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Episodic memory and recognition are influenced by cues' sensory modality: Comparing odours, music and faces using virtual reality

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Abstract

Most everyday experiences are multisensory, and all senses can trigger the conscious re-experience of unique personal events from the past embedded in their specific spatio-temporal context. Yet, little is known about how a cue's sensory modality influences episodic memory retrieval, and which step of this process is impacted. This study investigated recognition and episodic memory across olfactory, auditory and visual sensory modalities in a laboratory-ecological task using a non-immersive virtual reality device presenting a three-room house where boxes delivered odours, musical pieces and pictures of face. At encoding, participants freely, actively and non-explicitly explored unique and rich episodes. At retrieval, participants were presented with modality-specific memory cues and were told to 1) recognize encoded cues among distractors and, 2) go to the room and select the box in which they encountered them at encoding. Memory performance and response times consistently revealed that music and faces outperformed odours in recognition memory, but that odours and faces outperformed music in evoking episodic context retrieval. Interestingly, correct recognition of music and faces was accompanied by more profound inspirations than was correct rejection of music and faces. By directly comparing memory performance across sensory modalities, our study provides further knowledge about specificities of olfactory memory and demonstrated that despite limited recognition, odours are powerful cues to evoke specific episodic memory retrieval.

Keywords: episodic memory; recognition memory; odour; music; face; virtual reality; breathing; human cognition.

1 Introduction

In a multisensory world, life episodes are rich in sensations, perceptions and emotions. These episodes are encoded, consolidated, stored in memory and re-evoked later on. Episodic memory is the memory that allows for the conscious re-experience of these unique personal episodes embedded in their specific spatio-temporal context. It is defined by its content, notably *what* happened, *where* and *in which context* or *occasion* (Easton & Eacott, 2008; Tulving, 1983). Episodic memory retrieval is reconstructive, that is, memories are constructed out of the initially-encoded elements (Bartlett, 1995; Schacter & Addis, 2007). Several variables influence the content of memories and the associated phenomenological features, among which the sensory modality of the memory cues (Ernst et al., 2021; Hutmacher, 2021). One well-known example is the Proust phenomenon (Chu & Downes, 2000, 2002), suggesting the uniqueness of odour-evoked memories compared to memories evoked by other sensory cues (for reviews, Annett, 1996; Hackländer et al., 2018; Herz & Engen, 1996; Larsson et al., 2014; Saive, Royet, & Plailly, 2014). This hypothesis has been mainly investigated by comparing voluntarily evoked memories of life events triggered by odours to those evoked by images, sounds and words (Chu & Downes, 2002; de Bruijn & Bender, 2017; Ernst et al., 2021; Goddard et al., 2005; Herz, 2004; Herz & Schooler, 2002; Karlsson et al., 2013; Miles & Berntsen, 2011; Rubin et al., 1984; Willander et al., 2015). Findings have congruently shown that while olfactory cues evoke fewer autobiographical memories, odour-evoked memories are more emotional, older, and less often rehearsed, thought of and talked about than memories evoked by other sensory modality cues. Odour-evoked episodic memory has also been studied in few experiments in laboratory settings with memories encoded and retrieved in a fully controlled way. In this controlled experimental approach, episodic memory characteristics overlap with those observed in approaches focusing on autobiographical

memory (for reviews, Annett, 1996; Hackländer et al., 2018; Herz & Engen, 1996; Larsson et al., 2014; Saive, Royet, & Plailly, 2014). While odours are less recognized than visual cues when presented among distractors (e.g., Cameron et al., 2021; Cornell Karnekull et al., 2015; Engen, 1987), they show similar strength to initiate the retrieval of previously associated items (paintings, numbers, pictures) than show visual, tactile, musical or verbal cues (Davis, 1977; Herz, 1998). However, the very limited number of studies urges to be cautious about conclusions about the uniqueness of odours as cues for episodic memory.

Odours are not the only potent memory cues. Some studies suggested that other stimuli with strong ecological validity, such as music and faces, also demonstrate specificities for evoking episodic memory. Music-evoked autobiographical memories are reported to be consistently associated with strong emotions (Jakubowski & Eerola, 2022; Janata et al., 2007; Schulkind et al., 1999) and are also suggested to be very vivid (Belfi et al., 2016; Jakubowski et al., 2021). Interestingly, as for odours, the recognition performance of unfamiliar music is weaker than that of visual objects (Cohen et al., 2009, 2011; Deffler & Halpern, 2011) and a recent study suggests that music elicited fewer memories in comparison to environmental sound and word cues (Jakubowski & Eerola, 2022). Faces are more likely than voices to evoke both episodic and semantic information about an individual, even when faces are blurred to limit recognition (for an overview, see Brédart and Barsics, 2012). Although these findings suggest that episodic memory might be influenced by the sensory modality of the retrieval cue for odours, music and faces, strong evidence for these differences is still missing. Aiming to bridge this gap, the present study challenged odour-evoked episodic memory specificities by directly comparing odour-evoked episodes with the same episodes evoked by other potent memory cues, notably music and faces.

Two main approaches have guided episodic memory investigations (McDermott et al., 2009). Naturalistic or autobiographical approaches investigate memories of real-life events in an ecological way. They, however, lack experimental control on non-measured variables and accuracy measures. In contrast, laboratory approaches investigate memories artificially created in the laboratory, allowing the control of all memory stages, but with only limited ecological validity. These differences might partly explain some of the discrepancies reported across episodic memory studies, and argue for the need to develop ecologically valid experiments in controlled laboratory settings (McDermott et al., 2009). Our lab is part of that process and has developed new experimental paradigms to study the encoding and retrieval of unique olfactory memories in a controlled manner (Plailly et al., 2019; Saive et al., 2013, 2015; Saive, Royet, Ravel, et al., 2014). The present study takes ecological-laboratory protocols a step further by using virtual reality to investigate episodic memory retrieval as a function of the sensory modality of the retrieval cue (Smith, 2019). Here, participants discovered life-like episodes during a first-person and self-paced exploration of a three-room house, where boxes disposed at unique places simultaneously delivered an odour, a piece of music and a face. Later on, episodic memory retrieval was triggered with either odour, music or face cues. Episodic memory was investigated by computing the probability to (1) recognize the memory cue among distractors, and in case of accurate recognition, to remember (2) the room and then (3) the box in which the cue was initially encoded, therefore allowing for a detailed examination of recognition memory and episodic retrieval processes. Response times and breathing were also measured during these tasks. The modulations of response times provide further insight into task difficulty. Breathing has been shown to be influenced by olfactory memory processes, with odour-evoked autobiographical memory and odour-evoked episodic memory being accompanied with slower and larger inspirations than are non-

memory conditions (Masaoka et al., 2012; Saive, Royet, Ravel, et al., 2014). Whether this phenomenon is related to olfactory processes only or could be generalized to other sensory modalities is still unknown.

Our study had three main goals: 1) to investigate the effect of the sensory modality of the cue on recognition memory and episodic memory retrieval; 2) to investigate breathing behaviour associated with memory retrieval as a function of the sensory modality of the memory cues; 3) to validate our laboratory-ecological approach. We hypothesized that odour and music recognition might be less good than face recognition, but once a cue was recognized, the retrieval of its encoding context would be more accurate with odours than with other sensory cues.

2 Materials and Methods

This study used two versions of the same experimental implementation (Version1, V1 and Version2, V2). Given that the two versions differed only slightly for the retrieval test (see 2.4.2), and that the main results did not differ between versions, the two versions were combined in the analyses presented here, unless otherwise noted.

2.1 Ethics Statement

All participants provided written informed consent prior to participation. The protocol was approved by the national Ethical Committee, according to French regulations for biomedical experiments with healthy volunteers [CPP IDF8 (April 25,2017), ID RCB: 2016-A01931-50].

2.2 Participants

Fifty-four healthy participants [31 women, 23 men; aged 22.8 ± 2.3 years (mean \pm standard deviation)] consented to participate and received 40 euros in compensation. All participants

reported normal sense of smell and no visual and auditory impairments. They were recruited through campus electronic mails and posters. Given the implicit nature of the experiment, they were told that the study aimed to investigate the perception of various environments involving odours, music and pictures. Three participants had been excluded because of technical issues. Twenty-eight participants reported having on average 5.7 (\pm 3.2) years of formal musical training on an instrument.

