After giving written informed consent, participants were asked to complete the preliminary screening questionnaire, and thus state whether they had any chronic/transient problems in the olfactory, visual or respiratory systems, which might impair their ability to perform the task, and basic socio-demographic information. They were also asked to report whether they had ever worked (if so, for how long) in the perfumery industry/retail. Subsequently, participants were screened with the Sniffin' Sticks Screening 12, Odofin™ and completed the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971).

They were then required to sit on an adjustable chair, rest their chin and forehead on a mouth and chin rest, and position the nosepiece at a distance enabling a comfortable experience with the odors delivered by the olfactometer. The task required to classify olfactory stimuli as accurately and quickly as possible in two categories: fruity and gourmand (first experiment) or citrus and fruity (second experiment, had it been conducted). To perform the task, participants pressed one of two buttons, each assigned to a specific category. The session included 4 blocks (2 mappings × 2 hand conditions) of 24 trials each (Caldana & Rusconi, 2023; Demattè et al., 2006), presented in a counterbalanced order (the schedule is available at the following link: https://osf.io/8tr3c). Both the assignment of odor categories to response buttons (e.g., fruity-top button and gourmand-bottom button, or fruity-bottom button and gourmand-top button) and the assignment of hands to response buttons (i.e., left hand-top button and right hand-bottom button, or left hand-bottom button and right hand-top button) was thus balanced within participants. In the first experiment, the compatible condition corresponded to the following assignment: fruity odor-top button, gourmand odor-bottom button, and the incompatible condition to: fruity odor-bottom button, gourmand odor-top button. In the second experiment, the compatible condition would correspond to the following assignment: citrus odor-top button, fruity odor-bottom button, and the incompatible condition to: citrus odor-bottom button, fruity odor-top button. The shape–button association was counterbalanced between participants, that is half of the participants found the asterisk on the top button and the hash mark on the bottom button, the other half found the hash mark on the top button and the asterisk on the bottom button. Trials were presented in a pseudorandomized order, to make sure that all olfactory stimuli appeared the same number of times within each block. Each experimental block lasted about 8 min. The total duration of the olfactory stimulus was 1200 msec and instructions emphasized both speed and accuracy of response, although the program collected responses until the onset of the following stimulus. The interstimulus interval varied between 11 and 13 sec to minimize possible carryover effects (Olofsson et al., 2012). To familiarize participants with the task, each block started with a presentation of the instructions followed by 6 practice trials, providing feedback on the accuracy of the answers. Only if a participant gave more than 50% correct responses in practice trials, s/he would be able to proceed to the experimental trials. During the task, participants were required to keep their eyes on the fixation point and instructed to inhale whenever instructions under the fixation point appeared in short form (e.g., "press * for gourmand, press # for fruity"). These short form instructions were used both as a reminder of the current assignment of responses to buttons and as a signal when to inhale.

After completing the speeded-choice task, participants were given a 5-min break. Right after, participants were asked to select from a slider the pitch that best matched each odor presented. Participants were able to familiarise with the slider before starting the matching task. Participants were exposed to one olfactory stimulus at a time and, for each stimulus, they selected the pitch that they thought corresponded to the odor. They were free to listen to as many tones as they wished before selecting the pitch that best matched the presented odor. The olfactory stimulus had a duration of 1200 msec, and participants were able to reassess the olfactory stimulus only two times, by pressing an ad hoc key. They were able to freely assess the tones for evaluation by positioning the mouse on different points of the slider and pressing the screen button "listen". To provide the response, participants then positioned the cursor on the desired position of the slider and pressed the screen button "confirm". Once the response was confirmed, there was an interval of 11 sec before moving on to the presentation of the next olfactory stimulus.

On completion of the crossmodal matching task, instructions were shown on the PC display requiring participants to score the degree of perceived heaviness/lightness of each of the 6 olfactory stimuli, presented in random order, by selecting a number from 1 (extremely heavy) to 7 (extremely light) on a keyboard attached to the computer. Participants were asked to report the score in the text box provided and press confirm to move on to evaluate the next olfactory stimulus. After pressing the confirm button, an interstimulus interval of 11 sec followed, to avoid olfactory fatigue. The duration of the olfactory stimulus was 1200 msec and participants were free to have a stimulus redelivered for a maximum of two times by pressing a button. The same procedure was used to assess the degree of perceived pleasantness, where participants were required to rate the stimuli by selecting a number between 1 (extremely unpleasant) and 7 (extremely pleasant), and the perceived intensity of each stimulus, by rating each stimulus with a number from 1 (extremely weak) to 7 (extremely strong).

Finally, participants were given an odor identification test. In the identification test the 6 target odors were presented individually in random order, the stimulation duration was 1200 msec, and participants were free to have the odor redelivered a maximum of two times. A list of 12 odors to choose from (see Apparatus and Stimuli; Ward, Rahman, et al., 2022; Ward, Wuerger et al., 2022, 2023) was provided on the computer display in a fixed position. Once they had made their choice, participants pressed a button next to the chosen name and then pressed confirm. The presentation of the olfactory stimuli for the cross-modal matching, rating and identification tasks were pseudorandomized for each participant (as determined by a random number generator in *Arduino IDE*), while the order of tests was kept fixed across participants (see Fig. 2). The whole experimental session lasted about 60 min.

2.1.5. *Manipulation checks*

With this work we aimed to establish whether a vertical SRC effect may manifest itself in the olfactory domain (Study 1). If such an effect was found, we aimed to provide a first test of the possible sources of dimensional overlap between olfaction and spatial elevation (Study 2). For each of the proposed studies, in addition to the main task (Fig. 2, Step 3) a series of manipulation checks have been introduced as aids to result interpretation (Fig. 2, Steps 4–8). All manipulation checks were posterior to the experimental manipulation, in order not to prime participants to pay attention to other stimulus characteristics than the relevant one in the main task, and provided secondary outcomes. Nonetheless, we have included them in Table 1, along with a specification of the main analysis we planned to conduct on their outcomes. In this section we clarify how manipulation checks would be used to aid result interpretation (i.e., the outcome of the preregistered test on the vertical SRC effect, calculated as the difference between the mean of median correct RTs in the incompatible condition and the mean of median correct RTs in the compatible condition).

Our initial choice of odor categories was supported by an analysis of the literature on crossmodal correspondences, showing systematic (and currently unexplained) associations between exemplars of the chosen categories and sounds of different pitch. Our design includes a direct measure of such crossmodal correspondences between pure tones and the odor stimuli used in the experimental task (Fig. 2, Step 4). If the association is confirmed, and so is the presence of a vertical SRC effect at the group level, then the idea that the vertical SRC effect elicited by odor quality may derive from an implicit spatial representation, analogous to the mental representation of sound pitch would look both plausible and parsimonious. In case evidence for a crossmodal association is found but evidence for a vertical SRC effect is not, this manipulation check would be still informative. Indeed, it would suggest that a crossmodal association between odors and pitch may not be sufficient to justify the expectation of an association between odors and spatial elevation. If the odor-pitch association is not confirmed, in the presence of a vertical SRC effect, odor–space associations as revealed by the vertical SRC effect would not be framed as strongly within the same spatial structural hypothesis proposed for odor-pitch associations; in the presence of a negative result for the vertical SRC effect, the absence of evidence for an odor-pitch association would leave open the possibility that a crossmodal association between odors and pitch might be necessary for a relation between odors and spatial elevation to be manifested. Regardless of whether a vertical SRC effect or an odor-pitch association are found at the group level, the correlation between individual measures of vertical SRC effect and odor-pitch crossmodal associations would also be tested directly (see Table 1).

