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Olfactory crossmodal redirection for improving perceptual experiences in virtual reality

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Virtual reality (VR) environments rely on multisensory integration to create convincing perceptual experiences, but delivering many distinct odours is costly and technically challenging. We tested whether visual context is associated with context-dependent differences in evaluations of a compressed odour set in VR. Thirty participants viewed 20 distinct visual scenes while experiencing four odour blends representing floral, citrus, woody, and oriental; eight control scenes received randomly assigned blends or no odour. The family-congruent conditions reused the same physical odour blend across different visual contexts, and linear mixed-effects models (LMMs) assessed associations between the observed visual-odour conditions and the perceptual and physiological outcomes. The LMMs showed variation between visual stimulus and perceived visual-odour match, smell naturalness, and heart rate variability (HRV). No statistically significant associations were observed for perceived odour intensity, pleasantness, visual naturalness, or galvanic skin response (GSR). Odour family was not associated with statistically significant variation in the subjective ratings but was associated with HRV within the observed visual-odour pairings. Exploratory within-blend comparisons showed that these effects varied across blends and outcome measures. Stimulus-level Pearson correlations were then conducted as secondary, hypothesis-guided analyses to characterise whether the observed condition-level evaluation profiles covaried with perceived visual-odour match. Perceived visual-odour match was significantly associated with perceived intensity ($r = 0.90$), perceived pleasantness ($r = -0.78$), and smell naturalness ($r = 0.92$), but not with visual naturalness, HRV or GSR. These correlations indicate that perceived match was associated with a broader perceptual profile rather than being an isolated semantic judgement of fit. This pattern may be consistent with a congruence-based account of crossmodal redirection, but we cannot prove that account. Overall, the findings indicate that the same physical odour blends were associated with selective, context-dependent differences in evaluation across visual scenes in VR.

KEYWORDS
crossmodal perception, galvanic skin response, heart rate variability, multisensory integration, odour perception, olfactory display, virtual reality, visual-olfactory congruence

1 Introduction

In recent years, virtual reality (VR) has emerged as a powerful tool to create immersive environments, in turn creating opportunities to explore how multisensory stimuli may influence human perception. Olfactory perception and olfactory display systems (Micaroni et al., 2019) remain relatively underexplored because of their technical complexity. Current olfactory displays are constrained by the small number of odour channels they can support. This makes it difficult to deliver varied and contextually appropriate scent experiences without increasing hardware complexity, cost, and the risk of odour contamination. In VR, odours are typically delivered through an olfactory display that presents odours programmatically. These systems rely on the use of essential and/or fragrant oils and bespoke hardware (Yanagida et al., 2004; Yamada et al., 2006; Micaroni et al., 2019; Niedenthal et al., 2023). Vision relies on the concept of primary colours (red, green, and blue) to generate a wide range of different colours. The same premise, at least for now, cannot be applied to synthesise odours. Current olfactory displays typically support only a small number of physically distinct odour channels (often around 4) (Yanagida et al., 2004; Yamada et al., 2006; Micaroni et al., 2019; Niedenthal et al., 2023) due to hardware, cost, control, and physical space constraints. Therefore, providing more odours, or at least the illusion of odours, to be used in VR would be greatly beneficial for creating more immersive and realistic experiences. Building on this, our approach focuses on expanding the perceived olfactory space by combining a limited number of physical odours with systematically varied visual contexts. Rather than changing the physical properties of individual odours, our broader goal is to increase the apparent variety of olfactory experience using a compressed physical odour set. We refer to this as olfactory crossmodal redirection. In the present study, this term denotes context-dependent changes in higher-level odour evaluations (e.g., perceived visual-odour match, smell naturalness) and associated physiological responses (e.g., heart rate variability (HRV)) when the same physical odour blend is paired with different visual scenes in VR. We do not claim that visual context creates new odour identities; rather, we test whether a limited set of blends can support multiple, context-specific evaluation profiles across different visuals.

Here, 'apparent variety' refers to context-dependent changes in higher-level odour evaluations (e.g., perceived match and smell naturalness) and associated physiological responses (e.g., HRV and galvanic skin response (GSR)), rather than to an increase in the number of physically distinct odours. Our primary research aim was to test whether visual context is associated with context-dependent differences in evaluations of a compressed odour set in VR. Because immersive VR experiences are not only perceptual but also affective and physiological, we also consider autonomic responses as part of this apparent variety. Here, redirection refers to context-dependent differences in the evaluation of a fixed odour when it is paired with different visual information. The physical odour remains unchanged; the present study therefore examines whether evaluations such as perceived visual-odour match and smell naturalness vary across visual contexts.

Previous studies demonstrate that our senses do not operate in isolation and that visual context can systematically shape smell perception. Colour cues can bias odour and flavour judgements (Zellner and Kautz, 1990; Zellner and Whitten, 1999), and manipulating visual colour can lead people to misidentify the underlying flavour (DuBose et al., 1980). Smell and taste are deeply intertwined, with over 80% of what we taste coming from our sense of smell (Spence, 2015). Neuroimaging work has shown that semantic congruence between images and odours engages the crossmodal associative mechanism in the hippocampus (Gottfried and Dolan, 2003). Our prior work indicates that odours can also influence colour perception, suggesting bidirectional links between visual and olfactory processing (Ward et al., 2023). Age-related changes in olfactory function and potential sex/gender differences in smell perception suggest that these factors may influence how participants experience olfactory stimuli (Boyce and Shone, 2006; Wang et al., 2019). Taken together, these findings indicate that visual context can be associated with differences in how odours are categorised and experienced. They provide a foundation for examining whether visual information in VR is associated with context-dependent differences in the evaluation of a limited odour set. Individual differences, such as age and sex/gender, may also moderate olfactory crossmodal redirection, given age-related changes in olfactory function and potential sex/gender differences in smell perception (Boyce and Shone, 2006; Wang et al., 2019). Despite evidence that vision is associated with differences in odour perception, it remains unclear whether VR visuals are associated with multiple context-dependent evaluation profiles for a limited odour set.

Incorporating olfactory stimuli into VR can enhance realism and immersion (Archer et al., 2022) to create richer and multidimensional virtual environments. Multisensory approaches in VR typically outperform purely visual experiences (Melo et al., 2022) in domains such as training simulations (Spencer, 2006), virtual tourism (Manchanda and Deb, 2022), improving performance in tasks (Cooper et al., 2018; Marucci et al., 2021), and overall experience (Cooper et al., 2018). Smell is uniquely tied to memory, emotion, and context (LeDoux, 2007) and has been shown to influence people's perception (Djordjevic et al., 2008; Ghinea and Ademoye, 2012; Sabiniewicz et al., 2021) and physiological responses (Djordjevic et al., 2008; Hedblom et al., 2019; Marucci et al., 2021), supporting its use in diverse applications. Incorporating the chemical senses (smell and taste) into VR is a further step towards more immersive experiences. Empirical work has shown that adding odour cues to virtual environments can enhance presence (Archer et al., 2022), improve task performance and workload (Marucci et al., 2021), and reduce physiological stress in nature scenes (Hedblom et al., 2019). Taken together, these findings suggest that while odour can enhance immersion and presence in VR, its impact is tightly coupled with multisensory context, motivating our focus on how visual context can be used to redirect and enrich olfactory experiences in VR.

In immersive VR, prior studies have typically paired a small number of scenes (often 2–3) with one or a few odours and manipulated semantic congruence between the visual and olfactory stimuli (Manesse et al., 2020; Sabiniewicz et al., 2021; Archer et al., 2022). These experiments generally present congruent, incongruent, and no-odour control conditions in block or trial-wise designs, with exposure durations ranging from fixed intervals to self-paced exploration (Hedblom et al., 2019; Sabiniewicz et al., 2021; Archer et al., 2022). Across these paradigms, strong congruent

pairings (e.g., rose odour with a rose garden, orange odour with an odour basket) are used to modulate the perceived pleasantness, presence, and, in some cases, memory for the environment, whereas weakly congruent or ambiguous combinations produce smaller or null effects (Ripp et al., 2018; Manesse et al., 2020; Sabiniewicz et al., 2021; Archer et al., 2022).

Physiological measures such as heart rate, HRV, and GSR have been used sparingly in the literature, with some evidence that congruent multisensory environments influence autonomic indices, although findings are not uniform across studies (Hedblom et al., 2019; Kuhne et al., 2023). More broadly, work on multisensory integration suggests that incongruent or unexpected crossmodal combinations can increase cognitive load and arousal, which in turn may be reflected in reduced HRV and elevated GSR, whereas congruent combinations are often associated with more efficient processing and more positive affective appraisal (Calvert et al., 2005; Spence, 2015). Including HRV and GSR alongside perceptual ratings allows us to examine whether condition-level variation is observed in subjective judgements, autonomic measures, or both. If perceived visual-odour match is associated with physiological responses, this would indicate that match covaries with a broader physiological profile rather than representing only an isolated semantic judgement of fit. Such associations would provide converging evidence that well-matched visual-odour pairings may support richer, more physiologically engaging multisensory experiences, which is relevant to immersion, presence, and potential applied uses of olfaction in VR.