2.3 *Stimuli and materials*

2.3.1 *Multidimensional episodes*

A software called EpisOdor was developed using Unity 5.2.2 (Unity Technologies, USA) by a local technical platform (*NeuroImmersion*, CRNL). EpisOdor allowed the presentation of a virtual 3D house in a first-person view (non-immersive virtual reality) that can be actively explored using a trackball (Kensington, Redwood Shores, CA, USA). This house was composed of three rooms, a bedroom, an office and a living room (defining the *Which context* component), connected to a corridor by closable doors (Figure 1A). Each room had distinct furniture (*e.g.*, chair, bed, table, piano) and decorative elements (*e.g.*, painting, carpet). Three clickable boxes were placed in each room at specific locations (defining the *Where* component), for a total of nine boxes. An arrow appeared above the boxes when participants got close enough to open them. These boxes were relatively distantly located from each other within a given room and were arranged differently between each room. EpisOdor had two modes: one for the encoding phase and one for the retrieval phase. In the encoding mode, participants started in the corridor and a unique door was opened. When participants entered the room and clicked on one of the three boxes, the box opened and three unique stimuli were presented simultaneously (defining the *What* component): an odour, a piece of music and a face (Figure 1B), for a total of nine sensory stimulations by episode. In the retrieval mode,

participants started in the corridor where they faced a closed box, and the three doors were closed. After clicking on the corridor's box, a stimulus was presented, and the retrieval questions were asked. Then, as a function of the participants' response, the three doors might open and participants can enter any room and click on any box, but no stimuli were presented. The virtual 3D house and the location of the boxes in each room were constant across participants, but the three stimuli assigned to each box in the encoding mode were randomly defined across participants.

2.3.2 *Stimuli and apparatus*

Eighteen stimuli for each sensory modality (odour, music, face) were selected from a behavioural pre-test from a set of 24 items. Sixteen participants judged items using subjective scales from 0 (minimum) to 10 (maximum) on pleasantness (from “extremely unpleasant” to “extremely pleasant”, with ‘neutral’ in the middle), emotional intensity (from “not intense at all” to “extremely intense”), familiarity (from “not familiar at all” to “extremely familiar”) and complexity (from “not complex at all” to “extremely complex”). The selected items were judged as rather neutral (mean \pm standard deviation; Odour, 4.9 ± 1.5 ; Music, 6.34 ± 0.6 ; Face, 5.3 ± 0.9), and relatively medium emotional intensity (Odour, 5.5 ± 0.8 ; Music, 5.0 ± 1.0 ; Face, 4.2 ± 0.7), familiarity (Odour, 5.8 ± 1.5 ; Music, 4.3 ± 1.2 ; Face, 3.5 ± 0.6) and complexity (Odour, 5.8 ± 0.7 ; Music, 4.7 ± 1.2 ; Face, 4.9 ± 0.7). This selection aimed to limit the potential effects of subjective sensory evaluations on episodic memory (Brédart & Barsics, 2012; Cornell Kärnekull et al., 2015; Holland & Kensinger, 2010; Saive et al., 2015; Saive, Royet, Ravel, et al., 2014; Stalinski & Schellenberg, 2013; Tolin & Deleghans, 1973), and to favour the comparability of the stimuli within and between sensory modalities. The 18 stimuli of each sensory modality were divided into two subsets of nine stimuli (set 1 and set 2) matched for pleasantness, emotional intensity, familiarity and complexity. Sets 1 and 2 were

then pseudo-randomly assigned as target or distractor items for each participant so that each set was equally represented as target or distractor among them.

2.3.2.1 Odourants. Odourants consisting of essential oils, single or mixtures of monomolecular chemical compounds, and fragrances were used, including odourants previously used in our laboratory (Plailly et al., 2019; Saive, 2015; Saive et al., 2013; Saive, Royet, Ravel, et al., 2014). Set 1 was composed of Carrot (Givaudan-Roure, Vernier, Suisse), Cis-3-hexenyl salicylate (Créations aromatiques, Neuilly-Sur-Seine, France), Daffodil (Givaudan-Roure), Lovely Ion (EmoSens, Lyon, France), Methyl octine carbonate (Créations aromatiques), Musk (Givaudan-Roure), Secret de Hammam (EmoSens), Stemone (Créations aromatiques) and Teck Lounge (EmoSens). Set 2 was composed of 9-decen-1-ol (Sigma-Aldrich®, Saint-Louis, MS, USA), Basil (Créations aromatiques), Bien-Être (EmoSens), Birch oil (Sigma-Aldrich), Citronellol (Sigma-Aldrich), Linalyl acetate (Sigma-Aldrich), Osmose (EmoSens), Tobacco (Givaudan-Roure) and Tomato (Givaudan-Roure). The undiluted odourants were placed in 10 ml U-shaped Pyrex® tubes (VS Technologies, Saint-Priest, France) filled with microporous substances.

The odourants were presented with a 20-channel computer-controlled olfactometer adapted from Sezille et al. (2013). This odour diffusion system was developed to synchronize odourous stimuli with breathing. Participants' nasal respiratory signal was acquired using a nasal canula (Teleflex, Le Faget, France) and was used to trigger the odour stimulation through an airflow sensor. During odour stimulation, the olfactometer waited for the participants' expiration, allowing the odour to be perceived at the beginning of the subsequent inspiration. When this expiration was detected, an unodourized airflow was sent to one of the U-shaped odourous tubes. Odourized airflow and air carrier were sent to and mixed in a homemade mixing head made of polytetrafluoroethylene. It was connected to the nostrils

through two Teflon tubes, fixed to the nasal canula, opening out under the nostrils. The olfactometer airflow rate was set between 2.6 and 5.0 L/min depending on the odourants' physical intensity. The odourants were delivered over 6 s. The olfactometer was controlled by an in-house LabView software (National Instruments, Austin, TX, USA) and interacted with EpisOdor software to synchronize odour stimulation with box opening via a TCI-IP connection.

2.3.2.2 Musical stimuli. Musical stimuli were selected from the material of Vieillard et al. (2008) (Copyright, Bernard Bouchard, 1998) (http://www.peretzlab.ca/knowledge_transfer/). They were modified in MIDI (Digital Performer®, MOTU, Cambridge, USA) aiming to reduce features that might potentially evoke emotions. The modifications included changes in tempo, mode (major/minor), and/or a few notes, depending on the stimulus. The musical stimuli were played with an acoustic piano timbre (Cubase®, Steinberg Media Technologies, Hamburg Germany) and presented with EpisOdor at a comfortable loudness level over headphones. The two music sets were matched for their number of events (28.50 ± 7.83), tempo (76.72 ± 19.35 pulses per min) and duration (7.78 ± 1.31 s).

2.3.2.3 Pictures of faces. Pictures of faces were selected from the Chicago Face Database (Ma et al., 2015) (<https://chicagofaces.org/default/>). They were composed of the faces of nine women and nine men from various origins (Asian, Caucasian, African American, Latin American; Figure 1C). All faces were presented on a white background, their relative position and dimensions were similar, and all persons wore a grey sweatshirt. To limit their distinctiveness, they were turned into black and white, and the most prominent details of each face were erased (spots, freckles; Photoshop®, Adobe, Dublin, Ireland). In the Episodor software, the 2863 x 1718 pixels pictures were presented in jpeg format inside the box cover, on the centre of the screen. The duration of their presentation was adjusted to the music

duration when presented simultaneously and was 6 s otherwise.

2.4 Experimental procedure

As in our previous investigations of episodic memory (Plailly et al., 2019; Saive et al., 2013, 2015; Saive, Royet, Ravel, et al., 2014), the experiment was divided into four consecutive sessions, one session per day (Figure 1D). The first three days were devoted to the encoding phase, and the last day was divided into three parts: retrieval test, questionnaires (see Supplementary data 1), and stimuli evaluation. A night of sleep followed each of the sessions to promote consolidation and reduce interference (Abichou et al., 2019; Maquet, 2001; Stickgold, 2005). Participants completed the four sessions at the same time each day to limit the differential influences of internal states (hunger, satiety) on olfactory and cognitive processes between sessions (Jiang et al., 2008; Plailly et al., 2011). The participants were requested to breathe through their nose as naturally as possible without consciously modifying their respiration and to avoid sniffing behaviour.

2.4.1 Encoding

During each encoding session, participants freely explored the room with the door open, one different room on each of the three days. The order of the rooms was counterbalanced across participants. Participants were encouraged to pay attention to each detail of the rooms and were told to click at least five times on each box to be sure they sufficiently explored each stimulus. The fifth click was indicated to the participant with a change of the box's arrow colour, from green to red. Encoding sessions lasted a minimum of 10 min and up to a maximum duration until the three boxes were opened five times. No instructions for memorization were given, but participants were informed that they would be questioned about their perception of the episodes on the fourth day. This procedure aimed to ensure a free

encoding similar to real-life situations.

2.4.2 Retrieval

The retrieval test took place in the same virtual house and was composed of 54 trials. Each trial started in the corridor where a closed box was placed in the centre, with the three doors being closed (Figure 1E). Participants were told to click on the box, which triggered its opening and the presentation of a unimodal cue (odour, music, face). Half of the cues had not been encountered during the encoding phase (27 distractors), and the others had been explored during the three preceding days (27 targets). The cues were presented pseudo-randomly with the constraint to avoid the presentation of two odours, three pieces of music, or three faces in a row. This avoided olfactory saturation and any habituation to the stimulus type. Participants were first asked whether they recognized the cue as having been presented at the encoding phase or not (Recognition response; “*Do you recognize this stimulus? (Y/N)*”). The answer was given with a left or a right click on the trackball. In the case of a “No” response, the trial ended. Therefore, the cue diffusion stopped, participants were taken back into the corridor, and another closed box containing another cue was placed in front of them. In the case of a “Yes” response, in V1, the cue diffusion stopped, the box closed, and the corridor appeared with all doors opened. Participants were asked to move into a room in order to click on the box in which they previously encountered the cue. A click on a box ended the trial (Episodic response). In V2, the stimulus diffusion was maintained until participants had given their response to the additional question asking whether they remembered the context (the room and the box) where they previously encountered the cue (Subjective recollection response; “*Do you remember the context? (Y/N)*”). This allowed for metacognitive knowledge evaluation. Regardless of their response, the doors opened and participants had to move into a room, and to click on the box in which they previously encountered the cue. The click on a

box ended the trial (as in V1).