The choice of using equal levels of concentration across odors is based on the assumption that subjective perceptions of intensity, pleasantness and lightness/heaviness do not play a crucial role in the vertical SRC effect (Caldana & Rusconi, 2023), which is consistent with what is known about the role of such perceptions in odor-pitch correspondences (Belkin et al., 1997; Persson, 2011). To enable an internal check on whether the vertical SRC effect elicited by odor quality may be explained by different subjective characteristics of the stimulus (indeed, some of them may covary with odor quality; Caldana & Rusconi, 2023), we asked our participants to provide judgments on the perceived intensity, pleasantness and heaviness/lightness of each odor (Fig. 2, Steps 5–7; Table 1). The mere presence of a significant difference along one or more of these dimensions between odor categories is expected and would not be considered as indicative of a potential role in the vertical SRC effect. Regardless of the outcome of the group level analysis, the presence of a significant correlation between judgments along one or more of these dimensions and the vertical SRC effect, however, would require a shift in focus from odor quality to the interaction between odor quality and such alternative dimension(s), and to the possible role of such dimension(s) in the outcome of our preregistered tests on the vertical SRC effect.

Finally, based on previous literature, we argue that specific odor identification or recognition should be immaterial to the manifestation of a vertical SRC effect for odors (also in analogy with pitch-odor correspondences), as the effect may be determined by structural rather than semantic features. We have therefore included in our design a recognition test (Fig. 2, Step 8; Table 1) as a further manipulation check to assess whether correct recognition may in fact be associated with the vertical SRC effect. In case of evidence for an association, our default interpretation of the main result would be revised by including odor semantics as a potential factor in the manifestation (or its lack) of the SRC effect at the group level.

2.1.6. *Summary of measurement tools*

To recapitulate, our primary measurement tool is the computerized odor classification task, from which individual performance measures (namely, speed and accuracy) were obtained enabling the quantification of the spatial SRC effect. Other measurement tools have been included to assess whether the participant meets our inclusion or exclusion criteria, for exploratory purposes and/or as manipulation checks (see Fig. 2). These additional tools are:

- ad hoc screening questionnaire (for basic demographic information, professional experience and health status);
- Sniffin' Sticks Screening 12 (for exclusion of anosmia);
- Edinburgh Handedness Inventory (for individual handedness);
- odor-pitch crossmodal correspondences (manipulation check);
- subjective judgments on odor intensity, pleasantness, heaviness/lightness (manipulation checks);
- odor recognition test (manipulation check).

2.2. *Analysis plan*

Statistical analysis were carried out with *RStudio 2023.09.1* + 494, *SPSS* v. 29 and *JASP* v. .19.3, .95.1.0. Only completing, naïve participants were included in the preregistered analysis and a cut-off was set so that they gave at least 50% correct responses in the two-choice categorization task. Trials with an incorrect or a missing response were discarded. Median RTs were calculated for each cell of the category × response button table; means of median RTs were then calculated for the compatible and incompatible conditions, and normality checks carried out on their distributions via Kolmogorov–Smirnov tests, with α_{FW} = .02. A significance level of $\alpha = .02$, one-tailed, was set for each of the two registered independent contrasts. The planned contrasts were *t*-tests (or Wilcoxon signed-rank tests, depending on the outcome of preliminary normality checks), on means of median correct RTs in the compatible versus incompatible condition. 95%-confidence intervals (95%-CIs) would be provided for the observed effects.

To control for the potential of a misleading result, confirmatory Bayesian *t*-tests (or Wilcoxon signed-rank tests, depending on the outcome of preliminary normality checks) with a default JZS prior (scale parameter: sqrt(2)/2; Schönbrodt & Wagenmakers, 2018) on means of median correct RTs in the compatible versus incompatible condition were also planned. 95%-credibility intervals (95%-CrIs) would be provided for the observed effects. In case of $BF_{10} < 5$ in Study 1, the strength of evidence in favour of the alternative hypothesis would not be considered sufficient to proceed, and this could prompt future replication efforts in case of inconclusive results (here defined as in the range of $1/5 < BF < 5$; Lee and Wagenmakers, 2014).

Successively, analysis on manipulation checks were performed as specified in Table 1, with Bonferroni-Holm correction to control for multiplicity, along with confirmatory Bayesian tests with a default JSZ prior in case of non-significant result (for Bayes Factor interpretation used the same moderate evidence threshold as previously specified, that is $BF = 1/5$ and $BF = 5$; Lee and Wagenmakers, 2014). A series of exploratory analysis was also performed involving the entire database and including Bayesian versions of the main frequentist tests.

3. Results

3.1. *Level of bias control*

This study achieved a bias control Level 6. No part of the data or evidence that was used to answer the research question was generated until after IPA.

3.2. *Final sample*

One hundred and fourteen participants were tested. Four (3M, 1F; all right-handed; age: M = 25.5, SD = 8.5) were replaced due to failure to reach the cutoff (10 correct identifications out of 12; Sniffin' Sticks Screening Test, Odofin™) at the basic test of olfactory function. The rest (N = 110) reached or exceeded the cutoff, did not report any professional experience related to perfumes and did not obtain accuracy levels inferior to 50% at the main task. They were thus retained for subsequent analyses. The final sample comprised 85 females and 25 males, mostly right-handed (EHI score: M = 79.59; SE = 3.41), with an average age of 24.15 (SE = .71). Their average score at the Sniffin' Sticks Screening Test was 10.85 (SE = .84). About 25% of the sample reported being a habitual or occasional smoker and 20% reported mild respiratory symptoms at the time of testing, attributable to generic nasal congestion, cold, allergic rhinitis, sinusitis and asthma, yet they passed the initial screening. So did the 6 participants who self-reported as anosmic/hyposmic and were thus retained.

Table 2 – Descriptive and test statistics on the vertical SRC effect are shown for the preregistered analysis on median RTs and for the same analysis on alternative indices of central tendency (mean RTs and restricted mean RTs).