Building on the literature, we examine olfactory crossmodal redirection as a framework for testing whether visual context is associated with context-dependent differences in evaluations of a compressed odour set. Our primary research aim was to test whether visual context is associated with context-dependent differences in evaluations of a compressed odour set in VR. The family-congruent conditions reused the same physical odour blend across different visual contexts. Perceived visual-odour match was the central measure of perceived congruence. As a secondary, hypothesis-guided analysis, stimulus-level correlations characterised whether the observed condition-level evaluation profiles covaried with perceived visual-odour match. These correlations were descriptive and associational; they were not causal or mediation tests. We hypothesised that visual context would be associated with systematic differences in odour evaluation, particularly perceived visual-odour match and smell naturalness, while recognising that the partially crossed design does not permit fully independent estimates of visual and odour-family effects. We further examined whether perceived match covaried with other perceptual and physiological measures, including odour intensity, pleasantness, smell naturalness, visual naturalness, HRV, and GSR. In addition to subjective ratings, physiological measures can reveal how multisensory context modulates autonomic engagement.

HRV reflects parasympathetic regulation and emotion valence, with higher variability typically reflecting more positive engagement (Malińska et al., 2015; Marín-Morales et al., 2021) and GSR indexes sympathetic arousal and cognitive-emotional load, capturing phasic changes in skin conductance associated with attention and stress (Kuhne et al., 2023; Caldas et al., 2024). In the context of multisensory and VR research, higher HRV is typically interpreted as indicating greater parasympathetic (vagal) engagement and more regulated or positive affective appraisal of the experience, whereas higher GSR is interpreted as indicating greater sympathetic arousal and/or cognitive-emotional load (Shi et al., 2007; Thayer et al., 2012; Kuhne et al., 2023). Including HRV and GSR alongside perceptual ratings allowed us to assess whether condition-level variation was also observed in autonomic activity or was limited to subjective judgements. Prior work shows that autonomic cardiac control, indexed by high-frequency heart rate variability (HF HRV), is sensitive to congruency between internal bodily signals and external feedback. In a biofeedback paradigm, low-level congruency between visual cardiac feedback and participants' actual heartbeat systematically modulated HRV, independently of regulation instructions (Hodossy and Tsakiris, 2020). This provides evidence that autonomic responses can covary with experimentally manipulated congruence.

In immersive and multisensory environments, combining visual and olfactory cues has been shown to alter physiological markers of relaxation and autonomic balance, including HRV and heart rate. Studies of garden plant stimuli and other naturalistic VR settings report that combined visual-olfactory stimulation produces larger changes in HRV and related indices than unimodal stimulation, consistent with multisensory integration influencing autonomic state (Lopes and Falk, 2024). We hypothesised that congruent visual-odour pairings would be rated as more appropriate and more natural than less congruent or random pairings, and that these differences would be reflected in HRV and, potentially, GSR. Specifically, we expected that more congruent (higher-match) pairings would be associated with higher HRV, consistent with more positive or regulated affective appraisal, and lower GSR, consistent with reduced sympathetic arousal and cognitive load; these predictions were exploratory given the limited and mixed prior evidence in olfactory-visual VR contexts.

Our study extends existing work on visual-odour congruence and olfactory VR in three ways. First, rather than pairing many distinct odours with specific scenes, we use a compressed set of four multicomponent blends representing the fragrance families and systematically reuse each blend across multiple visuals and random controls, directly testing whether a limited physical odour palette can support context-dependent variety in evaluation. Second, we treat perceived visual-odour match as a central measure of crossmodal congruence and redirection, examining how this match relates to intensity, pleasantness, visual naturalness, olfactory naturalness, HRV, and GSR. Third, we combine these perceptual measures with autonomic indices (HRV and GSR) to assess whether context-dependent differences in odour evaluation are accompanied by differences in physiological response in immersive VR. Together, these contributions address whether a compressed odour set is associated with context-dependent differences in evaluation when the same physical blends are paired with multiple visual contexts, without increasing hardware complexity. This design builds on prior VR work on visual-olfactory congruence and multisensory experiences (Manesse et al., 2020; Sabiniewicz et al., 2021; Archer et al., 2022), extending it in two key respects: first, whereas previous studies have typically examined a small number of scenes and odours, often pairing individual odours with a specific visual environment (Manesse et al., 2020; Sabiniewicz et al., 2021; Archer et al.,

TABLE 1 Overview of independent, dependent, and derived variables.

Type	Variable	Description/Levels	Measurement/Unit
Independent	Visual stimulus	20 virtual objects (3 per fragrance family +8 random controls)	Categorical (20 levels; trial-wise)
Independent	Odour category	Citrus, floral, woody, oriental; random assignment for 8 control stimuli; no odour scenes	Categorical (5 levels including random/no odour)
Independent	Participant ID	Individual participant identifier	Categorical
Independent	Age	Age of the participant	Continuous, years
Independent	Gender	Gender of the participant (only male or female)	Categorical
Dependent	Q1: Odour intensity	"How intensity is the smell?"	9-Point likert (1–9), per trial
Dependent	Q2: Odour pleasantness	"How pleasant is the smell?"	9-Point likert (1–9), per trial
Dependent	Q3: Perceived match	"Does this smell match this object?"	9-Point likert (1–9), per trial, used as the central continuous measure of perceived visual-odour congruence
Dependent	Q4: Smell naturalness	"How natural is the smell?"	9-Point likert (1–9), per trial
Dependent	Q5: Visual naturalness	"How natural is the visual?"	9-Point likert (1–9), per trial
Dependent	HRV	HRV during each exposure	SD of inter-beat intervals (ms) per trial
Dependent	GSR	GSR peak amplitude during each exposure	µS (skin conductance) per trial
Derived	Mean ratings per stimulus	Mean Q1-Q5 per visual–odour pairing	Average across participants for each visual stimulus
Derived	Mean HRV/GSR per stimulus	Mean HRV and GSR per visualodour pairing	Average across participants for each stimulus

2022), we systematically reuse the same physical odour blends across multiple visuals within each fragrance family, explicitly testing whether a compressed palette can support context-dependent variety. Second, we treat perceived visual-odour match as a central continuous measure of crossmodal congruence and combine it with trial-wise physiological recordings (HRV, GSR), allowing us to examine how subjective and autonomic responses vary across observed visual-odour conditions, including family-congruent conditions in which the underlying physical blend is held constant across visual contexts (Hedblom et al., 2019; Kuhne et al., 2023). By combining perceived match with HRV and GSR, we examine whether condition-level evaluation profiles covary with autonomic measures in addition to subjective ratings.

2 Materials & methods

2.1 Study design

This study used a within-subject, repeated-measures experimental design in an immersive VR environment. Each visual stimulus was paired with one odour category per trial; congruent pairings were fixed by design, and random control pairings were randomised across participants, yielding a partially crossed design. The visual-odour factors were not fully crossed: presenting all 20 visual objects with each of the four odour blends would have required 80 odour exposures and 400 questionnaire responses per participant. Given the risk of olfactory adaptation and carryover, together with participant fatigue associated with prolonged repeated odour exposure, we prioritised a reduced within-subject design that reused each blend across multiple family-congruent visuals and included randomised control pairings. This pragmatic design reduced participant burden but meant that visual object and odour blend were not fully orthogonal; consequently, their independent effects cannot be estimated in a fully orthogonal manner. In this study, HRV (SD of inter-beat intervals) is interpreted as an index of parasympathetic engagement and emotion regulation, with higher values reflecting greater vagal tone and more regulated or positive affective appraisal of the multisensory experience. GSR (maximum conductance within each exposure) is interpreted as an index of sympathetic arousal and cognitive-emotional load, with higher values reflecting greater autonomic arousal and/or attentional demand. These interpretations are consistent with prior work linking HRV to parasympathetic regulation and emotion (Thayer et al., 2012; Malińska et al., 2015; Marín-Morales et al., 2021) and GSR to sympathetic activation and cognitive load (Shi et al., 2007; Kuhne et al., 2023; Caldas et al., 2024). Table 1 summarises the independent, dependent, and derived variables used in this study.

The study had two linked analytical objectives. First, we used linear mixed-effects models (LMMs) to examine whether the observed visual-odour conditions were associated with variation in perceptual and physiological responses, with participant included as a random intercept. These models addressed the primary research