2.4.3 *Sensory evaluations*

At the end of the experiment, participants were required to rate the 54 stimuli (targets and distractors from all sensory modalities) in terms of pleasantness (unpleasant – neutral – pleasant), emotional intensity (very weak – very intense), familiarity (unknown – very familiar), and complexity (very simple – very complex) using 15cm-non-graduated bounded linear scales presented with an in-house LabView software. The pleasantness scale was divided into two equal parts by a “neutral” value separating the ratings of unpleasantness and pleasantness. Each unimodal stimulus was presented for about 6 s and participants were given 5 s to respond to each question. Participants were trained with a short practice session consisting of one new stimulus for each sensory modality.

2.5 *Data analyses*

2.5.1 *Memory responses*

2.5.1.1 Cue recognition. Considering cue recognition, four response categories were defined from the experimental conditions (target vs. distractor) and participants' behavioural responses (“*Yes*” vs. “*No*”) and based on signal detection theory (Lockhart & Murdock, 1970): *Hit* and *Miss* occurred when target items were respectively correctly recognized and incorrectly rejected, and correct rejection (*CR*) and false alarm (*FA*) occurred when distractor items were respectively correctly rejected and incorrectly recognized.

Cue recognition performance was computed as the probability to accurately recognize target cues and to accurately reject distractor cues among all cues presented. These probabilities were 1) analysed as a function of Sensory Modality (odour, music, face) and

Version (V1, V2) and 2) compared to chance levels (1 response out of 2, “Yes” or “No”; *i.e.*, 50 % chance to pick the correct answer). Recognition performance was also resumed with two metrics: The memory score (d') reflects the participant's ability to discriminate between target and distractor items (the higher the d' , the better the performance), and the response bias score (c) reflects the participant's tendency to give more “Yes” (positive score) or “No” (negative score) responses regardless of experimental conditions.

2.5.1.2 Episodic memory. The analyses of episodic memory retrieval responses detailed the memory process step by step. A complete episodic memory retrieval started from the presentation of the target cues (step “Cue”) and requires the accurate recognition of the cue (step “Cue+”) and then to enter the accurate room (step “Room+”) and to choose the accurate box (step “Box+”), in which the cue had been presented during encoding (Figure 3A). Note that the first step corresponded to the Hit response category in the frame of recognition memory. Note also that conditions were interdependent, such that Room+ implied Cue+, and Box+ implied Room+. Three episodic response categories were defined, based on the room entered and the box selected: *Room-Box-* when the incorrect room was entered (and thus an incorrect box was selected); *Room+Box-* when the correct room was entered, but an incorrect box was selected; *Room+Box+* when the participants entered the correct room and selected the correct box.

Memory performance was computed as the probability to reach each episodic step (Figure 3A), that was: (1) to accurately recognize the target cues (*from Cue to Cue+*; 1 response out of 2, “Yes” or “No”; *i.e.*, 50 % chance to pick the correct answer), and in case of an accurate recognition, to remember (2) the room (*from Cue+ to Room+*; 1 room out of 3; *i.e.*, 33 % chance to enter the correct room) and then (3) the box (*from Room+ to Box+*; 1 box out of 3; *i.e.*, 33 % chance to click on the correct box) in which the cue was initially encoded.

Global episodic memory performance was also evaluated by computing probabilities across several episodic steps. This was done by computing the probability to fully remember the episodes (4) from the cue presentation (*from Cue to Box+*; $1/2 * 1/3 * 1/3$; *i.e.*, 5 % chance to succeed), and (5) from the cue recognition (*from Cue+ to Box+*; $1/3 * 1/3$, *i.e.*, 11 % chance to succeed). All these probabilities were (1) analysed as a function of Sensory Modality (odour, music, face) and Version (V1, V2), and (2) compared to chance levels.

2.5.1.3 Subjective recollection. Subjective recollection responses were only available in V2 (N = 21). They were analysed as the probability to give a “Yes” response (over “Yes” and “No” responses) as a function of Sensory Modality (odour, music, face) and of subsequent episodic memory responses (Room-Box-, Room+Box-, Room+Box+).

2.5.2 Response times

Response times were computed for cue recognition, subjective recollection (V2 only) and episodic retrieval response categories (Figure 1E). The response times corresponded to the durations between the presentation of the cue (or the first inspiration after an odour presentation) and 1) the “Yes/No” recognition response (recognition period), 2) the “Yes/No” subjective recollection response (subjective recollection period), and 3) the click on the box for the episodic retrieval (episodic period). Outlier response times were removed by setting aside data that were above the 9th decile of the mean computed by Participant and Sensory Modality. Response times were analysed as a function of Response Category (recognition: Hit, Miss, CR, FA; subjective recollection: Yes, No; episodic: Room-Box-, Room+Box-, Room+Box+), Sensory Modality (odour, music, face) and Version (V1, V2). For the recognition and the subjective recollection periods, the effect of subsequent episodic memory responses (Room-Box-, Room+Box-, Room+Box+) was also analysed.

2.5.3 *Breathing parameters*

Breathing parameters consisted of respiratory frequency, and inspiration amplitude and volume. They were computed for the same conditions and within the same boundaries as those defined for response times analyses during the recognition and the episodic periods only, no hypothesis being associated with the subjective recollection period. Breathing parameters were analysed as a function of Response Category (recognition period: Hit, CR; episodic period: Room-Box-, Room+Box-, Room+Box+), Sensory Modality (odour, music, face) and Version (V1, V2).

2.5.4 *Sensory evaluations*

Pleasantness, emotional intensity, familiarity, and complexity ratings of the stimuli were measured with millimetre precision and were *a posteriori* transformed into scores from 0 to 10. They were analysed as a function of Sensory Modality (odour, music, face) to test for the comparability of the memory cues. Due to technical issues, some data were missing (a maximum of 5.5% per sensory feature over all participants).

[Insert Figure 1 about here]

2.6 *Statistical analyses*

2.6.1 *General statistical information*

Statistical analyses were performed in R studio with R 4.0.4 (R Development Core Team, 2021), with orthogonal sum-to-zero contrasts set in the default settings, and with the *afex* library version 0.28-1 that is based on *lme4* package (Bates et al., 2015; Singmann et al., 2021). When effects were significant, *posthoc* Bonferroni comparisons were run to determine significant differences among the estimated marginal means (EMM) with *emmeans* package

version 1.5.5-1 (Lenth et al., 2020). The same package was used to test the difference against chance level. The significance level was set to $p \leq .05$. For clarity purposes, only tests addressing the main goal of the present paper were detailed below. Similarly, when an interaction between effects was statistically significant, the effects of the main factors were not reported. When interactions between variables were tested, the trend of the slope was reported. Data were described with estimated marginal means and its standard error of the mean (EMM \pm SEM).

2.6.2 Memory responses, response times and sensory evaluations

The analyses of memory responses, response times and sensory evaluations were conducted with linear and generalized linear mixed-effect models (LMM and GLMM, respectively), which contain both fixed and random effects. Fixed effects are the effects of interest, whereas random effects represent levels that randomly vary across the population and that are expected to be controlled for. Here, Sensory Modality was a fixed effect as the major goal of this study was to determine whether memory performance varied within its three levels (odour, music, face). Participant and/or Item (sensory cues) were accounted as random effects to explain between-Participants and/or between-Items variability without investigating them [for more explanations about fixed and random effects, see (Brauer & Curtin, 2018; Brown, 2021; Singmann & Kellen, 2019)]. Therefore, the age, gender and even the level of musical expertise were implicitly taken into account in the random effect Participant. These models can represent data following a Gaussian variation (LMM) as well as other kinds of variations, from gamma to binomial (GLMM). In addition to the fact that these methods are now more frequently used in biology and psychology research (Brown, 2021; DeBruine & Barr, 2021; Harrison et al., 2018; Meteyard & Davies, 2020), this choice had been motivated by two main advantages. First, they allowed for analysing the effect of Sensory Modality on memory

accuracy by taking into account its binomial nature (Jaeger, 2008; Meteyard & Davies, 2020). Second, they allowed for the modelling of more than one random effect (non-controlled environmental variability), thus rendering our results more powerful and generalizable (Jaeger, 2008; Brown, 2021; DeBruine and Barr, 2021). Mixed models are also more robust to missing data and unbalanced design (Brown, 2021).