Analysis	Condition	M	SE	z	*p (one-tailed)*	r (SE)	Bca 95%-CI	BF_{10}	95%-CrIs	α	SRC effect (SE)	N
❧ Median RTs	Compatible	1308.28	30.99	.980	.164	r = .108 (.11)	1251.36–1364.03	.315	1246.87–1369.70	.939	19.44 (20)	110
	Incompatible	1327.72	32.88				1265.80–1391.32		1262.55–1392.89	.943		
Mean RTs	Compatible	1389.63	34.77	1.955	.025	r = .215 (.11)	1324.41–1454.48	1.013	1319.00–1460.00	.928	56.48 (27)	110
	Incompatible	1446.11	39.95				1368.89–1524.92		1366.00–1526.00	.918		
Restricted mean RTs	Compatible	1340.69	32.56	2.079	.019	r = .230 (.11)	1279.53–1401.41	1.143	1275.00–1407.00	.944	47.66 (22)	110
	Incompatible	1388.35	36.31				1319.54–1458.67		1316.00–1461.00	.942		

3.3. *Section plan*

The Result section is organised by research question, following the structure of Design Table 1. Preregistered analysis are signposted with the symbol: ❧, for rapid identification and are accompanied by preliminary checks and exploratory analysis. Exploratory analysis are aimed to provide necessary contextualisation and specification. Due to their indicative rather than conclusive character, exploratory analysis were targeted, limited to the essential and reported without corrections. Whenever a significant test was performed according to a one-tailed hypothesis, this has been specified; if no specification is given, the test was performed according to a two-tailed hypothesis. Bayesian versions of the tests are based on data augmented using 5 chains of 5000 iterations and Bias Corrected accelerated (BCa) 95%-CrIs on a 5000-sample bootstrap.

3.4. *Vertical SRC effect*

3.4.1. *Preliminary checks (exploratory)*

On average, participants achieved an accuracy of 93.83% (SE = .51) in the forced-choice odor classification task, with evidence in favour of no difference in accuracy between the compatible (M = 93.75%; SD = .62) and the incompatible (M = 93.90%; SE = .51) condition (Kolmogorov–Smirnov test for normality of distribution: ps <. 001; Wilcoxon signed-rank test: z = .19, *p* = .849; matched rank biserial r = .023, SE = .12; BF_{10} = .11).

They responded on average in 1318.00 msec (SE = 30.36) and were 19 msec faster in the compatible than in the incompatible condition (see Table 1). Cronbach's alpha, based on the odor categories contributing to each condition, was .939 and .943 for the compatible and incompatible condition respectively. Kolmogorov–Smirnov tests indicated significant deviation from normality for both the compatible and the incompatible condition (*ps* ≤ .001). Spearman correlations returned non-significant negative coefficients, thus no evidence of speed-accuracy trade-offs overall or by compatibility condition was found (all *ps* ≥ .100).

3.4.2. ❧ *Preregistered target analysis*

A Wilcoxon Signed-Rank test did not support the directional hypothesis in favor of the compatible condition (see Table 2). Given this outcome, Experiment 2 was not performed. The Bayesian version of the test returned a BF_{10} superior to 1/5 and inferior to 5, indicating inconclusive evidence.

3.4.3. *Alternative data preprocessing and statistical approach (exploratory)*

The use of medians solves the issue of potential RT outliers without discarding any data but downgrades interval data to rank data, leading to information loss (Field, 2009; Thompson, 2006). Restricted (i.e., with outliers removed) or unrestricted means are more often used in the literature (Balota & Yap, 2011; Berger & Kiefer, 2021; Van Selst & Jolicoeur, 1994). Additionally, the use of non-parametric rather than parametric tests in our preregistered analysis may dampen design sensitivity (Field, 2009; Thompson, 2006). In this exploratory

Table 3 – Descriptive and test statistics on the vertical SRC effect are shown by category, overall and for the three clusters of participants.

Cluster	Category	Condition	M	SE	z	p	r (SE)	BF10	SRC effect (SE)	N
OVERALL	FRUITY	Compatible	1296.56	33	2.129	.017[a]	.234 (.11)	2,459	19.44 (20)	110
		Incompatible	1343.78	34						
	GOURMAND	Compatible	1320.01	31	1.236	.892	.136 (.10)	.062		
		Incompatible	1311.66	34						
1	FRUITY	Compatible	1512.73	68	4.782	<.001	1 (.21)	1946.86	−202.09 (61)	30
		Incompatible	1315.40	54						
	GOURMAND	Compatible	1531.38	68	4.700	<.001	.98 (.21)	5390.22		
		Incompatible	1324.53	67						
2	FRUITY	Compatible	1347.29	73	3.823	<.001	1 (.26)	1855.47	321.13 (71)	19
		Incompatible	1721.58	88						
	GOURMAND	Compatible	1418.66	74	3.099	.002	.81 (.26)	62.86		
		Incompatible	1686.63	78						
3	FRUITY	Compatible	1174.44	35	3.979	<.001	.59 (.15)	477.12	34.41 (33)	61
		Incompatible	1240.06	37						
	GOURMAND	Compatible	1185.33	30	.646	.518	.09 (.15)	.14		
		Incompatible	1188.54	34						

[a] One-tailed.

section, we adopt a different preprocessing approach and replicate the key preregistered analysis by using restricted means as central tendency indices for the main task, with outliers eliminated by participant and condition (category × response) using the non-recursive procedure with moving criterion proposed by Van Selst and Jolicoeur (1994). This procedure led to the exclusion of 3.12% of correct RTs overall. Because assumptions for parametric tests were violated, we perform their non-parametric version and provide robust Bias Corrected and accelerated (BCa) 95%-CIs for the means based on data augmented using 5 chains of 5000 iterations, alongside the relevant parametric test (Tibshirani & Efron, 1993).

Participants responded on average in 1364.52 msec (SE = 33) and faster in the compatible than in the incompatible condition (see Table 2). Cronbach's alpha was .944 and .942 for the compatible and incompatible condition respectively. Kolmogorov–Smirnov tests indicated significant deviation from normality for both the compatible and the incompatible condition ($ps \leq .001$). Spearman correlations between accuracy and RTs returned non-significant negative coefficients, thus excluding the presence of speed-accuracy trade-offs overall or by compatibility condition (all $ps \geq .09$).

The compatible condition was about 48 msec faster than the incompatible condition. Both a Wilcoxon Signed-Rank test (see Table 2) and a *t*-test ($M = 47.66$ msec; $t_{109} = 2.078$, $MSE = 22.93$, one-tailed $p = .020$; BCa 95%-CIs: 5.38–90.26; $d = .20$) supported the directional hypothesis in favor of the compatible condition. The Bayesian version of the tests returned a BF_{10} superior to 1/5 and inferior to 5 ($BF_{10} = 2.340$ for the non-parametric test and $BF_{10} = 1.635$ for the parametric test), indicating inconclusive evidence. As shown in Table 2, the same conclusions would be reached by analysing means without applying any trimming procedure.

3.4.4. *Analysis by category of odors (exploratory)*

To gauge the potential of our manipulation checks, a further analysis was performed separately for the two categories of odors, in the same fashion as the preregistered analysis on the main outcome (which was focused on the overall SRC effect instead). A Wilcoxon Signed-Rank test supported the directional hypothesis in favor of the compatible condition for fruity odors but not for gourmand odors (see Table 3). In the latter case (gourmand) the BF_{10} indicates evidence of no advantage for the compatible over the incompatible condition, in the former case (fruity) it indicates inconclusive evidence ($1/5 < BF_{10} < 5$) of an advantage for the compatible over the incompatible condition. Spearman correlations between RTs and percentages of accuracy by category and compatibility conditions returned non-significant negative or null coefficients, thus no speed-accuracy trade-offs overall or by compatibility condition were found (all $ps \geq .072$). Cronbach's alpha, based on the odors contributing to each condition, was .900 (compatible) and .875 (incompatible) for the fruity category, and of .915 (compatible) and .917 (incompatible) for the gourmand category.