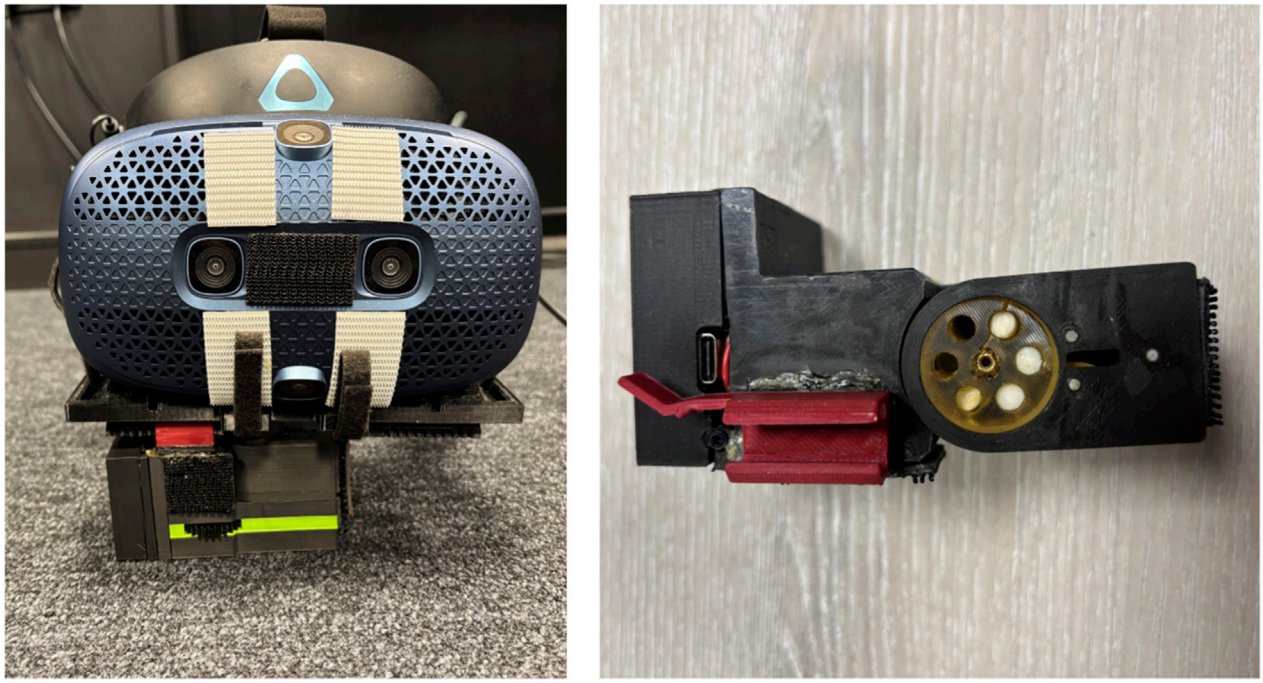


FIGURE 1
Odour-delivery apparatus used in the experiment (Left) The rotary olfactory display mounted on an HTC VIVE Pro headset of the same model as used in the study; the exact headset used for data collection was not available for photography, so a different headset is shown. Calibrated servos rotated the odour wheel to position the target chamber directly beneath the participant's nostrils (≈5 cm) (Right) Top-down view of the odour wheel showing the six chambers, each containing a cotton sliver saturated with essential oil blend (four active odour chambers and two clean-air chambers). This is the actual apparatus that was used to deliver odours in the experiment. An airtight seal was placed over the cotton slivers during the experiments. The odour was rotated under the participants' nose during odour presentation, and a clean, unscented chamber was rotated under the participants' nose when no odour was presented. A small fan pushed scented air from under the user's nose into a carbon filter between trials to minimise odour residue.

aim by assessing associations between the observed visual-odour conditions and the perceptual and physiological outcomes within the partially crossed design.

As a secondary, hypothesis-guided analysis, we examined whether the observed condition-level evaluation profiles covaried with perceived visual-odour match, the central measure of perceived congruence. Stimulus-level Pearson correlations characterised whether pairings with higher perceived match also tended to show different odour-related ratings and physiological values.

2.2 Participants

Thirty participants were recruited for the experiment (12 men and 18 women). The participants ranged from 18 to 63 years old (M = 32.6, SD = 14.5). Inclusion criteria: adults aged 18+ with normal or corrected-to-normal vision, no self-reported history of chronic olfactory impairment (e.g., recent COVID-19, anosmia, parosmia, cold, or flu), no colour vision deficiencies (e.g., colour blindness), and no acute respiratory illness. No participants reported any olfactory impairment (i.e., COVID, cold, or flu). No participants reported any issues with their colour vision. Twenty-four participants reported using VR at least once prior to the experiment, and six reported having never used VR. Participants were instructed not to wear any scented deodorants or perfumes on the day of the experiment. The experiment obtained ethical approval from the University of Liverpool and was conducted in accordance with the Declaration of Helsinki's standard for medical research involving human subjects. Participants were recruited using a variety of resources (posters, word of mouth, and mass e-mail).

2.3 Hardware setup

The experiment was conducted in a dedicated VR space, allowing for large room-scale tracking. An HTC VIVE Pro VR headset was used to deliver the visuals and the audio to the participants. Outside-in tracking was used with three VIVE Lighthouses to ensure reliable tracking of the user inside the virtual environment. The GSR data was collected using a Shimmer3 GSR+ (Shimmer Sensing) and was connected to the experiment PC using Bluetooth. Heart rate data for subsequent HRV calculation was recorded using an optical ear-clip sensor (Seeed Studio, ear-clip heart rate sensor) attached to an Arduino and connected to the spare USB port on the HTC VIVE headset and transmitted over a serial connection. All data was logged in real time along with timestamps. A custom 6-chamber rotary olfactory display (Immersive Laboratory, University of Liverpool) delivered odours programmatically when the participants' virtual nose approached smellable objects (<10 cm). Four active chambers each contained a cotton sliver saturated with three drops (≈0.15 mL) of an essential oil blend, with two inactive/clean air chambers; this is shown in Figure 1. Calibrated servos rotated the odour wheel to position the target chamber directly beneath the participants' nostrils (≈5 cm). Isolated chambers prevented odour mixing. A User

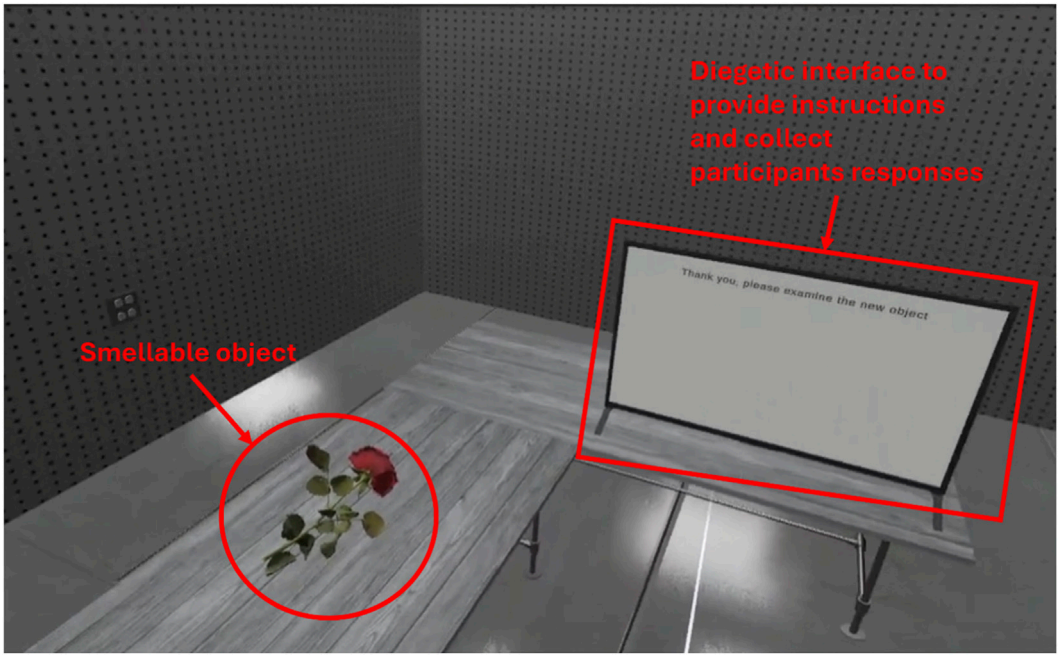


FIGURE 2
Sample screenshot of the virtual environment utilised in the experiment. Simple Garage | 3D Interior | Unity Asset Store. Used under the license provided by the Unity Asset Store.

Datagram Protocol connection was used to send commands from the experiment PC to the olfactory display.

2.4 Apparatus

The experiment was programmed using Unity 2021.3.2f. The experiment included five questions, presented to participants in the following order.

1. How intense is the smell
2. How pleasant is the smell
3. Does this smell match this object
4. How natural is the smell
5. How natural is the visual

Each question was rated on a nine-point Likert scale (1–9). The response endpoints were displayed to participants in the VR questionnaire interface: Q1 ranged from "cannot smell" (1) to "very intense" (9); Q2 from "very pleasant" (1) to "very unpleasant" (9); Q3 from "not similar at all" (1) to "exactly" (9); and Q4 and Q5 from "very artificial" (1) to "very natural" (9). Participants had to smell each object at least once to answer the questions (see Section Olfactory & Visual Stimuli for more information). Participants were not restricted to smelling each object for a fixed amount of time, as olfactory sensitivity, sniffing behaviour, and perceptual latency can vary substantially from person to person; allowing self-paced exposure helped ensure that each participant could adequately sample the odour before making a judgment. Twenty different virtual objects were implemented for this experiment. Each object has a corresponding smell. When the participant's virtual nose was in range of the object, the odour was triggered; similarly, if the participant were to move their head away from the object, the smell would stop being released. A sniffing sound was played every time a smell was released as a cue to prompt the participant to sniff (short nasal inhale cue, ≈0.5s). A minimum of 5 seconds was required between each sniffing cue to stop the sound from being overplayed. Each block of five questions was presented after the participant sniffed the object, resulting in each participant needing to answer one hundred questions in total. The experiment took, on average, 16 min (min = 12 min, max = 29 min). Figure 2 shows the virtual environment that was set up for this experiment.

2.5 Olfactory and visual stimuli

Considerable planning was devoted to the creation of each scent (e.g., it was not deemed appropriate to mix scents) and the selection of the visual stimuli presented to the users. Essential oil blends were used for the purpose of this experiment. Four blends were selected to align with the fragrance wheel families (citrus, woody, floral, and oriental), and were supplied by the Authentic Oil Co. These are proprietary multi-component blends representing their respective fragrance families, with no single dominant note within each blend, allowing us to reuse each blend across multiple visuals within a family while keeping the physical odour constant. Importantly, the same physical blend was used across multiple visuals within each family, allowing condition-level differences in evaluation to be examined when the physical blend was held constant across those visual contexts. Three different visual stimuli were associated with each odour blend. The random category had eight visual stimuli and was assigned one of the four odour blends or a no-odour condition at random. The order of the stimuli was randomised, and no two runs of the experiment were

TABLE 2 Odour blends and their respective visual stimuli assignments.