In the current study, mixed models were fitted with the “mixed” function from the *afex* library. These mixed models were fitted with the Laplace approximation method. The global procedure used to construct models was the following: Unless specified, the maximal model justified by the design and by the number of data points was constructed first (Barr et al., 2013). In case of singular fit or convergence errors, random effects were selected (reduced) by comparing nested models with a likelihood ratio test and a backward selection heuristic, so the model complexity was reduced until the statistical test was significant (same method as in Matuschek et al., 2017) or no more errors were noted. With the experiment being a within-participant design, the random Participant intercept was never dropped. For clarity purposes, the maximal and final models were detailed in the supplementary material (Supplementary data 2, 3 and 4). LMMs were checked using the package *performance* (Lüdtke et al., 2021) from the *easystat* collection (Lüdtke et al., 2022). *P*-values were computed using the package *lmerTest* (Kuznetsova et al., 2015) by the Kenward-Roger approximation with type 2 tests when the model did not contain interactions, and type 3 tests when it did. GLMM were checked using the *DHARMA* package (Hartig, 2021) and *p*-values were computed by likelihood ratio tests.

2.6.3 Recognition metrics and breathing parameters

Recognition metrics included the memory score d' and the bias score c . These scores were

computed by adapting the signal detection theory framework to GLMM analysis, as presented in the supplementary material (Supplementary data 2). The effects of Sensory Modality and Version on each of the recognition metric was then tested. As analyses of variance (ANOVAs) assumptions were violated, Friedman and Kruskal-Wallis Rank Sum tests were computed and followed by pairwise tests of Wilcoxon with Bonferroni correction.

During recognition and episodic periods, breathing parameters (breathing frequency, inspiration amplitude and inspiration volume) were analysed with two-way ANOVAs for repeated measures using the *aov_car* function from the *afex* library with Sensory Modality (odour, music, face) and Response Category (recognition: Hit, CR; episodic: Room-Box-, Room+Box-, Room+Box+) as within-participant factors, and Version (V1, V2) as a between-participants factor. For the recognition period, due to a limited number of breathing cycles for inaccurate rejection (Miss) and recognition (FA) response categories, only Hit and CR response categories were considered. For recognition and episodic periods, due to response categories' data being unbalanced between sensory modalities, the effects of episodic responses on breathing data were tested separately for the three sensory modalities. When the Mauchly test for Sphericity was significant, Greenhouse-Geisser correction was applied. When ANOVA assumptions were violated, Friedman and Kruskal-Wallis Rank Sum tests were computed and followed by pairwise tests of Wilcoxon with Bonferroni correction.

3 Results

3.1 Cue recognition

The results of cue recognition are displayed in Figure 2.

3.1.1 Memory performance

The performance of cue recognition involved the probability to accurately recognize the target cues (Hits) and to accurately reject the distractors cues (CRs). A significant interaction between Sensory Modality (odour, music, face) and Item Type (target, distractor) ($\chi^2_{(2)} = 6.68$, $p < .05$) showed that the probability for a Hit was significantly higher for music (EMM \pm SEM, 98.2 ± 0.8 %) and faces (95.0 ± 1.5 %) than for odours (79.9 ± 3.8 %; z 's ≥ 4.45 , p 's $< .001$; Figure 2A). No significant difference was observed for Hits between music and faces ($z = 2.19$, $p = .086$). Similarly, the probability for a CR was higher for music (94.9 ± 41.5 %) and faces (97.7 ± 0.9 %) than for odours (76.9 ± 3.8 %; z 's ≥ 4.98 , p 's $< .001$). No significant differences were observed for CR between music and faces ($z = 1.76$, $p = .24$). The probability for a Hit was higher than the probability for a CR for music ($z = 2.21$, $p < .05$), but not for odours and faces (z 's ≤ 1.67 , p 's $\geq .095$). Moreover, for cues from all sensory modalities, the probability to obtain Hits and CRs differed significantly from random responses (z 's ≥ 6.56 , p 's $< .001$). Congruently, memory score d' was estimated at 1.50 ± 0.52 for odours, 3.77 ± 0.57 for music, and 3.57 ± 0.52 for faces. A significant effect of the Sensory Modality ($\chi^2_{(2)} = 91.41$, $p < .001$) revealed that d' for music was higher than d' for faces ($p < .001$) and that d' for both music and faces were higher than d' for odours (p 's $< .001$). These findings demonstrated that all cues were efficiently recognized, but that odour cues evoked less accurate recognition and rejection than music and face cues. Bias score c was estimated at 0.05 ± 0.31 for odours, 0.23 ± 0.04 for music, and -0.17 ± 0.00 for faces. Regarding the c score, a significant effect of the Sensory Modality ($\chi^2_{(2)} = 51.29$, $p < .001$) revealed that c score for odours was higher than c score for faces ($p < .001$), and that c score for both odours and faces were higher than c score for music (p 's $< .001$). Furthermore, the c score for odours was not significantly different from 0 ($p = .34$), while it was significantly higher than 0 for music ($p < .001$), and significantly lower than 0 for faces ($p < .001$). These

findings demonstrated that odour recognition was not biased toward more Yes or No responses, while music recognition was associated with liberal behaviour, and face recognition was associated with conservative behaviour.

3.1.2 Response times

For recognition response times, a significant interaction between Sensory Modality and Recognition Response Category ($F_{(6,147)} = 7.77, p < .001$) was observed (Figure 2B). Within-sensory modalities effects were revealed. For target cues, Hit responses were faster than Miss responses for odours (Hit, 4.49 ± 0.27 s; Miss, 6.33 ± 0.52 s) and faces (Hit, 2.58 ± 0.14 s; Miss, 4.32 ± 0.47 s; $t's \geq 4.94, p's < .001$) but not for music (Hit, 4.40 ± 0.27 s; Miss, 6.24 ± 0.88 s; $t_{(240)} = 2.64, p = .054$). For distractor cues, CR responses were faster than FA responses for faces (CR, 2.24 ± 0.14 s; FA, 5.38 ± 0.66 s; $t_{(191)} = 7.26, p < 0.001$), but not for odours (CR, 4.83 ± 0.33 s; FA, 5.74 ± 0.42 s) nor music (CR, 4.92 ± 0.35 s; FA, 6.18 ± 0.65 s; $t's \leq 2.42, p's \geq .12$). Among correct responses, CR responses were faster than Hit responses for faces ($t_{(73)} = 2.98, p < .05$), and no significant differences were found for odours and music ($t's \leq 2.39, p's \geq .12$). Among incorrect responses, response times did not differ significantly between Miss and FA for all three sensory modalities ($t's \leq 1.761, p's \geq .66$). Between-sensory modalities effects were also revealed. For both Hit and CR, responses were faster for faces than for both odours and music ($t's \geq 8.67, p's < .001$), and no difference was observed between odours and music ($t's \leq 0.31, p's = 1.00$). For Miss responses, responses were faster for faces than for odours ($t_{(269)} = 3.44, p < .01$), and no differences were observed with music ($t_{(383)} \leq 2.32, p's \geq .06$). For FA, no significant differences were observed ($t's \leq 0.94, p's = 1.00$). Moreover, a significant interaction between Sensory Modality and Version ($F_{(2,49)} = 6.32, p < .01$) revealed that music induced faster recognition responses in V2 (3.77 ± 0.36 s) than in V1 (4.88 ± 0.40 s; $t_{(50)} = 2.21, p < .05$).

When considering Hits only, the analysis of response times as a function of Subsequent Episodic Responses was fitted. The effect of Subsequent Episodic Responses just fell short of significance (Figure 2C; $F_{(2,1097)} = 3.00, p = 0.050$), suggesting that Hit responses were faster when followed by accurate episodic responses (Room+Box+, 3.55 ± 0.18 s) than by inaccurate episodic responses (Room-Box-, 3.84 ± 0.18 s; $t_{(1103)} = 2.44, p < .05$). No differences of response times were observed with the response category Room+Box- (3.70 ± 0.19 s; $t_{(1097)} \leq 1.14, p \geq 0.77$).

3.1.3 Breathing parameters

During the recognition period, for *mean amplitude of inspirations*, a significant interaction between Sensory Modality and Recognition Response Category (Figure 2D, $F_{(2,98)} = 3.69, p < .05$) revealed that mean amplitude of inspirations was higher during Hits than CRs, for music and faces (t 's $\geq 2.38, p$'s $< .05$), but not for odours ($t_{(146)} = 0.25, p = .80$). Mean amplitude of inspirations was also higher for odours than for faces and music, for both Hits and CRs (t 's $\geq 3.00, p$'s $< .01$), and did not significantly differ between music and faces (t 's $\leq 0.77, p$'s = 1.00).

Considering the *mean volume of inspirations*, a significant effect of the Sensory Modality ($\chi^2_{(2)} = 56.94, p < .001$) showed that mean volumes of inspiration were higher during odours than during music and faces (p 's $< .001$), and did not significantly differ between music and faces ($p = .86$). No significant effects of Recognition Response Category were observed ($\chi^2_{(1)} = 3.31, p = .069$).

The *mean respiratory frequencies* did not significantly differ with Sensory Modality and Recognition Response Category (F 's $\leq 2.83, p$'s $\geq .064$).