A moderate positive correlation was found between the SRC effect for fruity and the SRC effect for gourmand odors ($rho = .521$, $p < .001$; $BF_{10} = 265{,}631.900$). This signals individual consistency in the direction and rank of the difference between the incompatible (lower response) and the compatible (higher response) condition for fruity odors, and the direction and rank of the difference between the incompatible (higher response) and the compatible (lower response) condition for gourmand odors, although the latter was not significant at the group level.

3.4.5. *Cluster analysis: subgroups behaving differently (exploratory)*

Non-significant group outcomes might reflect genuine lack of difference between conditions or subtend subgroups of participants behaving differently (Kanai & Rees, 2011). A two-step cluster analysis based on log-likelihood distance and Schwarz's Bayesian Information Criterion (BIC), with no restriction on the number of clusters to identify, was performed to help disambiguate the outcome of the main preregistered

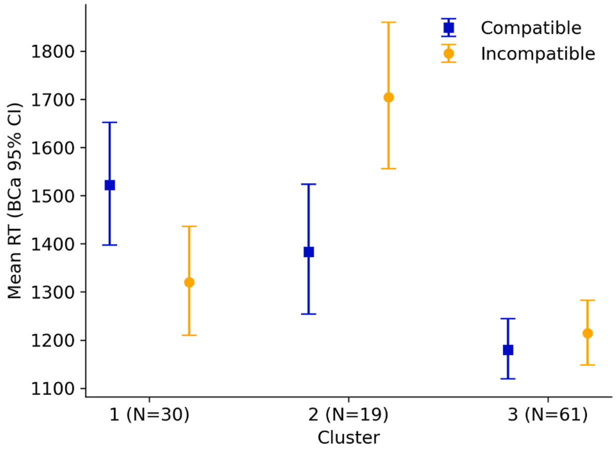

Fig. 3 – Vertical SRC effect by subgroup. Mean RTs in the compatible and incompatible conditions are shown for each cluster. Vertical bars correspond to BCa 95% CIs of the mean.

analysis on the vertical SRC effect (i.e., the RT difference between the incompatible and the compatible condition).

Three clusters were isolated in the data. A first cluster comprised 30 participants (27% of the sample), a second cluster comprised 19 participants (17% of the sample) and a third cluster comprised 61 participants (56% of the sample). Centroids for the three clusters were $M = -202.09$ msec ($SE = 61.05$), $M = 321.13$ msec ($SE = 71.46$) and $M = 34.41$ msec ($SE = 32.60$), respectively. Therefore, Cluster 1 is characterized by a large vertical SRC effect in the opposite direction than expected, that is with faster RTs in the incompatible than in the compatible condition ($z = -4.782$, $p < .001$, rank biserial $r = 1$, $SE = .20$; $BF_{10} = 54{,}813.56$), Cluster 2 by a large vertical SRC effect in the expected direction, that is with faster RTs in the compatible than in the incompatible condition ($z = 3.823$, $p < .001$, rank biserial $r = 1$, $SE = .26$; $BF_{10} = 543.61$) and Cluster 3 by a smaller, though still significant, effect in the expected direction ($z = 3.390$, $p < .001$, rank biserial $r = .50$, $SE = .15$; $BF_{10} = 175.99$).

Fig. 3 shows mean RTs in the compatible and incompatible conditions for each cluster. On visual inspection, in addition to exhibiting larger differences between the incompatible and the compatible condition than Cluster 3, both Cluster 1 and Cluster 2 have noticeably slower RTs than Cluster 3 according to Mann–Whitney tests (Cluster 1: $M = 1421.01$, $SE = 61.05$; Cluster 2: $M = 1543.54$, $SE = 71.46$; Cluster 3: $M = 1197$, $SE = 32.60$; Cluster 1 *vs* Cluster 2: $z = 1.50$, $p = .134$, rank biserial $r = .256$, $SE = .17$; $BF_{10} = .72$; Cluster 1 *vs* Cluster 3: $z = 3.18$, $p = .001$, rank biserial $r = .412$, $SE = .13$; $BF_{10} = 7.23$; Cluster 2 *vs* Cluster 3: $z = 4.28$, $p < .001$, rank biserial $r = .653$, $SE = .15$; $BF_{10} = 30.94$). A further discriminant feature will soon become apparent.

Analysis on the primary outcome were also performed separately for the two categories of odors in each of the three clusters of participants. Whereas both Cluster 1 and Cluster 2 showed a significant difference between incompatible and compatible conditions (reversed for Cluster 1 and regular for Cluster 2) for both categories of odors, Cluster 3 showed a significant difference (regular SRC effect) for the fruity category of odors only (see Table 3).

3.4.6. *Interim summary*

In conclusion:

- no speed-accuracy tradeoff was found in the data;
- RT and accuracy data are not normally distributed, thus non-parametric tests were used;
- the preregistered analysis on the primary outcome did not confirm the presence of significant SRC effect (RT difference between the incompatible and the compatible condition) and was not conclusive with regards to its absence;
- by using restricted means rather than medians, the primary analysis performed in the same fashion as the preregistered test, confirmed the presence of a vertical SRC effect, however the evidence was not conclusive;
- exploratory analysis in the same fashion as the preregistered analysis revealed an asymmetry between odor categories, with a significant SRC effect (RT difference between the incompatible and the compatible condition) for fruity odors but not for gourmand odors;
- a moderate positive correlation was found between the SRC effect for fruity and the SRC effect for gourmand odors, suggesting intra-individual consistency;
- an exploratory cluster analysis detected the presence of 3 distinct subgroups with different behavioural features: one with a large reverse SRC effect (Cluster 1, $N = 30$), one with a large regular SRC effect (Cluster 2, $N = 19$), one with a smaller, regular SRC effect (Cluster 3, $N = 61$);
- overall, both subgroups with a large effect (i.e., Cluster 1 and 2) have slower RTs than the subgroup with a smaller effect (i.e., Cluster 3);
- the SRC asymmetry between odor categories characterizes the subgroup of participants with the overall smaller SRC effect and faster RTs (i.e., Cluster 3).

3.5. *Manipulation checks*

Due to the apparent presence of a significant SRC effect for fruity but not for gourmand odors, in addition to the

Table 4 – Descriptive and test statistics on manipulation checks, alongside the results of a Spearman's correlation test with the vertical SRC effect are shown.