Citrus	Woody	Floral	Oriental	Random
Lemon	Campfire	Lavender	Star anise	Books
Lime	Pine tree	Rose	Cinnamon	Comb
Orange	Pile of chopped wood	Tulips	Vanilla ice cream	Bag
				Tires
				Sushi
				Potato
				Pizza
				Empty white mug

The citrus, woody, floral, and oriental blends were each paired with three semantically related visuals, while the eight random visuals received odour assignments that varied across participants.

identical. The visual stimuli were presented in a random order to negate any odour or visual order effects. See Table 2 for the odour and visual pairings. The design included three types of visual-odour pairing: (1) family-congruent (3 visuals per odour family); (2) within-family variations (semantic differences within blends); (3) random incongruent (8 visuals with random odours or a no-odour condition). All visual objects were selected to represent a range of everyday items that vary in real-world size and typical interaction style (e.g., small handheld objects such as lemons and limes, *versus* larger objects such as a campfire or pile of chopped wood). Our design principle was that participants should be able to interact with each virtual object in the same way they would expect in real life. Accordingly, objects that would normally be picked up (e.g., lemon, lime, orange, comb, mug) were implemented as graspable and could be picked up in VR, whereas larger or potentially hazardous objects (e.g., campfire, pine tree, pile of chopped wood) were not graspable and were instead inspected by approaching and sniffing. This variation in object size and interaction style was intentional to maximise ecological validity: in natural and virtual settings, odours are encountered from objects of different sizes and at different interaction distances. No participants reported that the objects felt unnatural or confusing to interact with.

Pairings were designed based on the fragrance wheel, where the oriental family encompasses warm, spicy, and gourmand (sweet and creamy) notes. For example, the oriental blend (cinnamon, star anise, and clove notes) pair semantically with both star anise (spicy subcategory) and vanilla (gourmand subcategory), as vanilla's warm, resinous profile aligns with oriental characteristics despite its sweet presentation. The random condition (8 visual stimuli) served as a control to assess baseline incongruence effects and odour contamination risks. The eight random visual stimuli were selected to represent everyday objects with no strong semantic association to any fragrance family, minimising the floor/ceiling effects in perceptual ratings. For the random condition, odour assignment order was randomised uniquely for each participant using a random number generator to select one of the four blends with two for each category (i.e., the book and potato stimuli may be assigned to be citrus for one participant while the empty white mug and comb stimuli may be assigned to be citrus for a different participant). The order of all 20 stimuli (congruent + random) was also randomised per participant to control order and fatigue effects. This design allowed us to characterise perceptual responses to the observed pairings and quantify perceived match independently of the intended pairing assignment.

2.6 Experimental setup

First, the participants completed a consent form before the experiment. After that, demographic information was collected for each participant via a graphical user interface. The participant had the sensors (GSR and heart rate) attached to them and was immersed in the VR environment. After sniffing each object at least once, the questions for each object appeared on a diegetic interface (see Figure 2) inside the experiment. The questions appeared in sequence, and the user selecting the "Done" button would trigger the next question in the sequence. Once the sequence was completed, a new object would appear in the VR environment, and the old one was removed. The user would need to smell the object at least once before being able to answer the questions. See Figure 3 for a flow chart of the user trials. Each of the 30 participants completed 100 ratings (20 unique visual stimuli x five ratings per trial), with a randomised stimulus order unique per participant. No trials or subjects were excluded post-screening. Odour delivery occurred automatically when the virtual nose entered a 10 cm proximity radius to the virtual and smellable object. A clean air chamber was rotated under the participant's nose when the virtual nose was more than 10 cm away from the virtual and smellable objects. In our system, the fixed 10 cm proximity threshold was determined by the physical geometry of the headset and olfactory display, which constrained the odour outlet to a stable focal point at a single nose-to-source distance, This 10 cm threshold aligns with typical evaluation distances used in olfactory research, where odours are commonly assessed at fixed nose-source distances around 10–30 cm (Hayes et al., 2013; Hopper et al., 2024; Surakka et al., 2025). The experiments were self-paced, consistent with olfactory research, accommodating individual sniffing differences (see (Spence, 2015)). For example, individual sniffing patterns and perceived intensity can vary across participants (Oleszkiewicz et al., 2020). The olfactory display dealt with olfactory residue by utilising a small fan pushing the scented air from under the user's nose and into a

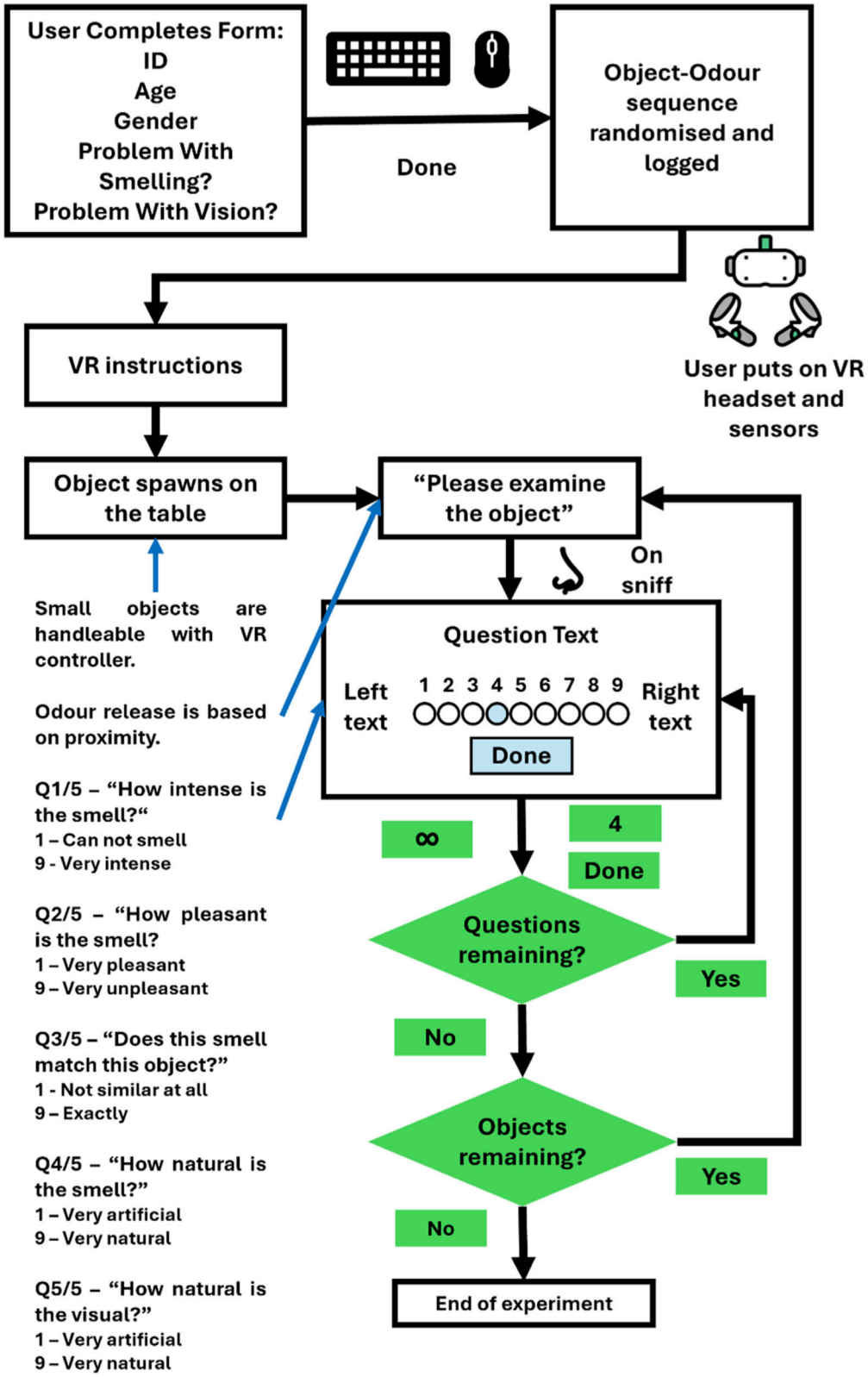


FIGURE 3
User trials flowchart.

carbon filter. The fan was always active, except for odour presentation, when the target odour chamber was positioned beneath the participant's nostrils. The clean-air (inactive) chamber was rotated under the participant's nose whenever the virtual nose was more than 10 cm from a smellable object and remained active throughout the inter-trial interval, ensuring unscented air was delivered between trials. The room in which the experiment took place was also well ventilated to further minimise olfactory residue. Participants took a minimum inter-trial break of 30 s away from the odours while completing the questionnaire and were instructed to take an additional break if they felt that their sense of smell had been reduced. No direct measurement of residual odour concentration was performed, and no blank/sham validation condition was included; therefore, although the system was designed to minimise carryover, we cannot establish that residual odour was negligible. The participants were also instructed to take a break if they felt like their sense of smell had been reduced.