No significant effects of Subsequent Episodic Responses were observed for mean

frequency, inspiration amplitude and inspiration volume of breathing. See supplementary material (Supplementary data 5) for detailed results.

[Insert Figure 2 about here]

3.2 Episodic memory retrieval

The results of episodic memory are displayed in Figure 3.

3.2.1 Memory performance

The performance of episodic memory is summarized in Figure 3B and detailed in Figure 3C.

3.2.1.1 From Cue to Cue+. This step corresponded to the Hits in the recognition memory task (see 3.1.1. Memory performance; Figure 2A).

3.2.1.2 From Cue+ to Room+. The probability to retrieve the correct room after accurately recognizing a target cue was significantly influenced by the Sensory Modality of the cue ($\chi^2(2) = 44.47, p < .001$), such that it was higher for faces ($71.6 \pm 3.4\%$) than for both music ($34.8 \pm 2.5\%$) and odours ($51.5 \pm 3.0\%$; z 's $\geq 4.49, p$'s $< .001$), and higher for odours than for music ($z = 4.31, p < .001$). Moreover, this probability was significantly higher than chance level for odours and faces (z 's $\geq 6.09, p$'s $< .001$), but not for music ($z = 0.58, p = 1.00$).

These results showed that when participants accurately recognized faces and odours, they were able to retrieve the correct room, but this was not the case for music.

3.2.1.3 From Room+ to Box+. The probability to retrieve the correct box after entering the correct room was significantly influenced by the Sensory Modality of the cue ($\chi^2(2) = 16.35, p < .001$), such that it was higher for faces ($73.0 \pm 4.3\%$) than for both odours ($52.2 \pm 4.3\%$) and music ($44.4 \pm 4.4\%$; z 's $\geq 3.34, p$'s $< .001$). The probability for odours and for music did

not significantly differ ($z = 1.19, p = .70$). Moreover, this probability was significantly higher than chance level for the cues of all sensory modalities (z 's $\geq 2.52, p$'s $< .05$). In other words, during retrieval, when participants were in the correct room, they were able to accurately retrieve the correct box for odours, music and faces, with faces showing the best performance.

3.2.1.4 From Cue to Box+. The probability to accurately retrieve the complete episode, that is from the presentation of a target cue to the selection of the correct box, was affected by the Sensory Modality of the cue ($\chi^2_{(2)} = 34.17, p < .001$), such that it was higher for faces ($44.5 \pm 4.4\%$) than both odours ($19.2 \pm 2.4\%$) and music ($14.5 \pm 1.9\%$; z 's $\geq 5.69, p$'s $< .001$). The probability was not significantly different between odours and music ($z = 1.46, p = .43$). Moreover, this probability was significantly higher than chance level for cues of all sensory modalities (z 's $\geq 4.70, p$'s $< .001$). In other words, cues from all sensory modalities were able to trigger the recall of an episodic memory, faces being the most efficient cues.

3.2.1.5 From Cue+ to Box+. The probability to accurately retrieve the complete episode after recognizing a target cue was significantly influenced by the Sensory Modality of the cue ($\chi^2_{(2)} = 34.96, p < .001$), such that it was higher for faces ($48.2 \pm 4.5\%$) than for odours ($26.0 \pm 2.9\%$), and higher for odours than for music ($14.8 \pm 2.0\%$; z 's $\geq 2.98, p$'s $< .01$). Moreover, this probability was significantly higher than chance level for odours and faces (z 's $\geq 5.11, p$'s $< .001$), but not music ($z = 1.89, p = .17$). In other words, faces and odours, once recognized, were associated with their initial context and location, but this was not the case for music.

3.2.2 Response times

For episodic response times, a significant interaction between Sensory Modality and Episodic Response Category (Figure 3D; $F_{(4,1145)} = 3.48, p < .01$) was observed. Within-sensory modalities differences were revealed. Correct episodic responses were faster than incorrect

episodic responses for odours (Room+Box+, 16.88 ± 0.95 s; Room-Box-, 20.78 ± 1.00 s) and faces (Room+Box+, 15.89 ± 0.74 s; Room-Box-, 19.71 ± 1.01 s; t 's ≥ 3.81 , p 's $< .001$), but not music (Room+Box+, 19.88 ± 1.23 s; Room-Box-, 19.94 ± 0.86 s; $t_{(1144)} = 0.05$, $p = 1.00$). Similarly, correct episodic responses were faster than Room+Box- response for odours (22.76 ± 1.31 s) and faces (18.53 ± 1.07 s; t 's ≥ 2.81 , p 's $< .05$), but not music (20.32 ± 1.17 s; $t_{(1142)} = 0.32$, $p = 1.00$). Between-sensory modalities differences were also revealed. Correct episodic responses were faster for odours and faces than for music (t 's ≥ 2.45 , p 's $< .05$), with no differences between faces and odours ($t_{(1142)} = 1.15$, $p = 0.75$). Room+Box- response for faces were faster responses than for odours ($t_{(1142)} = 3.20$, $p < 0.01$), with no differences for music (t 's ≤ 1.43 , p 's $\geq .46$), and there were no sensory modality effects on Room-Box- responses (t 's ≤ 1.07 , p 's $\geq .85$).

3.2.3 Breathing parameters

During the episodic period, no significant effects of Episodic Response Category were observed for mean frequency, inspiration amplitude and inspiration volume of breathing. See supplementary material (Supplementary data 5) for detailed results.

[Insert Figure 3 about here]

3.3 Subjective recollection

The results of subjective recollection are displayed in Figure 4.

3.3.1 Memory responses

When participants had answered that they recognized the cue, they were asked whether they were feeling they could remember the entire associated episode or not. The probability to answer “Yes” significantly differed with the Sensory Modality of the cues (Figure 4A; $\chi^2_{(2)} =$

41.52, $p < .001$). It was higher for faces ($82.4 \pm 5.6 \%$) than for both odours ($48.1 \pm 9.1 \%$) and music ($32.2 \pm 7.4 \%$; z 's ≥ 3.85 , p 's $< .001$), with no difference between odour and music cues ($z = 2.00$, $p = 0.14$). The probability to answer “Yes” differed also significantly with the Subsequent Episodic Score (Figure 4B; $\chi^2_{(2)} = 7.22$, $p < .05$). It was higher before an accurate episodic response (Room+Box+; $70.8 \pm 8.4 \%$) than before an inaccurate episodic response (Room-Box-; $44.4 \pm 8.1 \%$; $z = 2.82$, $p < .05$), but not before a Room+Box- episodic response ($51.4 \pm 9.9 \%$; $z = 1.42$, $p = 1.00$). No differences were revealed between Room-Box- and Room+Box- episodic responses ($z = 0.77$, $p = .28$). To sum up, participants felt more frequently they recollected an episode when the cue was a face, than when it was an odour or a music, and these feelings were in agreement with the observed episodic memory performance.

3.3.2 Response times

For subjective recollection response times, a significant interaction between Sensory Modality and Subjective Recollection Response Category was observed (Figure 4C; $F_{(2,82)} = 5.65$, $p < .01$). It revealed that “Yes” responses were faster for faces (6.52 ± 0.628 s) than for music (8.92 ± 0.95 s; $t_{(112)} = 3.86$, $p < .001$), and no differences were observed with odours (7.59 ± 0.80 s; t 's < 1.88 , p 's $> .20$). No differences of response times with Sensory Modality were observed for “No” responses (t 's < 1.05 , p 's $> .88$). “Yes” responses were also faster than “No” responses for odours (“No”, 9.83 ± 1.02 s; $t_{(65)} = 2.76$, $p < .01$) and faces (“No”, 10.58 ± 1.21 s; $t_{(70)} = 5.08$, $p < .001$), but not for music (“No”, 9.58 ± 0.94 s; $t_{(61)} = 0.79$, $p = .43$).

[Insert Figure 4 about here]

3.4 Sensory evaluations

Pleasantness, Emotional intensity, and Familiarity sensory evaluations differed significantly

between odours and both music and faces (F 's > 6.66 , p 's $< .01$). Odours (pleasantness, 4.42 ± 0.29 ; emotional intensity, 5.71 ± 0.19 ; familiarity, 5.54 ± 0.25) were judged as being less pleasant, evoking stronger emotion and being more familiar than music (pleasantness, 6.39 ± 0.29 ; emotional intensity, 5.05 ± 0.19 ; familiarity, 4.64 ± 0.30) and faces (pleasantness, 5.55 ± 0.28 ; emotional intensity, 4.78 ± 0.18 ; familiarity, 4.34 ± 0.32 ; t 's ≥ 2.57 , p 's $< .05$). Sensory evaluations did not significantly differ between faces and music (t 's < 2.07 , p 's $> .13$).

Complexity evaluations also significantly differed with Sensory Modality ($F_{(2,75)} = 5.73$, $p < .01$), indicating that odours (5.22 ± 0.19) were judged as being more complex than music only (4.24 ± 0.23 ; $t_{(84)} = 3.39$, $p < .01$). No significant differences of complexity were observed between faces (4.82 ± 0.21) and both odours and music (t 's ≤ 1.92 , p 's $\geq .18$).