Manipulation Check	Category	M	SE	z	p	BF_{10}	95%-CrIs	Correlation with SRC effect (p)
Associated pitch	Fruity	717.49	20.22	8,277	<.001	9.095 × 109	677.41–757.57	.068 (.241[a])
	Gourmand	364.87	17.88				329.43–400.32	
Pleasantness	Fruity	4.66	.12	2,612	.008	2.520	4.44–4.90	−.052 (.587)
	Gourmand	4.13	.14				3.86–4.41	
Heaviness	Fruity	4.81	.12	6,207	<.001	1.1997 × 106	4.57–5.05	−.040 (.681)
	Gourmand	3.31	.10				3.11–3.51	
Intensity	Fruity	4.32	.12	3,636	<.001	46.412	4.08–4.56	−.082 (.396)
	Gourmand	4.86	.10				4.67–5.06	
Identification	Fruity	45.45	28.82	2,318	.020	2.926	40.01–50.90	.007 (.942)
	Gourmand	54.84	23.72				50.37–59.33	

[a] One-tailed.

preregistered correlation analysis involving the overall SRC effect and manipulation checks 1 and 5 (see Design Table 1), here we also focus more specifically on variables related to the fruity category. These analyses have been signposted as exploratory. The preregistered analyses for manipulation checks 2, 3 and 4 already included tests by category, therefore they did not require exploratory integrations.

3.5.1. *Manipulation check 1: odor-pitch crossmodal association*

3.5.1.1. ❧ Crossmodal association between odor and pitch (preregistered). Participants associated pure tones of higher frequency to fruity odors than to gourmand odors (see Table 4). Cronbach's alpha based on the three odors contributing to each category was .581 for the crossmodal association of fruity odors and .378 for the crossmodal association of gourmand odors. Although the distribution of frequencies associated to fruity odors did not significantly deviate from normality ($p = .055$), the distribution of frequencies associated to gourmand odors did ($p < .001$), therefore a Wilcoxon Signed-Rank test was performed. The test detected a significant difference between fruity and gourmand odors ($z = 8.277$, $p < .001$, matched rank biserial $r = .909$, $SE = .11$). The Bayesian version of the test returned a BF_{10} much greater than 5, indicating very strong evidence in favor of the alternative hypothesis.

3.5.1.2. ❧ Relation between odor-pitch association and the vertical SRC effect (preregistered). A Spearman correlation between the odor-pitch crossmodal association (measured as the difference in associated frequency between fruity and gourmand odors) and the vertical SRC effect with odors (measured as the difference in RTs between the incompatible and the compatible condition) did not detect a significant effect ($rho = .068$, one-tailed $p = .241$). The Bayesian version of the test returned a BF_{10} of .141, indicating moderate evidence in favor of the null hypothesis (see Table 4). Noteworthy, the same conclusions were reached with an exploratory version of the test using the significant vertical SRC effect based on restricted means.

3.5.1.3. Relation between associated pitch frequency and RTs to fruity odors (exploratory). Because it would not be possible to partial out the contribution of gourmand odors from the overall crossmodal association effect, a targeted correlation analysis was performed to assess whether the speed in responding to fruity odors with the higher response key (compatible condition) in the classification task had any relation with the frequency of the sound associated to fruity odors. A Spearman correlation test returned a significant negative coefficient ($rho = -.203$, $p = .034$; $BF_{10} = 1.820$), indicating that the higher the frequency of the sound associated to fruity odors, the faster the response to the same odors with the higher key. No correlation was found with RTs for responses with the lower key ($p = .150$; $BF_{10} = .531$), which may suggest that the relation has spatial specificity and is facilitatory.

3.5.1.4. Interim summary. In conclusion:

- the preregistered manipulation check 1 confirmed the presence of a robust crossmodal association between the chosen categories of odors and sound pitch;
- no relation was found between the difference in the frequency of sounds associated to fruity and gourmand odors and the difference between incompatible and compatible conditions in the forced-choice RT task (overall SRC effect);
- an exploratory analysis on fruity odors detected a significant negative correlation between associated sound frequency and RTs with the higher response key in the forced choice task, which was not present with the lower response key.

3.5.2. *Manipulation checks 2, 3 and 4: perceived pleasantness, heaviness and intensity*

3.5.2.1. ❧ Difference between odor categories for perceived pleasantness, heaviness and intensity (preregistered). On a scale from 1 (extremely unpleasant) to 7 (extremely pleasant), the difference between fruity and gourmand odors was significant, with fruity odors judged as more pleasant than gourmand odors ($z = 2.612$, $p = .008$, matched rank biserial $r = .298$, $SE = .11$; see Table 4). The Bayesian version of the test returned a BF_{10} of 2.520, indicating inconclusive evidence in favor of the alternative hypothesis. Cronbach's alpha was .584 for the fruity and .591 for the gourmand category.

On a scale from 1 (extremely heavy) to 7 (extremely light), the difference between fruity and gourmand odors was significant, with gourmand odors judged as heavier than fruity odors ($z = 6.207$, $p < .001$, matched rank biserial $r = .691$, $SE = .11$; see Table 4). The Bayesian version of the test returned a BF_{10} of 1.1997×10^6, indicating very strong evidence in favor of the alternative hypothesis. Cronbach's alpha was .674 for the fruity and .430 for the gourmand category.

On a scale from 1 (extremely weak) to 7 (extremely strong), the difference between fruity and gourmand odors was significant ($z = -3.636$, $p < .001$, matched rank biserial $r = -.410$, $SE = .12$; see Table 4). The Bayesian version of the test returned a BF_{10} of 46.412, indicating very strong evidence in favor of the alternative hypothesis. Cronbach's alpha indicated a reliability of .582 and .168 for the fruity and for the gourmand category respectively.

3.5.2.2. ❧ Relation between perceived pleasantness, heaviness and intensity and the vertical SRC effect overall and by category (preregistered). Three series of Spearman correlations were performed to assess the presence of a relation between pleasantness and the vertical SRC. No significant correlation was found between pleasantness and vertical SRC overall (see Table 4) and by odor category (fruity: rho $= -.105$, $p = .277$; gourmand: rho $= .023$, $p = .814$) and the Bayesian version of the test returned an indication of moderate evidence in favor of the null hypothesis (see Table 4; fruity: $BF_{10} = .149$; gourmand: $BF_{10} = .133$). Likewise, no significant correlation was found between heaviness and vertical SRC overall (see Table 4) and by odor category (fruity: rho $= -.009$, $p = .926$; gourmand: rho $= -.142$, $p = .139$) and the Bayesian version of the test returned an indication of moderate evidence in favor of the null hypothesis (see Table 4; fruity: $BF_{10} = .117$; gourmand: $BF_{10} = .229$). Finally, no significant correlation was found between intensity and vertical SRC overall (see Table 4) or by odor category (fruity: rho $= -.016$, $p = .872$; gourmand: rho $= .091$, $p = .343$) and the Bayesian version of the test returned an indication of mostly moderate evidence in favor of the null hypothesis (see Table 4; fruity: $BF_{10} = .126$; gourmand: $BF_{10} = .149$). The same conclusions were reached with exploratory tests using the significant vertical SRC effect based on restricted means.