2.7 Data analysis

The entire data analysis and figure preparation were performed using Python 3.12 with pandas, scipy, and statsmodels. Cardiac activity was recorded using a Grove-Ear-clip Heart Rate Sensor connected to an Arduino. The sensor generated a digital pulse for each detected heartbeat, and pulse timestamps were recorded using interrupt-based timing. Successive inter-beat intervals (IBIs) were calculated from the pulse timestamps. Trial-level cardiac variability was then calculated as the standard deviation of valid inter-beat intervals. GSR was recorded continuously at 43 Hz using a Shimmer3 GSR sensor. The signal was inspected programmatically for missing data, saturation, abrupt discontinuities, and movement-related artefacts. The signal was then low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 1 Hz. Linear detrending was applied to reduce slow signal drift. Trial-specific epochs were extracted using timestamps generated by the Unity application. GSR was quantified as the maximum observed conductance within each visual-odour exposure. A five-point moving average filter was applied to reduce high-frequency noise in both the heart rate and GSR physiological recordings before feature extraction. For the heart rate, this was applied to the continuous cardiac-derived signal. All HRV and GSR processing was performed programmatically and identically for all participants, with no manual visual inspection of individual traces, Artefacts were minimised via signal processing and feature selection, including the application of a five-point moving-average filter to the continuous signals before feature extraction. Missing or invalid data (e.g., due to sensor dropouts or physiologically implausible intervals) were excluded from the analysis prior to further pre-processing and feature extraction. All participants retained a sufficient number of valid data points for all the stimuli to compute trial-level HRV and GSR. Optical ear-clip sensors provide a practical means of recording heart rate in VR but are more susceptible to motion artefacts than ECG-based systems. Respiration was not measured in this study; therefore, respiratory influences on HRV cannot be ruled out and should be considered when interpreting the HRV findings. Our primary research aim was to test whether visual context is associated with context-dependent differences in evaluations of a compressed odour set. The family-congruent conditions reused the same physical odour blend across different visual contexts, and the LMMs assessed associations between these observed pairings and the perceptual and physiological outcomes. Perceived visual-odour match was the central measure of perceived congruence. Stimulus-level Pearson correlations were conducted as secondary, hypothesis-guided analyses to characterise whether the observed condition-level evaluation profiles covaried with perceived match and other perceptual and physiological measures. These correlations were descriptive and associational, not causal or mediation tests.

2.7.1 Primary analysis: Associations within observed visual-odour conditions

We fitted separate linear mixed-effects models (LMMs) for each outcome variable, with Visual Stimulus, Odour Category, age, and gender as fixed effects and participant as a random intercept. Age was entered as a continuous predictor.

In principle, visual stimulus and odour category could be treated as categorical factors. However, because the design was partially crossed (not all visual stimuli were paired with all odours), a fully expanded factorial specification produced rank-deficient model matrices and unstable parameter estimates. To obtain identifiable models, Visual Stimulus and Odour Category were therefore represented using reduced numeric codings that summarise broad condition-level trends across the observed visual-odour pairings, rather than estimating all level-specific reference-coded contrasts. Visual Stimulus was coded as an integer from 1 to 20, with stimuli 1–3 representing the citrus family, 4–6 floral, 7–9 woody, 10–12 oriental, and 13–20 the random controls. Odour Category was coded as an integer from one to 5 (citrus, floral, woody, oriental, random/no-odour). A one-unit increase corresponds to moving to the next stimulus/category.

The reported coefficients for Visual Stimulus and Odour Category should thus be interpreted as reflecting overall trends associated with these predictors under this reduced coding, not as omnibus tests of categorical factors or as independent main effects in a fully crossed factorial design. We report unadjusted p-values for the fixed effects.

2.7.2 Exploratory within-blend comparisons

Following the LMM analyses, exploratory paired comparisons were conducted among the three visual stimuli associated with each physical odour blend. Paired-samples t-tests were conducted for all three pairwise comparisons within each blend, separately for perceived visual-odour match, smell naturalness, and HRV. Holm-Bonferroni correction was applied separately within each blend-specific family of three comparisons. These analyses were intended to characterise differences among the observed visual-odour pairings.

2.7.3 Secondary, hypothesis-guided analysis: Associations with perceived visual-odour match

Pearson correlations examined associations between the mean perceived match ratings across the 20 visual stimuli

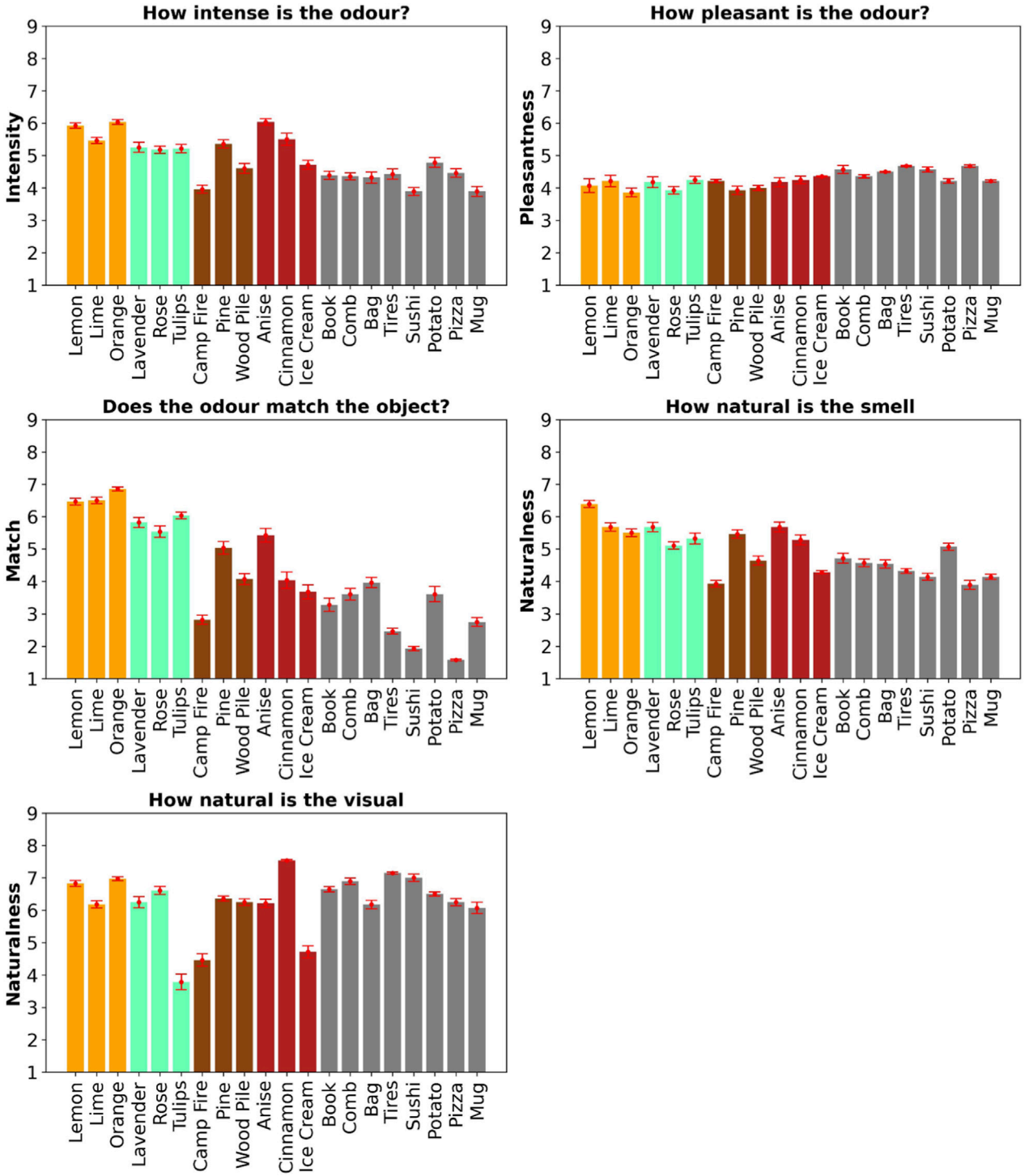


FIGURE 4
Mean ratings for perceptual dimension. Error bars denote standard error. Colour is dependent on the assigned odour category: yellow for citrus, green for floral, brown for woody, red for oriental, and grey for random.

and the corresponding mean values for each perceptual and physiological measure, with a Holm-Bonferroni correction. Perceived visual-odour match was the central measure of perceived congruence. The correlations characterised whether the observed condition-level evaluation profiles covaried with perceived match and therefore whether match was associated with a broader perceptual and physiological profile rather than being an isolated semantic judgement of fit. These analyses were descriptive and associational, not causal or mediation tests.

TABLE 3 LMMs for the perceptual and physiological outcomes.