4 Discussion

Our study demonstrated major influences of the sensory modality of the memory cue on memory processes. Importantly, our ecological-laboratory experimental approach allowed distinguishing recognition memory and episodic memory, notably revealing that the influence of the cues' sensory modality on memory retrieval differed between recognition and episodic memory. While odours were less recognized than music and faces, they were able to evoke episodic retrieval. Pieces of music were perfectly recognized, but once recognized they failed at initiating the retrieval of their context of encoding. Faces were perfectly recognized and were proficient in evoking episodic memories. Interestingly, breathing patterns varied according to the recognition memory process.

4.1 Music and faces outperform odours for recognition memory

Each test trial started with a recognition phase. The participants were presented with the cues they encountered during free encoding, together with new distractor cues. They were asked to

decide whether they recognized the cues or not. The participants were proficient in accurately recognizing target cues among distractor cues with cues from all sensory modalities.

Importantly, recognition abilities varied with the sensory modality of the cues. They were higher for both music (98 %) and faces (95 %) than for odours (80 %).

The level of odour recognition performance was in agreement with our previous studies (Plailly et al., 2019; Saive et al., 2013, 2015; Saive, Royet, Ravel, et al., 2014), as well as with those from other research teams (e.g., Larsson et al., 2009; Levy, 2004; Nguyen et al., 2012). Given that the paradigms and the total number of to-be-remembered cues were different across the studies, the obtained similar levels of memory performance suggest some consistency of the involved memory processes. Response times corroborated the relatively good olfactory recognition performance. The participants answered faster during accurate recognition of odours than when they failed at recognising or rejecting the odour cues. This is consistent with previous reports where Hits were always the fastest response (Jehl et al., 1997; Olsson & Cain, 2003; Royet et al., 2011; Saive, Royet, Ravel, et al., 2014). The lower recognition score for odours than for other sensory cues confirmed our hypothesis. It is also in agreement with studies where the recognition of odours was compared to the recognition of other stimuli, such as faces (Cornell Kärnekull et al., 2015), environmental sounds (Cornell Kärnekull et al., 2018) and common pictures (Cameron et al., 2021), even if no recognition memory performance differences were observed between odours and abstract simple shapes (Lawless, 1978). This reduced ability to recognize unidentifiable odours can be attributed to the difficulty of verbally categorising and communicating about odours (Jraissati & Deroy, 2021; Majid & Burenhult, 2014). The odour perceptual system might be implemented differently than other sensory systems, and be less tied to semantization processes (Olofsson & Gottfried, 2015). Indeed, a stimulus that is less easily categorized could undergo a more

shallow encoding than stimuli that are more easily categorizable, leading to decreased recognition performance (Craik & Lockhart, 1972; Craik & Tulving, 1975).

Considering music and faces, recognition memory scores were almost perfect. On the one hand, the recognition of familiar music can be fast: only 500 ms (Filipic et al., 2010) or only two to three notes are sufficient to tell if the upcoming music is familiar, and two to three more notes to be able to tell its title (Schulkind, 2009). Music memory is also resistant, as it is somewhat preserved in patients suffering from dementia, such as Alzheimer's disease (Cuddy, 2018; Platel & Groussard, 2010). On the other hand, recognition of music excerpts is shown to be poorer than recognition of visual objects, such as pictures of object, faces, abstract art pieces, degraded visual images of scenes, and facts (Cohen et al., 2009, 2011; Deffler & Halpern, 2011). In our present study, the musical pieces were unfamiliar, but their recognition was extremely good and at a similar level as face recognition. This pattern is different from our hypothesis and at first, can be considered surprising. As here the number of cues to recognize was inferior to that commonly used in recognition studies (nine targets here *versus* more than 60 in the studies of Cohen et al. (2009, 2011)), face and music recognition results may thus show ceiling performance, not allowing us to disentangle their potential differences. Regarding faces, their importance in social and everyday life and their omnipresence leads some researchers to sustain that humans are experts in face processing (Young & Burton, 2018). Recognizing specific pictures of faces seems to be incredibly easy, relative to other objects. Notably, recognition scores of face pictures were reported to be superior to that of pictures of scenes (Sato & Yoshikawa, 2013), houses, aeroplanes, moving persons (Yin, 1969), as well as of odours (Cornell Karnekull et al., 2015), and voices (Cortes et al., 2017; Damjanovic & Hanley, 2007). Our results confirmed the exceptional human ability to recognize faces, even unfamiliar ones (Sato & Yoshikawa, 2013), considering that the

recognition of unfamiliar faces is picture-based, in contrast to familiar faces for which recognition is identity-based (Longmore et al., 2008). Because of the limited number of incorrect recognitions and rejections with music and face cues, response time variation based on accuracy should be interpreted with caution. However, it is intriguing to note that the accurate recognition of faces was slower than the accurate rejection of faces, suggesting that the detection of unknown faces is evolutionary more important than the recognition of known faces. As face stimuli are processed over several steps (Maurer et al., 2002), our results suggest also that fewer steps may be required to reject a new face than to recognize a new face.

4.2 Odours and faces outperform music for episodic memory

Once participants had recognized the cue as being old (*i.e.*, encountered previously in the encoding session), they had to move into the room where it was previously encountered, and then select the box it was contained in. To investigate episodic memory processes and dissect their functioning, we first considered each memory step composing this process. This allowed the associative part of the episodic memory to be separated from its recognition part. It revealed that once recognized, odours and faces efficiently evoked a complete episodic memory, with faces (48 %) being more efficient than odours (26 %), and that music was unable to evoke episodic memory (15 %). Moreover, faces and odours evoked more episodic memories than did the music. Interestingly, the response times revealed that the episodic memory process was initiated from the recognition decision, the accurate recognition response being faster when followed by complete accurate episodic retrieval than when followed by inaccurate episodic retrieval, in agreement with our previous study (Saive, Royet, Ravel, et al., 2014). In brief, our study highlighted that recognition differed from more complex episodic memory, such as autobiographical memory, while showing that recognition

and episodic memory are interdependent.

Our data, therefore, confirmed one of the earliest results in the field of human olfactory memory: the olfactory modality, in comparison with the visual modality, suffers from inferior performance during recognition, but not during associative memory, which includes episodic memory (Davis, 1977). Odours are indeed potent stimuli to be associated with other objects and to be used as retrieval cues, even considering their somehow lower recognition scores (Davis, 1977; Herz, 1998; Herz and Cupchik, 1995; see Engen, 1987 for a review). This pattern of results was further supported by the observations made in ecological odour-evoked memory studies suggesting that autobiographical memory has a privileged relationship with the sense of smell (for reviews, Larsson & Willander, 2009; Saive et al., 2014a; Hackländer et al., 2019). These studies have shown that memories associated with odours are recalled less frequently than memories associated with cues from other sensory modalities, but are highly associated with the events' emotion (Hinton & Henley, 1993; Herz, 2004) and richness (Chu & Downes, 2002; de Bruijn & Bender, 2017), highlighting the strength of the memory trace. Going further with the findings of ecological and autobiographical studies, our results suggest that the limited amount of odour-evoked autobiographical memory in everyday life might be linked to their poor ability to be recognized. However, when recognized, odours demonstrate to be good episodic memory cues.

The specificity of our paradigm enabling the separation of the associative part of the episodic memory retrieval in several steps was also informative for music memory. The first association following cue recognition, where participants must enter the correct room, seemed to be crucial and to be responsible for the inability of the music cues to evoke episodic memory once recognized. While very efficiently recognized, music failed to evoke the

retrieval of contextual information. However, once the participants entered the correct room by chance, they were then able to select the right box with a probability that exceeded the chance level. Even if this probability was still lower than for face cues, it was similar to the probability for odour cues. The memory of the context in which the music was encountered may thus be encoded and stored, but the power of the music cue was not sufficient to initiate its retrieval. This weak link between music and its encoding context might have several reasons. First, music might be more strongly associated with a period of life than with a specific event. In their seminal work, Janata et al. (2007) studied the nature of autobiographical memories evoked by familiar music, and in particular the categories of memories. Results showed that only one-fifth of the memories were specific and related to a unique event, suggesting that music memories were more frequently associated with numerous life events than with specific episodes, as in our experiment. Similarly, using environmental sounds as memory cues, Ernst and colleagues (2021) have recently shown that auditory cues were associated with an over-representation of repetitive events among the memories evoked by the five senses. Jakubowski and Eerola (2022) also demonstrated that music elicited fewer memories in comparison to environmental sound cues and word cues and that these memories were rated as less unique than word-cued memories. According to the model of Conway (Conway et al., 2019; Conway & Pleydell-Pearce, 2000), music would be more potent to trigger autobiographical memories related to the conceptual self, that cover a period of life or repeated events, than episodic autobiographical memories, that involve precise and time-limited episodes of life. Second, music memory might be more tied to familiarity- than to recollection-based processes. We have previously demonstrated that a feeling of familiarity can be triggered by very short musical excerpts (*i.e.*, 500-msec), suggesting the importance of potential recognition processes in music cognition (Filipic et al.,

2010). Interestingly, the response pattern and the amount of information sufficient to trigger musical memory and reach a feeling of familiarity were similar for individuals with congenital amusia (*i.e.*, a neurodevelopmental disorder of music processing), even if amusics' increased response times suggest slower access to the information and/or difficulties in accessing the information consciously (Tillmann et al., 2014). To further test the respective importance of the familiarity and recollection process in our present experiment, it would have been interesting to identify the level of consciousness that accompanied the decision of recognition, for example by adding a remember/know question to our episodic memory paradigm, as we did previously (Saive et al., 2015). Third, music encoding might have been disturbed by the simultaneous encoding of odours and faces. When questioned about how participants' attention was caught during encoding, participants reported that they favoured odour and face over music perception (Supplementary data 1). The reasons for this priority are unknown, but we could hypothesize from an evolutionary perspective that faces and odours are stimuli that have to be considered in priority by humans because informing about a potential threat, while music is safe. It is also possible that the music used in our present study was not rewarding enough to be strongly encoded into episodic memory. Ferreri and collaborators have indeed shown that episodic memory performance, through a release of dopamine, was predicted by music-induced reward (Ferreri et al., 2021; Ferreri & Rodriguez-Fornells, 2017).