3.5.2.3. Interim summary. In conclusion:

- the preregistered manipulation checks 2, 3 and 4 confirmed the presence of a difference between categories of odors in perceived pleasantness (fruity being more pleasant), heaviness (fruity being lighter) and intensity (fruity being less intense);
- no significant correlation was found between perceived pleasantness, heaviness, intensity and SRC, overall and by category.

3.5.3. *Manipulation check 5: odor identification*

3.5.3.1. ❧ Relation between overall odor identification and the vertical SRC effect (preregistered). On average, participants correctly identified 50.15% ($SE = 1.74$) of the odors (see Table 4). The identification rate was unrelated to the vertical SRC effect (rho $= .007$, $p = .942$) and the Bayesian version of the test returned an indication of moderate evidence in favor of the null hypothesis ($BF_{10} = .126$). The same conclusions were reached with an exploratory test using the significant vertical SRC effect based on restricted means.

3.5.3.2. Relation between odor identification and the vertical SRC effect for the fruity category (exploratory). Identification rates were tested separately for fruity ($M = 45.45\%$, $SE = 2.75$) and gourmand ($M = 54.85\%$, $SE = 2.26$) categories, in relation to their respective SRC effects, and no significant correlation was found (*ps* > .159; fruity: $BF_{10} = .127$; gourmand: $BF_{10} = .681$).

3.5.3.3. Interim summary. In conclusion:

- the preregistered test between identification rates and overall SRC effect did not detect a significant correlation;
- an additional analysis restricted to the fruity category did not detect a significant correlation between identification rates and the SRC effect.

4. Discussion

The literature on crossmodal correspondences between pitch and olfactory stimuli has documented systematic associations. However, what characteristic of olfactory stimulation is relevant in guiding the mapping with pitch frequency and its underlying mechanism are still unclear. It has been shown that the choice of pitch for a certain odor is not ruled simply by a mapping with its semantic or hedonic aspects (Belkin et al., 1997; Crisinel et al., 2013; Crisinel & Spence, 2012; Speed et al., 2021; Stevenson et al., 2012; Ward, Wuerger, & Marshall, 2022). Moreover, odors and tones rarely co-occur in the environment in a manner that would support learning through internalization of statistical regularities. In the fields of spatial cognition and multisensory integration, it has been shown that certain characteristics of auditory stimulation, such as pitch height, can elicit attentional orientation along the vertical axis, regardless of the site of stimulation (e.g., central *vs* lateralized) and induce facilitation effects (faster RTs and higher accuracy) during the localization of stimuli in visual search tasks (Evans & Treisman, 2010). Although according to some authors the association between auditory pitch and spatial elevation might have a semantic/linguistic component (Dolscheid et al., 2020), where the use of the terms “high” and “low” influences the correspondence with pitch-height, studies have shown that this association appears early in the development, even before language acquisition (Dolscheid et al., 2014), it can be observed when pitch height is task-irrelevant (Rusconi et al., 2006) and in populations that do not use vocabulary referring to spatial elevation to indicate pitch (Parkinson et al., 2012). This suggests that the association between pitch and spatial elevation may reflect universally predisposed perceptual correspondences (Fernandez-Prieto et al., 2017; Parkinson et al., 2012) and/or originate in environmental statistics (Parise et al., 2014). On the other hand, in perfumery, scents are represented using a vertically structured model, the olfactory pyramid, and are described using vocabulary that evokes verticality (e.g., top, middle and base notes). This visuo-spatial representation and linguistic terminology may not be accidental or purely metaphorical but provide phenomenological evidence that the cognitive system assigns vertical spatial coordinates to olfactory qualities. Such assignment may be based on physicochemical characteristics subtending odor volatility and persistence. Thus, in parallel with established evidence attributing a significant role to pitch in spatial cognition, it is possible to hypothesize the existence of a functional and structural analogy between different olfactory qualities and pitch frequency, such that also olfactory qualities might be represented along the dimension of spatial elevation (e.g., Deroy et al., 2013).

The main objective of our study was to investigate whether olfactory quality, typically classified into top/head and base notes based on volatility and persistence, is spontaneously associated with a vertical spatial representation. We therefore tested, in a preregistered study, whether odors, that are normally classified by experts as top notes (lemon, orange, bergamot) and base notes (vanilla, caramel, coffee), and which have individually given rise to crossmodal correspondences with high and low auditory tones respectively, may give rise to a spatial SRC effect in a speeded classification task using non-spatial response categories (i.e., fruity *vs* gourmand). Based on the results of the main confirmatory analysis, it is currently not possible to conclude in favor of the presence of a vertical SRC effect in response latencies for the odor classification task. However, based on preregistered criteria for the interpretation of Bayesian statistics, it is also not possible to adopt a conclusive stance for its absence. Furthermore, an exploratory analysis performed after applying to the same dataset a common alternative pre-processing strategy (Van Selst & Jolicoeur, 1994) and using the same test and significant thresholds as the preregistered analysis, confirmed the presence of a vertical SRC effect. Also in this case, however, the pre-registered criteria for interpreting Bayesian statistics do not enable a conclusive stance.

According to Kornblum's model (1990) in case of a highly automatic process, stimulus-response congruence can be detected in participants' performance regardless of the allocation of attentional resources to (i.e., the task relevance of) the crucial dimension. Conversely, in case of a partially automatic process, the effect of dimensional overlap is typically modulated by task demands; in particular, it tends to be attenuated or absent in a task where the crucial dimension is not relevant (Kornblum et al., 1984, 1990). Thus, the present results suggest that, unlike auditory tones, odors may have a weaker, or less automatic, association with vertical space. Our odor classification task was based on volatility, conveyed through lexical labels referring to olfactory categories (fruity *vs* gourmand), rather than on dimensions such as intensity or hedonic valence (Belkin et al., 1997; Stevenson et al., 2012; Ward, Wuerger, & Marshall, 2022). Previous studies have shown that odor classification into olfactory macro-categories is linked to a process of perceptual encoding of the quality characterizing olfactory information (e.g., fruity, citrus, floral; Olofsson et al., 2012; Olofsson, 2014). For instance, based on Edwards' (2008) classification of olfactory substances from primary aromatic characteristics of perfumes and dominant olfactory components, Zarzo (2019) analyzed and mapped descriptors, and revealed the effectiveness of such classification - not only in categorizing perfumes but also in reflecting perceptual attributes identified both by experts and inexperienced individuals (Zarzo, 2019). This further supports the use of olfactory descriptors linked to macro-categories (instead of specific names, e.g., lemon) as effective in conveying the structural-perceptual character of an odorous substance to naïve individuals. However, the use of semantic categories as response alternatives in our task may have shifted the focus of attention to a semantic component rather than emphasizing purely structural characteristics of the stimulus. While the encoding of olfactory information begins with the identification of structural characteristics, such as molecular composition, at the bulb and anterior piriform cortex level, this chemotopic organization is not necessarily maintained in subsequent stages of processing, where higher-level representations of perceptual quality are obtained (Gottfried et al., 2006). The latter representations are supported by a complex network of feedback and feedforward connections between primary, secondary areas and the olfactory bulb, and provide the basis for top-down modulation of olfactory information processing (Gottfried et al., 2006). The representation of olfactory quality, therefore, has an integrative and plastic character, which can be modulated through different but not mutually exclusive mechanisms (e.g., sensory context, semantic associations, perceptual learning; Wilson, 2003; Wilson & Sullivan, 2003), including reentrant influences from the olfactory frontal cortex and the hippocampus (Gottfried & Dolan, 2003). It is thus reasonable to expect a modulation of attentional resources devoted to different stimulus characteristics, in relation to their relevance for the current objectives (e.g., foraging, space navigation, peer recognition, identification of potential dangers, etc.) or in relation to task instructions. The use of categories such as “top notes” and “base notes” would represent a more direct form of task, as it would emphasize the structural character of the olfactory stimulus in relation to the dimensions of volatility and persistence. However, the use of such a classification may be less understandable to non-experts and would also complicate result interpretation. Indeed, the potential SRC effect could be attributed to the use of spatial terms rather than to the mapping of olfactory stimuli on elevation.