Outcome	Fixed effect	Coefficient	SE	z	p-value	95% CI [0.025 0.975]
Odour intensity	Visual stimuli	−0.06	0.04	1.42	0.156	−0.14, 0.02
	Odour category	−0.12	0.16	−0.72	0.471	−0.43, 0.20
	Age	−0.02	0.02	−1.14	0.254	−0.05, 0.01
	Gender	0.05	0.42	0.12	0.9	−0.78, 0.88
Odour pleasantness	Visual stimuli	0.01	0.04	0.14	0.888	−0.06, 0.08
	Odour category	−0.09	0.141	−0.61	0.541	−0.36, 0.19
	Age	−0.01	0.01	−0.73	0.469	−0.04, 0.02
	Gender	−0.12	0.38	−0.52	0.603	−0.95, 0.55
Odour-object match	Visual stimuli	−0.14	0.05	−2.78	0.005 *	−0.24, −0.04
	Odour category	−0.28	0.20	−1.41	0.158	−0.66, 0.11
	Age	0.01	0.02	0.40	0.690	−0.02, 0.04
	Gender	0.55	0.42	1.31	0.192	−0.27, 1.36
Smell naturalness	Visual stimuli	−0.09	0.04	−2.39	0.002 *	−0.17, −0.02
	Odour category	0.03	0.15	0.18	0.856	−0.26, 0.32
	Age	0.01	0.02	0.29	0.772	−0.03, 0.04
	Gender	0.50	0.50	1.07	0.283	−0.42, 1.42
Visual naturalness	Visual stimuli	−0.00	0.04	−0.04	0.97	−0.09, 0.08
	Odour category	0.07	0.17	0.44	0.66	−0.25, 0.40
	Age	0.04	0.02	1.92	0.055	−0.00, 0.06
	Gender	0.20	0.46	0.43	0.669	−0.71, 1.10
HRV	Visual stimuli	3.34	0.73	4.59	<0.0001 *	1.92, 4.77
	Odour category	−9.09	2.80	−3.23	0.001 *	−14.53, −3.56
	Age	−0.06	0.16	−0.35	0.730	−0.38, 0.26
	Gender	8.47	4.51	1.88	0.061	−0.374, 17.20
GSR	Visual stimuli	−278.55	239.85	−1.16	0.245	−748, 191
	Odour category	908.77	922.02	0.97	0.324	−898 27
	Age	34.56	42.45	0.18	0.415	−48, 117
	Gender	1,508	1,204	1.25	0.210	−851, 2,869

* Denotes significant p-values after correction. All numbers in this table, with the exception of the p-values, have been rounded to two decimal places. Visual Stimulus and Odour Category were intended to be modelled as categorical factors. However, because the design was partially crossed, a fully expanded factorial specification produced rank-deficient models and unstable estimates. The reported models therefore used reduced numeric representations of Visual Stimulus and Odour Category to assess broad condition-level trends within the observed visual-odour pairings. The coefficients, standard errors, z-values, and p-values for these terms should not be interpreted as omnibus tests of categorical factors or as independent main effects in a fully crossed design.

3 Results

3.1 Perceptual ratings

We first examined the perceptual data collected throughout the experiment (see Figure 4). The plot shows the mean ratings for each visual-odour pairing, with stimuli coloured by odour family. For the twelve family-congruent stimuli, the same physical odour blend was used with three different visual stimuli within each family; variation in ratings across these stimuli therefore provides descriptive evidence of condition-level differences in evaluation when the physical blend was held constant. For the eight random stimuli, odour assignment varied across participants; these stimuli are therefore interpreted descriptively and do not represent replicated fixed-blend comparisons. We first report the LMMs assessing associations within the observed visual-odour conditions, followed by the exploratory within-blend paired comparisons and secondary stimulus-level correlations. In Figure 4, even when the same odour blend was present and only the visual stimulus changed within a fragrance family, the mean ratings varied for some perceptual dimensions but remained more relatively stable than others; we then proceeded to confirm this

statistically. Perceived pleasantness also showed relatively little variation across visual stimuli.

3.2 Effects of visual stimuli and odour category

Before fitting the LMMs, we checked for collinearity among fixed effects. VIFs were low (1.01–1.88, all <5), and correlations among outcomes were modest, supporting model stability. Table 3 reports the LMM results for the observed data, with age and gender as covariates and participant as a random intercept. Age was treated continuously and gender was treated as binary. An example of the model formula is Outcome ~ Visual Stimuli + Odour Category + age + gender, with the participant added as a random intercept. Visual Stimulus and Odour Category were represented using reduced numeric codings due to the partially crossed design, so the models estimate associations with the observed condition-level coding rather than level-by-level contrasts across all 20 visuals or all five odour categories. The Visual Stimulus and Odour Category terms are treated as fixed effects, not omnibus tests of the full factorial factors. Because the design is partially crossed, these results describe associations within observed visual–odour pairings and should not be construed as independent estimates across all levels. Within this framework, the Visual Stimulus term showed association with higher-level perceptual judgments, with perceived visual–odour match and smell naturalness varying with Visual Stimulus, while odour intensity, odour pleasantness, and visual naturalness showed no reliable associations with Visual Stimulus or the odour category term. The odour category term alone did not significantly affect perceptual ratings, and age or gender effects were not detected, though the modest sample limits generalisability. The observed Visual Stimulus associations reflect context-dependent differences rather than independent causal effects of visual context.

For HRV, the LMM showed associations with the Visual Stimulus and with the Odour Category (reduced-coding terms). This reflects condition-level variation across the observed visual–odour pairings and confirms an association with the reduced Odour Category term. The GSR model did not show significant associations with Visual Stimulus or Odour Category, and while directions varied, no reliable effects were detected for the experimental manipulation.

In Table 3, the Coefficient column reports the estimated regression coefficient (β) for each fixed effect. The 95% CI column reports the 95% confidence interval for each coefficient, i.e., the range of values that, under the model assumptions, would contain the true population coefficient in 95% of the repeated samples. These intervals are derived from the standard errors of the coefficients and are conditional on the specified model (including the random intercept for the participant). Each of these predictors is represented by a single coefficient. This coefficient reflects the direction and strength of the overall trend associated with that reduced predictor across conditions, not the difference between specific levels or an omnibus test of a categorical factor.

3.3 Exploratory within blend comparisons

For each outcome, we fitted a stimulus-only linear mixed-effects model with categorical visual stimulus as a fixed effect and participant as a random intercept. Odour category was omitted from these models because its inclusion alongside categorical visual stimulus produced a rank-deficient fixed-effects structure under the partially crossed design. The categorical stimulus term was evaluated using a joint Wald test of all 19 stimulus coefficients relative to the reference stimulus; this provided an omnibus test of differences among the 20 observed visual-odour conditions. We found significant findings for intensity ($\chi2\,(19) = 102.27$, $p < 0.0001$), match ($\chi2\,(19) = 416.66$, $p < 0.0001$), smell naturalness ($\chi2\,(19) = 131.24$, $p < 0.0001$), visual naturalness ($\chi2\,(19) = 131.23$, $p < 0.0001$), and HRV ($\chi2\,(19) = 155.51$, $p < 0.0001$). This indicates that these ratings differed overall across the stimulus conditions observed. Pleasantness ($\chi2\,(19) = 18.31$, $p = 0.50$) and GSR ($\chi2\,(19) = 19.96$, $p = 0.40$) were not significant, indicating that pleasantness and GSR did not differ across the observed stimulus conditions.

Post-hoc pair wise t-tests were conducted among the three visual stimuli associated with each physical odour blend. These comparisons examined whether responses differed across visual contexts while the underlying physical blend was held constant. These tests were conducted on the trial-level observations, with each participant providing one paired observation for each visual stimulus. Comparisons were made between the three visual stimuli associated with each physical odour blend. Holm-Bonferroni correction was applied separately to the three pairwise comparisons within each blend. Full statistical results for these exploratory paired comparisons, including t-statistics, degrees of freedom, Holm-Bonferroni-adjusted p-values, t-test confidence intervals, standard deviations, Cohans d, and Cohans d confidence intervals of the paired differences are provided in Supplementary Materials.

For perceived intensity we found that within the Floral blend, Lavender significantly differed from Tulips ($t\,(29) = 4.54$, $p = 0.0003$, $d = 0.76$), as did Rose and Tulips ($t\,(29) = 2.63$, $p = 0.0278$, $d = 0.74$). For the Woody blend Pine Tree significantly differed from Chopped Wood ($t\,(29) = -3.72$, $p = 0.0027$, $d = 0.65$). No significant difference was found for the Citrus or Oriental blends.

For perceived match we found that within the Citrus blend, Lemon significantly differed from Orange ($t\,(29) = 2.65$, $p = 0.0386$, $d = 0.61$), as did lime and Orange ($t\,(29) = 2.5$, $p = 0.0386$, $d = 0.57$). For the Floral blend, Lavender significantly differed from Tulips ($t\,(29) = 4.87$, $p < 0.0001$, $d = 1.33$), as did Rose and Tulips ($t\,(29) = 4.48$, $p = 0.0002$, $d = 1.13$). For the Woody blend, Campfire significantly differed from Pine Tree ($t\,(29) = 3.34$, $p = 0.0047$, $d = 0.64$), as did Pine Tree and Chopped Wood ($t\,(29) = -3.58$, $p = 0.0037$, $d = -0.66$). No significant results were found for the Oriental blend.

For smell naturalness we found no significant results within the Citrus blend. For the Floral blend we found significant differences between Lavender and Tulips ($t\,(29) = 4.09$, $p = 0.001$, $d = 0.76$), as well as between Rose and Tulips ($t\,(29) = 3.07$, $p = 0.0093$, $d = 0.62$). For the Woody blend we found significant differences between Campfire and Pine Tree ($t\,(29) = 3.02$, $p = 0.0106$, $d = 0.5549$) as well as between Pine tree and Chopped Wood ($t\,(29) = -3.36$, $p = 0.0065$, $d = 0.56$). No significant differences were found for the Oriental blend.

For visual naturalness we found that within the Floral blend, Lavender significantly differed from Rose ($t(29) = 9.43, p < 0.0001, d = 1.70$), as did Lavander and Tulips ($t(29) = 6.01, p < 0.0001, d = 1.08$), and Rose and Tulips ($t(29) = -2.5, p = 0.0188, d = -0.50$). For the Oriental blend, Star Anise significantly differed from Cinnamon ($t(29) = 7.36, p < 0.0001, d = 1.57$), as did Star Anise and Vanilla Ice Cream ($t(29) = 2.19, p = 0.0372, d = 0.59$), and Cinnamon and Vanilla Ice Cream ($t(29) = -6.05, p < 0.0001, d = 1.15$). No significant differences were found for the Citrus or Woody blends.