To investigate episodic memory processes in our experiment, we also considered this process as a whole, that is from the presentation of the memory cue to the selection of the box where it was encountered some days ago during encoding in the virtual environment. This process is the closest to real-life autobiographical memory retrieval, and it also allows comparing our results to those of previous studies. We showed that odour, music and faces

were all able to evoke episodic memory; with faces (44 %) being more efficient than odours (19 %) and music (14 %). This was observed even if faces were modified to be less distinctive and totally unknown to the participants. Our results are comparable to the findings showing that unknown faces are able to evoke - more likely than voices - the retrieval of both episodic and semantic information about an individual, even when faces are blurred in order to limit recognition (for an overview, see Brédart and Barsics, 2012). The superiority of face cues over odour and music cues was also observed for the subjective recollection question, revealing that participants had stronger feelings of recollection when cued by faces than by odours and music. Face superiority in evoking episodic memory was obvious in the current experiment, all data pointing to this conclusion. While the higher efficiency of odours than of music in evoking episodic memory was observed when considering the associative part of the episodic memory only, it was not shown when considering the performance for the whole episodic memory process. However, both response times to select the accurate box and to answer about the subjective feeling of recollection suggest a superiority of odours and faces over music. While the response times were shorter for correct episodic memory responses than for incorrect episodic memory responses when the memories were triggered by odours and faces, no difference was observed for music. Similarly, while *Yes* responses were faster than *No* responses for the subjective recollection evoked by odours and faces, there was no difference for subjective recollection evoked by music. Congruently, when participants were questioned about the ease at retrieval, they reported that the easiest cue to retrieve the episodes were faces, then odours and lastly music (Supplementary data 1). In conclusion, odours were better episodic memory cues than music in terms of memory richness and in ease of evoking episodic memories, but they were less efficient than faces. Our hypothesis was thus only partially confirmed.

4.3 Breathing was modulated by memory processes

In human olfaction research, respiration has always been a matter of interest as odour stimuli are transported by the air to the olfactory mucosa at the top of the nostrils based on respiratory behaviour. Olfactory stimulations influence breathing patterns. Unpleasant odours induce rapid and superficial breathing, while pleasant ones induce slow and deep breathing (Bensafi et al., 2002; Masaoka et al., 2005). Breathing parameters are therefore frequently recorded in olfactory perception and cognition studies (Arshamian et al., 2018; Masaoka et al., 2012; Plailly et al., 2008; Royet et al., 2011; Saive et al., 2015; Saive, Royet, Ravel, et al., 2014). In the investigation of cognitive processes in other sensory modalities, breathing was traditionally almost never recorded. Recently, this interest emerged (Criscuolo et al., 2022) and an increasing number of studies reported interactions between cognitive processes and respiration patterns (Huijbers et al., 2014; Iwabe et al., 2014; Zelano et al., 2016). For instance, Zelano et al (2016) demonstrated that recognition memory accuracy was enhanced for pictures presented during inspiration rather than during expiration phases at retrieval.

In our present study, results showed a relationship between breathing patterns and recognition memory responses. Accurate recognition of both music and faces, but not of odours, was related to an enhanced amplitude of inspiration, in comparison to accurate rejection of distractor cues. This was surprising for two reasons. First, here, a modulation of respiration was observed in the sensory modalities not conveyed by breathing, while it was absent in olfaction. Conversely, in a previous experiment, by investigating selective attention to the olfactory or auditory environment while keeping constant the environment in terms of odours and tones, we demonstrate that attention to odour, but not attention to tone, modulates respiratory parameters (Plailly et al., 2008). Until now, based on our current knowledge, the modulation of breathing patterns with the recognition memory process has only been

observed with odours (Royet et al., 2011; Saive, Royet, Ravel, et al., 2014). In order to learn more about this absence of breathing modulation with odour recognition, we performed supplementary analyses restricted to this sensory modality and encompassing the inaccurate responses. With these conditions, results coherently showed that the participants breathed faster when they accurately recognize target odours than when they inaccurately rejected them (Supplementary data 5). Second, in the current experiment, we observed that the amplitude of inspirations was higher when target music and faces were recognized than when distractor music and faces were rejected. Conversely, when observed in previous odour recognition studies, the duration of the breathing cycles is shorter and their frequency higher when odours are recognized (Hit and FA) than when they are rejected (Saive, Royet, Ravel, et al., 2014), and the inspiratory volume is lower for recognition than for rejection (Royet et al., 2011). These modulations of respiration are supposed to reflect the serial matching process between the memory cue and the memory traces (Bamber, 1969), where the participants keep searching until a match is found, and therefore keep inspiring to keep the odour in their nose, which is faster for a recognition than for a rejection. The current experiment allowed us to widen the results previously obtained in olfaction to other sensory modalities, such as audition and vision here, and to highlight the importance of investigating breathing patterns modulations with cognitive processes in order to enrich this promising field of research. However, an alternative explanation for these modulations of breathing in non-olfactory conditions would be that music and face recognition triggered the retrieval of the odour that was simultaneously presented with them, in the same box, at encoding. It is therefore important to stay cautious about the interpretation of these results, which calls for further investigation.

In our experiment, we did not demonstrate any relationship between breathing patterns

and the episodic memory process, during both recognition and episodic periods. However, in a previous experiment, we showed that odour-evoked episodic memory is accompanied by slower and deeper breathing (Saive, Royet, Ravel, et al., 2014). Similarly, retrieval of a positive autobiographical memory triggered by a personal pleasant odour is associated with slower and deeper breathing compared to the perception of control odours evoking no memory (Masaoka et al., 2012; Watanabe et al., 2018). As, in our paradigm, the participants had to move through the virtual house in order to click on the box in which the cue was encountered at encoding, we could speculate that this active behaviour might have mechanically and/or cognitively disturbed the body response to episodic memory retrieval.

4.4 Validity of our ecological laboratory experimental approach

Our protocol used a virtual reality software presenting a house where boxes delivered sensory stimulations. This software was designed to investigate episodic memory in a laboratory setting with ecological validity, enabling a non-explicit, and incidental encoding during an immersion in a moment of life, in a context with rich multisensory details. The protocol extended our previous works that used only odour cues (Plailly et al., 2019; Saive et al., 2013, 2015; Saive, Royet, Ravel, et al., 2014) to the controlled investigation of episodic memory evoked by cues from three sensory modalities: odours for olfaction, musical pieces for audition and face pictures for vision. In addition to the benefits of this controlled and cognitively plausible laboratory-ecological approach, our experiment had the following advantages. (1) Virtual reality allowed for the experimental conditions to be closer to real life than in impoverished experimental contexts (La Corte et al., 2019; Schöne et al., 2017; Smith, 2019). The encoding of the visuo-spatial context of the episodes might have been facilitated by the motor involvement and active exploration, as it is shown to favour visuo-spatial memory (Plancher et al., 2013). (2) The investigation of complex episodic memory retrieval

from a recognition decision, additionally to the use of mixed models, made it possible to address both cognitive processes simultaneously and allowed for the two to be compared. (3) Our protocol enabled the investigation of memory processes with complementary angles of view. In addition to memory performance, the potential modulation of responses times and the modulation of physiological responses explored through breathing provided further insight into the characterization of memory subprocesses, and the subjective feeling of recollecting the episode informed about the phenomenology of episodic memory.