Another important aspect to consider is that naïve participants were selected for this study, given that the association between pitch and odors was observed both with (presumably) familiar and unfamiliar odors and in samples of participants with (presumably) heterogeneous professional background (our inferences are based on clues in the available literature; no systematic control is reported on odor familiarity or participants’ expertise though; Belkin et al., 1997; Crisinel et al., 2013; Crisinel & Spence, 2012; Stevenson et al., 2012; Ward, Wuerger, & Marshall, 2022). As previously observed for other SRC effects (Umiltà et al., 2018), it is possible that the strength of the effect is modulated by the degree of expertise in the field. This adds to the fact that the use of a classification task with lexical labels referring to odor categories may have determined, in naïve participants, a focus on semantic rather than other perceptual characteristics (e.g., volatility) of the olfactory stimulus. For example, it has been reported that a change in focus from sensory to conceptual stimulus characteristics may even induce reverse SRC effects (Vicovaro & Dalmaso, 2021). Asking a sample of experts (e.g., from the perfumery industry), who tend to pay more attention to volatility information due to professional habits, to perform the task could thus provide a more sensitive test for our main hypothesis. Additionally, in a preliminary study where a significant vertical SRC effect for odors was reported, participants were generally slower (200–300 msec) than the participants of the current study in performing the required task, and showed a significant vertical SRC effect in the expected direction (Caldana & Rusconi, 2023). This suggests that response latency, in relation to the depth of information processing may be a critical variable for detecting access to a spatial code in the context of our speeded classification task (Caldana & Rusconi, 2023). According to the cascade model, different features become accessible to the perceiver at different time points, depending on the type of task (Olofsson, 2014). It is therefore plausible that the judgment required of participants may have led to a rapid processing of categorial information (i.e., related to task-relevant characteristics), whereas a task-irrelevant spatial code may require relatively longer to influence response selection. This possibility is further supported by the pattern of SRC effects across subgroups of participants that emerged from the exploratory cluster analysis where, notably, a large (in absolute value) SRC effect was found only in the slower subgroups.

An interesting aspect emerging from exploratory analyses is the different pattern for the two odor categories with respect to the vertical SRC effect. Specifically, in analyses conducted in the same fashion as the preregistered analysis but separately for each category, a significant difference was found between the compatible and the incompatible condition for the fruity category (incompatible RTs > compatible RTs), whereas no such difference was found for the gourmand category. Nevertheless, the vertical SRC effect observed for the fruity category was significantly correlated with the difference between incompatible and compatible conditions in the gourmand category, suggesting a potential role for individual differences in the relation between odors and vertical space. In light of this result, a cluster analysis was also conducted (see below). Although the group-level asymmetry between the two categories of odors in respect to the vertical SRC effect, with fruity odors showing a significant SRC effect and gourmand odors not showing any effect, was not predicted, this is not an infrequent find in the vertical SRC literature. For example, Vicovaro and Dalmaso (2021; Experiments 1 and 2) found an asymmetry whereby “heavier” but not “lighter” responses showed a significant advantage when associated with one of the response buttons (heavier was significantly faster with top than with bottom responses). Asymmetries have also been previously reported in the literature on spatial processing with crossmodal stimulation (Fernandez-Prieto & Navarra, 2017), and related to cognitive and neurological biases towards stimuli with certain sensory characteristics (e.g., sounds with high frequency) for stimulus localization purposes (Fernandez-Prieto & Navarra, 2017; Kishon-Rabin et al., 2004; Masterton et al., 1969). In the case of olfactory stimuli, volatility is key for detecting the presence of any odorous substances (Amoore & Buttery, 1978; Steele et al., 2023), where the greater the volatility of a substance, the faster and easier it is to detect and possibly locate it in space (Teixeira et al., 2009). Therefore, more volatile substances may convey spatial information more readily than less volatile substances. A further asymmetry related to substance volatility can be found in the timescale, and consequently the distribution, by which molecules with different volatility migrate through the nasal cavity. Less volatile molecules tend to migrate less rapidly, producing an irregular distribution of the odorant along the mucosa and resulting in a slower, more gradual signal development, whereas more volatile molecules show a more uniform and fast distribution along the flow path, reaching the olfactory epithelium more quickly and in a concentrated form (Hornung, 2006; Kent et al., 1996; Youngentob et al., 1995). Therefore, given the same stimulation duration, more volatile molecules are distributed more evenly and with greater concentration at the receptor surface, and could more easily reach the critical threshold level for subsequent processing. This, in turn could allow a sufficiently rapid spread of activation to the associated spatial codes to influence response selection. Thus, one possible reason for the documented asymmetry in the SRC effect can be traced back to the physicochemical properties of the odorants. More specifically, differences in space-time development would cause faster access from the more volatile substances (Texeira et al., 2009) to their associated spatial code, which could then facilitate the selection of a compatible response even when the classification judgment is given in a relatively short time.

To further explore the potential contribution of individual differences, an exploratory cluster analysis has been conducted. The analysis identified three distinct subgroups of participants based on their overall SRC. The two slower subgroups presented a large SRC in absolute value both for fruity and for gourmand odors. On the other hand, the fastest and largest subgroup showed a smaller overall SRC, driven by the fruity category. This pattern appears in line with the hypothesis that, with more volatile odors, the spatial code is accessed in advance of the less volatile compounds and may start influencing response selection earlier even though not yet to its full potential. Currently, these considerations remain speculative. Nevertheless, they open promising avenues for future research. On the one hand, they call for further investigation into the spatial–temporal characterization of olfactory information and, on the other, they highlight the need for additional studies to clarify the conditions under which the relationship between space and perceptual dimensions becomes asymmetric and/or reverse (Lakens, 2012). Indeed, although a predominant tendency to activate the expected spatial coding emerged overall, a subgroup including about one third of the sample showed a strong reverse SRC effect. Overall, considerable inter-individual variability in performance has been documented in the literature on established spatial SRC effects (Fias, 1996; Keus et al., 2005). Specifically, in previous studies, different SRC profiles have been documented within domain and between domains despite the use of similar tasks. For example, different subgroups with SRC effects of different sign were identified in a sample from the same population (Beecham et al., 2009). The presence of subgroups with opposite response patterns may explain in part the large variability and small differences between incompatible and compatible RTs reported in previous studies on SRC effects and in our group analysis. Potential key factors driving such variability have been suggested, such as expertise, response inhibition abilities, cognitive speed or even gender-related predispositions but the experimental literature has paid scarce attention to these factors, being typically focused on group effects (e.g., Beecham et al., 2009; Kanai & Rees, 2011; Rusconi et al., 2006). On the basis of our study, it was not possible to identify the source of such variability and the issue would need to be addressed in future ad hoc studies.