For HRV we found no significant results within the Citrus or Floral blends. However, we did find significant differences in the Woody blend between Campfire and Pinetree ($t(29) = -2.49, p = 0.0187, d = -0.55$), Campfire and Chopped Wood ($t(29) = 5.18, p < 0.0001, d = 1.33$), and Pine Tree and Chopped Wood ($t(29) = 5.27, p < 0.0001, d = 1.34$). For the Oriental blend we found significant differences between Star Anise and Cinnamon ($t(29) = -2.96, p = 0.0123, d = -0.79$), as well as between Cinnamon and Vanilla Ice Cream ($t(29) = 3.42, p = 0.0056, d = 0.88$).

Overall, the exploratory comparisons indicated that within-blend differences were outcome-dependent rather than uniform across measures. Perceived intensity showed difference for Floral and Woody blends. Perceived visual-odour match showed differences for the Citrus, Floral, and Woody blends, whereas smell naturalness showed differences for the Floral and Oriental blends. Visual naturalness showed differences in the Floral and Oriental Blends. HRV showed differences in Woody and Oriental blends. These findings suggest that changing the visual stimulus while retaining the same physical odour blend was associated with selective differences in perceived intensity, subjective congruence, perceived smell naturalness, perceived visual naturalness, and HRV. However, because the visual stimuli and odour blends were partially confounded, these comparisons should be interpreted as differences among the observed visual-odour pairings rather than as independent causal effects of visual context.

3.4 Perceived match and response associations

The correlations were descriptive and associational, not causal or mediation tests. They do not establish that visual context or perceived match caused the observed differences. The family-congruent stimuli reused the same physical odour blend across multiple visual contexts, whereas the random stimuli had participant-varying odour assignments and therefore do not represent replicated fixed-blend comparisons. The LMMs provided the primary evidence for condition-level variation relevant to the primary research aim; the correlations examined whether that variation covaried with perceived visual-odour match. A Holm-Bonferroni correction was applied to account for multiple comparisons. Pearson correlations were conducted to examine the relationship between perceived match for each odour-object pairing and the corresponding perceptual and physiological measures. It should be noted that, for the family-congruent stimuli, the same physical odour blend was reused across multiple visual contexts, whereas the random stimuli had odour assignments that varied across participants. Thus, the random stimuli contribute to the broader characterisation of visual-odour evaluation but does not represent replicated fixed-blend comparisons. Perceived match was significantly correlated with the perceived intensity ($r = 0.90, p < 0.0001$), perceived pleasantness ($r = -0.78, p < 0.0001$), and smell naturalness ($r = 0.92, p < 0.0001$). Critically, this analysis tests whether the global pattern of evaluations across the 20 visual-odour conditions is organised around perceived visual-odour match, as required by our crossmodal redirection framework, rather than merely showing that some stimuli are rated higher than others. Although pleasantness showed relatively little absolute variation across visual stimuli, it was strongly associated with perceived match at the stimulus level. This may indicate that small, consistent differences in pleasantness tracked differences in perceived visual-odour match, rather than that visual context produced large shifts in overall pleasantness. We did not find significant results for visual naturalness ($r = 0.04, p = 0.8579$), HRV ($r = -0.48, p = 0.0936$), or GSR ($r = 0.31, p = 0.3626$). Thus, perceived match was significantly associated with multiple perceptual measures, but not with visual naturalness, HRV or GSR (see Figure 5). Due to the pleasantness coding, the negative correlation indicates that higher perceived match was associated with more pleasant ratings. In practical terms, visual-odour pairings judged as better matching were also rated as more intense, more natural in smell, and more pleasant. This pattern is consistent with the hypothesis-guided expectation that perceived visual-odour match would covary with a broader perceptual and physiological profile. It may be consistent with a congruence-based account of crossmodal redirection, but the descriptive, stimulus-level correlations cannot prove that account or establish causal or mediation relationships.

4 Discussion

This study examined whether visual context is associated with context-dependent differences in evaluations of a compressed odour set in immersive VR. Four physical odour blends were reused across 20 visual stimuli: three family-congruent visuals per fragrance family and eight control visuals with participant-varying odour assignments or no odour. We used LMMs to test whether the observed visual-odour conditions were associated with variation in perceptual and physiological responses. The family-congruent conditions reused the same physical odour blend across different visual contexts, allowing the observed variation in evaluations to be considered in relation to visual context while recognising that the design was partially crossed. The perceived visual-odour match was our central measure of perceived congruence. The exploratory within-blend comparisons further showed that these associations were selective rather than uniform. Stimulus-level perceived match provide evidence that some of the perceptual judgments covary with the perceived match.

Our LMM's models describe variation associated with visual-odour pairings and blend assignments within the partially crossed design. The LMMs indicated associations between the observed visual-odour conditions and perceived match, smell naturalness, and HRV. In the family-congruent conditions, the same physical blends were reused across different visual contexts, making this

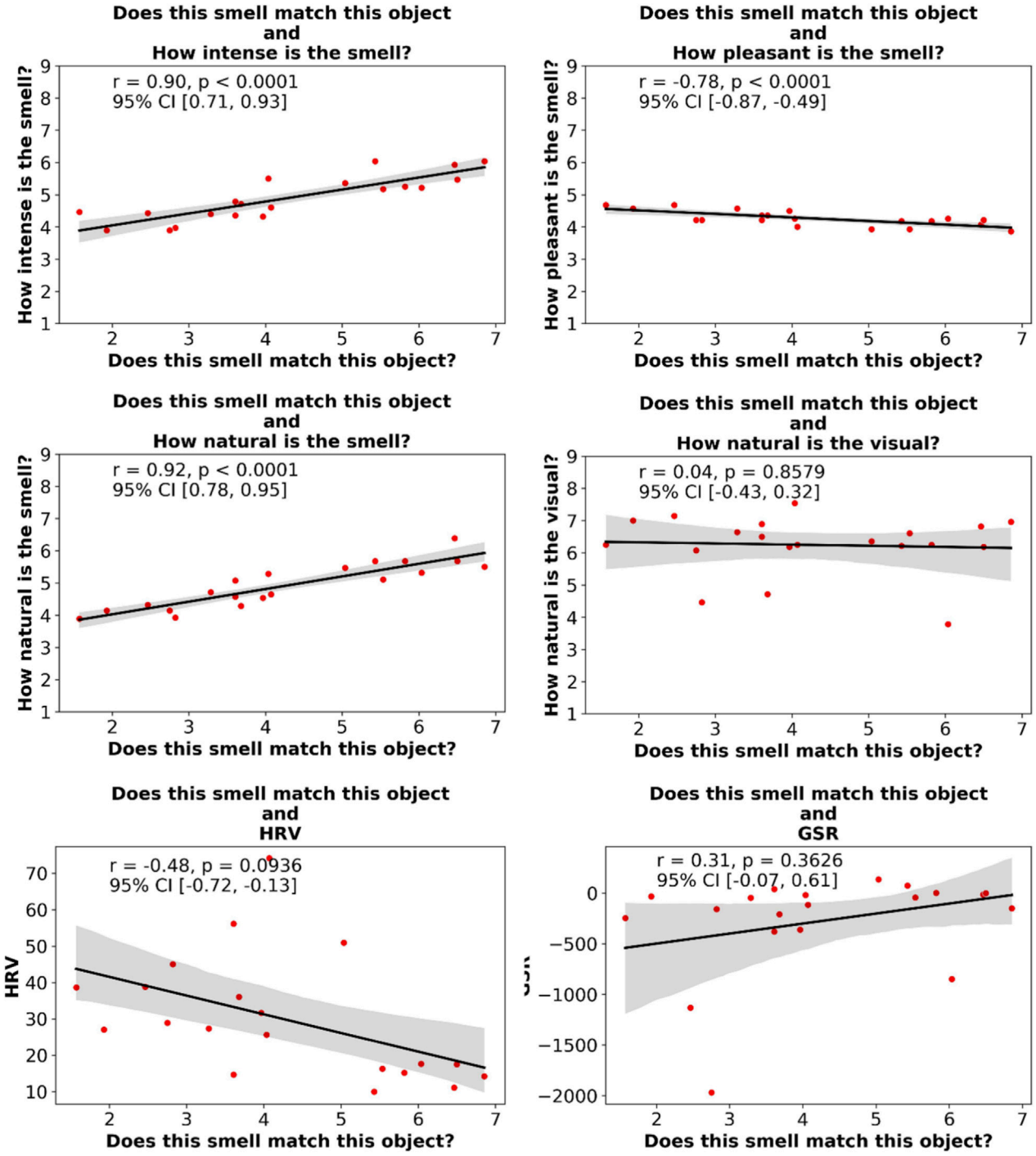


FIGURE 5
Pearson correlation plots showing the relationship between the mean perceived match ratings (n = 20) and the mean intensity, pleasantness, odour naturalness, visual naturalness, GSR, and HRV. The grey area around the fitted regression line denotes a 95% confidence bound.

pattern consistent with context-dependent differences in responses to those blends. The odour category term on its own did not significantly influence the perceptual measures but was associated with systematic differences in HRV. Physiological associations were measure-specific: HRV showed condition-level variation associated with visual stimulus and odour family, whereas GSR did not show statistically significant associations with these terms. No statistically significant associations with age or gender were detected; however, the modest sample and limited demographic representation do not establish demographic invariance. The observed visual-stimulus associations are consistent with responses to an identical odour differing across visual contexts. They do not establish an independent causal effect of visual context.