Interestingly, in line with and extending the existing literature, our preregistered analysis on manipulation checks confirmed the presence of a crossmodal correspondence effect between auditory pitch frequency and categories of odor stimuli (top and base notes). Incidentally, no relation was found between such odor-pitch crossmodal correspondence effect and the difference in pleasantness, familiarity, intensity and lightness-heaviness dimension between categories (all $ps > .13$, uncorrected). This finding supports the validity of the olfactory stimulus set employed. It is consistent with the hypothesis that the physicochemical structure of olfactory stimulation—metaphorically classified into top and base notes—is the dimension that plausibly drives the mapping between pitch and odor, and suggests that olfactory information can be aligned along the volatility gradient with the frequency of auditory tones. From this perspective, odor-pitch correspondences may reflect an underlying alignment between sensory dimensions constrained by the intrinsic structure of the stimuli themselves in terms of spatiotemporal evolution of the signal. This supports the need to further investigate spatiotemporal patterns of olfactory stimulation to better understand the perceptual organization of odor qualities and to establish links between molecular composition and perception. Preregistered analyses on manipulation checks did not confirm the relation between the odor-pitch crossmodal correspondence and the difference between incompatible and compatible RTs in the odor classification task. However, the absence of a significant correlation does not rule out the intriguing possibility that both odors and auditory tones are mentally mapped along the vertical axis. Indeed, such mental spatial representations may belong to domain-specific representation systems, as previously observed for auditory pitch and numerical magnitude (Beecham et al., 2009). This invites further exploration into how sensory information is organized across modalities. For example, no overlap was found in the literature between individual profiles for SRC effects across different domains (e.g., music and mathematics; Beecham et al., 2009). Finally, on average our participants correctly identified half the odors. This outcome was expected, given that humans generally exhibit a limited ability to verbally identify odors (Yeshurun & Sobel, 2010). The well-documented tip-of-the-nose phenomenon illustrates how, despite a sense of familiarity with an olfactory stimulus, accurate identification often remains elusive (Cain, 1979; de Wijk et al., 2014; Lawless & Engen, 1977). Preregistered and exploratory analyses on manipulation checks did not detect a relation between the spatial SRC effect and recognition levels. This finding was also expected and is consistent with the hypothesis of a potential role of physical-chemical perceptual features related to odor quality (e.g., volatility) rather than a possible semantic component in driving the SRC effect.

From an evolutionary perspective, smell is considered the oldest sensory system (Nijland & Burgess, 2010). Elementary olfactory mechanisms, such as chemotaxis, can already be observed in single-cell organisms and play a crucial role in approach and avoidance behaviors, highlighting the primary role of chemical senses in survival processes and spatial navigation (e.g., Nijland & Burgess, 2010). Even for human beings, in eras prior to the diffusion of artificial lighting, information from distal senses, such as hearing and smell, contributed substantially to spatial orientationin the surrounding environment through learning and memorization of relevant auditory and olfactory information, to find food and avoid environmental hazards (Hudson, 1999). Anecdotal accounts abound on the ability of sailors, hunters, and early aviators to exploit the statistical regularities of odor distribution in the air to define their position in space (Gatty, 1983). However, the specific contribution of smell to spatial navigation in humans remains relatively unexplored at the experimental level (Jacobs et al., 2015). Moreover, in recent years, numerous studies have dealt with the design of olfactory interaction in physical spaces, such as museums, exhibition environments, and automotive contexts, proposing diverse technological and conceptual solutions. For instance, olfactory stimulation contributes to increasing the feeling of presence (Ando et al., 2010) and has become part of museum installations to promote visitors' involvement (Lai, 2015). In light of studies showing that specific odour stimuli can increase alertness (Gould & Martin, 2001), an application of olfactory stimulation directed at drivers has been proposed in order to counteract drowsiness while driving through the use of activating odors (Funato et al., 2009; Yoshida et al., 2011). However, the design of olfactory interfaces still lacks a standardized methodology and design. Questions remain regarding the management of the spatial and temporal characteristics of olfactory stimulation, such as diffusion patterns, intensity, the distance between the source and the user, and airflow dynamics. There is therefore a need to expand research through systematic studies in order to identify ways of using smell as a functional mode of information transmission and interaction (Dmitrenko et al., 2017). The present evidence, based on preregistered analyses, currently does not allow to unequivocally conclude for the existence or the absence of a vertical SRC effect for odors. However, a series of exploratory analyses opens up multiple trajectories of investigation and suggests it could be worth to pursue this line of inquiry further. Indeed, the majority of individuals may represent olfactory categories in spatial format and, potentially, in a domain-specific manner. Modifying task instructions or employing different experimental paradigms could further disambiguate the data obtained and provide converging evidence on whether olfactory qualities might fall in the wide range of perceptual dimensions that are spatially represented. In light of these considerations, it seems particularly important to broaden the investigation into how the physico-chemical structural constraints of olfactory stimuli give rise to differential spatiotemporal processing patterns. Complementary studies could also be developed to investigate subjective spatial representations using qualitative measures, and it appears necessary to identify and investigate potential intervening variables underlying individual variability in spatial mapping. For instance, expertise in perfumes might drive a more consistent mapping in the expected direction. Finally, future efforts should consider the adoption of analytical strategies that could guarantee both robustness and sensitivity.

CRediT authorship contribution statement

MC: Conceptualization, Investigation, Methodology, Project administration, Resources, Writing—review & editing, Writing—original draft preparation.
ER: Conceptualization, Methodology, Project administration, Data curation, Formal Analysis, Visualization, Writing—review & editing, Writing—original draft preparation, Resources, Supervision.

Conflict of interest

The authors of this article declare that they have no financial conflict of interest with the content of this article.

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Scientific transparency statement

DATA: All raw and processed data supporting this research are publicly available: https://osf.io/8tr3c.
CODE: All analysis code supporting this research is publicly available: https://osf.io/8tr3c.
MATERIALS: Some study materials supporting this research are publicly available, while some are subject to restrictions: https://osf.io/8tr3c.
DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.
PRE-REGISTRATION: At least part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted: https://osf.io/jxk7p At least part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted: https://osf.io/jxk7p.
For full details, see the *Scientific Transparency Report* in the supplementary data to the online version of this article.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2026.02.010.

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