The exploratory within-blend comparisons show that significant differences were observed for perceived visual–odour match across select pairings within all blends, with perceived intensity also showing significant Floral and Wood blends, and visual naturalness showing significant differences in the Citrus, Floral, and Woody blends. Smell naturalness remained significant only within Floral and Woody blends, and HRV showed significance in the Woody and Oriental blends but not in Citrus or Floral blends. These results indicate that the observed differences depend on both the outcome measure and the odour blend.

One notable aspect of the present findings is the asymmetry between physiological measures: HRV showed systematic variation with Visual Stimulus and Odour Category, whereas GSR did not. This pattern is consistent with the view that HRV and GSR index are partially distinct aspects of autonomic engagement. HRV is widely regarded as an index of parasympathetic (vagal) control and emotion regulation, with higher vagally mediated HRV associated with greater emotional flexibility and adaptive regulation (Thayer et al., 2012; Malińska et al., 2015; Marín-Morales et al., 2021). By contrast, GSR (electrodermal activity) primarily reflects sympathetic activation and has been shown to be sensitive to cognitive load, arousal, and attentional demands (Shi et al., 2007; Kuhne et al., 2023; Caldas et al., 2024; Clemente et al., 2025). In the context of our multisensory VR task, the observed pattern is consistent with visual-odour congruence being more closely associated with evaluative and affective aspects of the experience than with phasic arousal or cognitive load. The null effects for GSR may also reflect the relatively passive nature of the task, the exposure durations, and the fact that participants were not required to perform effortful or stress-inducing actions, conditions under which GSR effects are often smaller or less reliable. By contrast, HRV may have been more sensitive to the subtle, context-dependent shifts in how the same odour blends were appraised across different visuals, consistent with evidence that HRV tracks changes in affective appraisal and regulatory processes even in the absence of large changes in arousal (Thayer et al., 2012; Malińska et al., 2015; Marín-Morales et al., 2021). This divergence indicates that HRV and GSR did not show identical patterns of association in the present dataset and should not be treated as interchangeable measures. HRV showed significant associations with the visual-stimulus and odour-category terms, whereas GSR did not show statistically significant associations with these terms. Whether HRV is more sensitive than GSR to context-dependent affective appraisal in multisensory VR remains an open question for future research and cannot be established from the present study (Shi et al., 2007; Kuhne et al., 2023; Caldas et al., 2024; Clemente et al., 2025). The exploratory within-blend comparisons are consistent with this measure-specific pattern: HRV differences were observed for selected woody and oriental visual pairings, whereas the subjective outcomes showed their strongest within-blend differences for selected floral and woody pairings.

As a secondary, stimulus-level analysis, we examined the relationship between perceived match and perceptual and physiological responses using Pearson correlations. We emphasise that, for the family-congruent stimuli, the same physical odour blend was reused across multiple visual contexts, whereas the random stimuli had participant-varying odour assignments. Consequently, the random stimuli inform the broader pattern of visual-odour evaluation but should not be interpreted as replicated fixed-blend comparisons. Perceived match was associated with odour intensity, pleasantness, smell naturalness, but not with visual naturalness, HRV, or GSR. These analyses tested whether perceived match was associated with a broader perceptual profile rather than merely being an isolated semantic judgement of fit. In contrast, perceived match was not significantly associated with visual naturalness, HRV, or GSR, indicating that associations were specific to odour-related ratings. Sensory congruence has previously been shown to affect the perceived pleasantness (Seo and Hummel, 2011; Amsellem and Ohla, 2016) and intensity (Kemp and Gilbert, 1997; Amsellem and Ohla, 2016) across odours and different sensory modalities. Additionally, smells perceived as more congruent were also perceived as more natural, despite the same essential oil blends being used across participants. The pattern of correlations between perceived match and other measures helps clarify how crossmodal redirection was operationalised in this study. Higher perceived match was associated with higher perceived intensity and smell naturalness, and more pleasant ratings. Thus, perceived match covaried with multiple perceptual measures, although the analysis does not establish causation. For researchers, these associations provide descriptive evidence that the evaluation of a fixed odour blend can covary with visual context and perceived visual-odour match. For practitioners designing VR and olfaction-enhanced applications, the results suggest that perceived visual-odour match may be relevant to both subjective and physiological evaluation profiles. Whether deliberately selecting well-matched pairings produces these outcomes remains to be tested.

A key limitation of this study is the potential for odour contamination or carryover effects between presented olfactory stimuli. Volatile compounds can linger in the environment and interact with olfactory adaptation, potentially influencing perceptual ratings. Olfaction exhibits slow temporal dynamics, and sensory adaptation may interact with residual odours to influence subsequent perceptual ratings (Spence, 2015). Although our system was designed to minimise these risks through on-demand odour release and proximity-based control, the possibility of cross-trial contamination cannot be ruled out. Future work should include direct measures of odour identity, categorisation, similarity, and discriminability to determine whether contextual effects extend beyond evaluation (Sabiniewicz et al., 2021; 2024). Each participant completed 100 ratings, which may have introduced fatigue or response burden; however, no participants reported excessive discomfort or a desire to stop. Future studies should assess workload, cybersickness, and fatigue using standardised measures. The absence of odour-alone and neutral-visual baselines means that we cannot quantify the magnitude of visual modulation relative to isolated odour presentation. Future studies should include such baselines. Finally, the modest sample ($N = 30$) and partially crossed design limit the precision and generalisability of the factor-level estimates.

Although the present study did not directly test applied outcomes in specific domains, its results suggest the possibility that olfactory crossmodal redirection could have exploratory implications for several areas where olfactory-visual congruence is relevant, for example, in VR environments and gaming to enhance

immersion and presence. In constrained hardware, a small number of physical odours could potentially be reused across visual contexts to support a broader range of context-specific experiences. Participants were not asked to identify or name the odours, select an odour category, judge whether presentations smelled the same or different, provide free descriptions, or rate perceptual similarity between conditions. A high match rating indicates that the odour was considered appropriate for a visual object; it does not demonstrate that the odour was experienced as a different identity. Future studies should directly assess odour identity and qualitative variety using forced-choice identification, category-selection tasks, free-description methods, descriptor ratings, perceptual similarity judgements, and confusion matrices. Future studies should systematically vary individual visual properties, such as colour, shape, or texture, while holding other scene characteristics constant. Additionally, future research could explore the mechanisms underlying these effects by examining individual differences such as prior experiences, cultural background, or olfactory sensitivity. A further direction is to compare the contextual coverage of individual odour blends with that of controlled mixtures. For example, binary mixtures of citrus and floral blends could be evaluated across a broader set of visual objects to determine whether blending increases the range of objects for which an odour is judged appropriate. Such work requires careful control of concentration, odour intensity, blend dominance, masking, and potential interactions between components. Importantly, it should include direct measures of perceived odour identity, categorisation, similarity, and discriminability, in addition to contextual match and naturalness. This approach could provide a more direct estimate of how many context-dependent evaluation profiles are associated with a limited physical olfactory palette.

5 Conclusion

The present study provides preliminary evidence that visual context is associated with context-dependent differences in how fixed odour blends are evaluated within immersive VR. The primary research aim was to test whether visual context is associated with context-dependent differences in evaluations of a compressed odour set in VR. The family-congruent conditions reused the same physical odour blend across different visual contexts. The LMMs assessed associations between the observed visual-odour conditions and the perceptual and physiological outcomes. The LMMs indicated statistically significant associations involving visual stimulus for perceived visual-odour match, smell naturalness, and HRV; HRV was also associated with the odour-family term. Exploratory within-blend paired comparisons further showed selective differences among the three visual stimuli associated with the same physical blend; perceived intensity showed difference for Floral and Woody blends. Perceived visual-odour match showed differences for the Citrus, Floral, and Woody blends, whereas smell naturalness showed differences for the Floral and Oriental blends. Visual naturalness showed differences in the Floral and Oriental Blends. HRV showed differences in Woody and Oriental blends. Stimulus-level Pearson correlations were secondary, hypothesis-guided analyses that characterised whether the observed condition-level evaluation profiles covaried with perceived visual-odour match. Perceived match was associated with intensity, pleasantness, smell naturalness, but not with visual naturalness, HRV or GSR. These correlations indicate that perceived match was associated with a broader perceptual profile rather than being an isolated semantic judgement of fit. This pattern may be consistent with a congruence-based account of crossmodal redirection, but further research is needed to confirm this. Because visual stimulus and odour family were not fully crossed, the findings do not provide a formal comparison of their independent or relative effects. Because odour identity, categorisation, similarity, and discriminability were not directly measured, the study does not establish that visual context generates distinct odour identities. Rather, it indicates that the same physical odour blends were associated with context-dependent differences in higher-level evaluation and related physiological responses across visual contexts.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by University of Liverpool Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

RW: Methodology, Supervision, Data curation, Writing – original draft, Investigation, Software, Conceptualization, Resources, Project administration, Writing – review and editing, Formal Analysis, Validation, Visualization, Funding acquisition. EG: Software, Funding acquisition, Conceptualization, Writing – review and editing. NK: Conceptualization, Methodology, Writing – review and editing. MS: Methodology, Writing – review and editing, Conceptualization. MB: Conceptualization, Writing – review and editing, Methodology. AM: Funding acquisition, Writing – review and editing, Conceptualization, Supervision, Methodology.

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Conflict of interest

Author(s) NK and MS were employed by Sony Europe Limited.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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