However, our protocol presents some limitations. First, as discussed above, our choice to present odour, music and face stimuli together at encoding, may have induced attention bias. As the sensory stimulations were simultaneous, the participants' attention might have been captured by one stimulus, limiting the attentional resources devoted to the other stimuli. These simultaneous stimulations at encoding might also have induced a binding bias, where a combination of two sensory modalities in the box (*e.g.*, face and odour) would have been more strongly associated than other combinations (*e.g.*, face and music). It was therefore impossible to disentangle whether an episode was evoked directly by the memory cue itself or whether it was evoked indirectly by the recall of a cue that was associated with it at encoding. Second, the spatial dimension of the episodes (Where; *i.e.*, the location of the box) was dependent on the contextual dimension of the episode (Which context; *i.e.*, the room), as the participants must enter the correct room in order to select the correct box. Future version of the virtual reality environment and the protocol should enable the two dimensions to be independent of one another, aiming to investigate whether the order of dimensions retrieval has an influence on memory performance or not, and whether this might be modality-dependent or modality-independent.

4.5 Conclusion

Our study demonstrated in a controlled, but ecologically relevant task the differential influence of the cue's sensory modality on recognition and episodic retrieval. Odours, music, and faces were associated with different patterns of memory. Odours were well recognized and were able to evoke episodic memories, music was very well recognized but showed limited ability to be associated with episodic dimensions, and faces were the most potent cues as they were both strongly recognized and evoked efficiently all episodic memory dimensions. Overall, while odours were less recognized than the pictures of the faces or musical pieces, they demonstrated a high ability for episodic retrieval, mimicking odour-evoked autobiographical memory specificities.

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6 Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7 Data availability statement

The data that support the findings of this study are openly available in the Open Science Framework (OSF) at <https://osf.io/u5s6m/>, DOI: 10.17605/OSF.IO/D436M.

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Figure 1

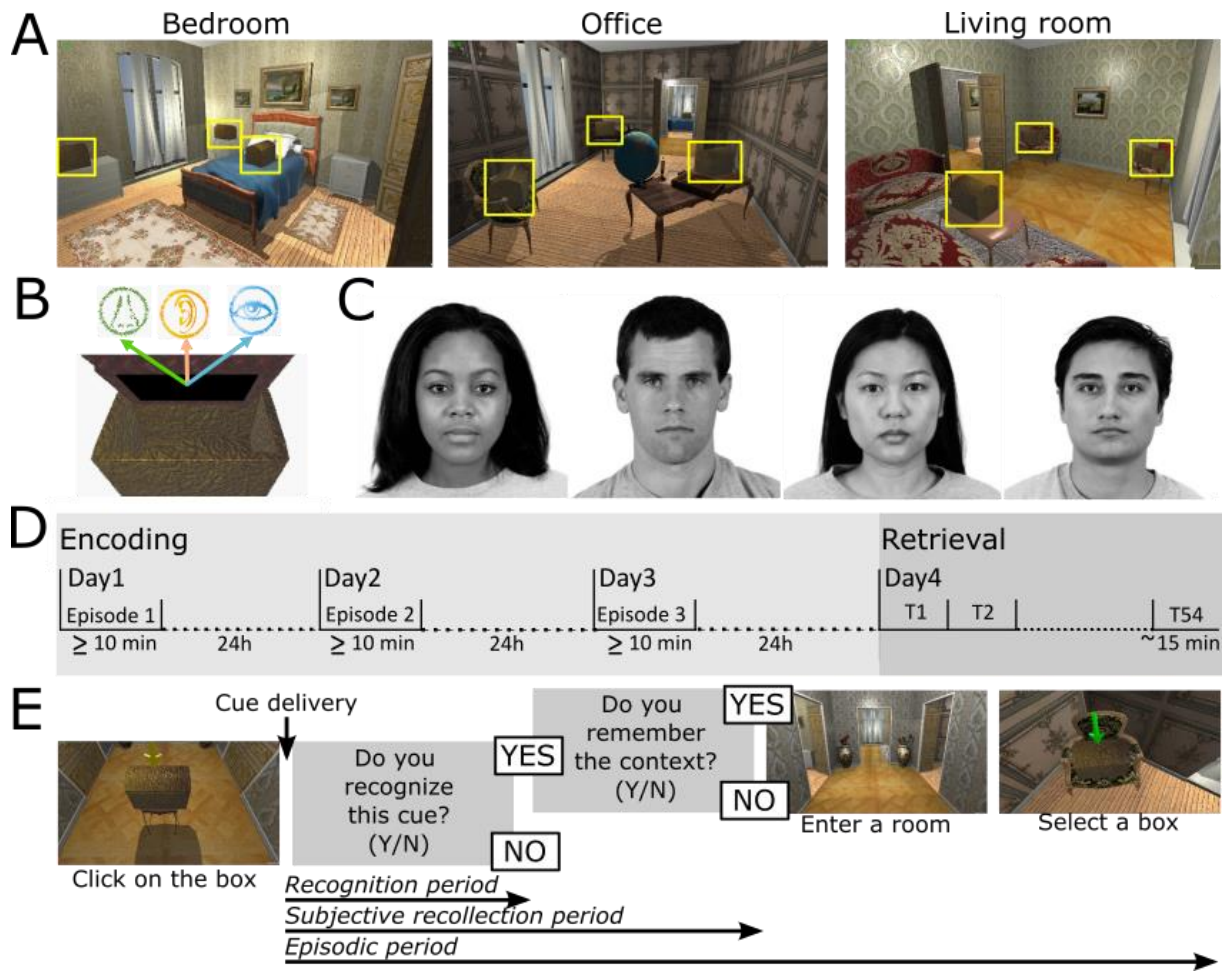


Figure 2

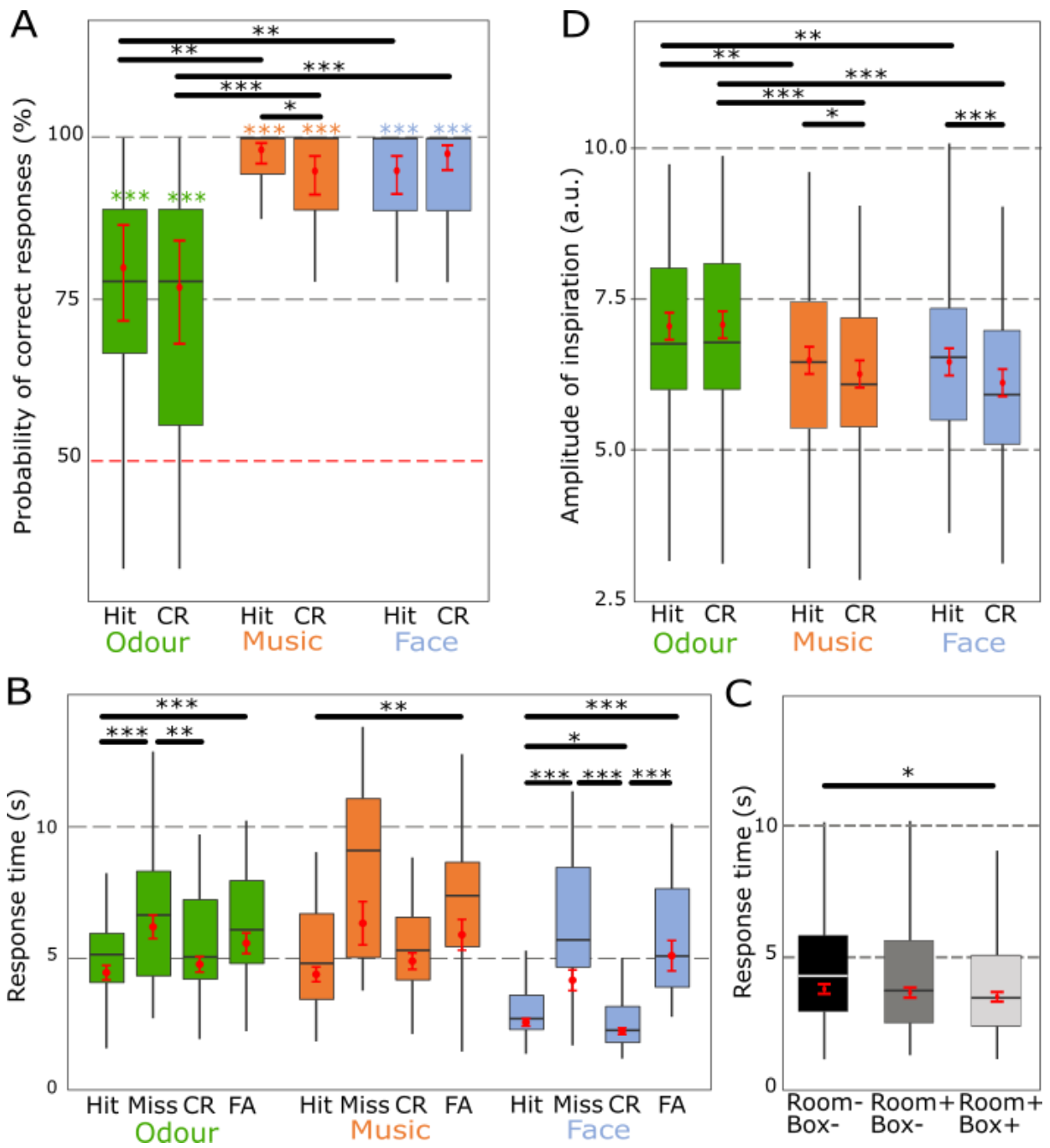


Figure 3

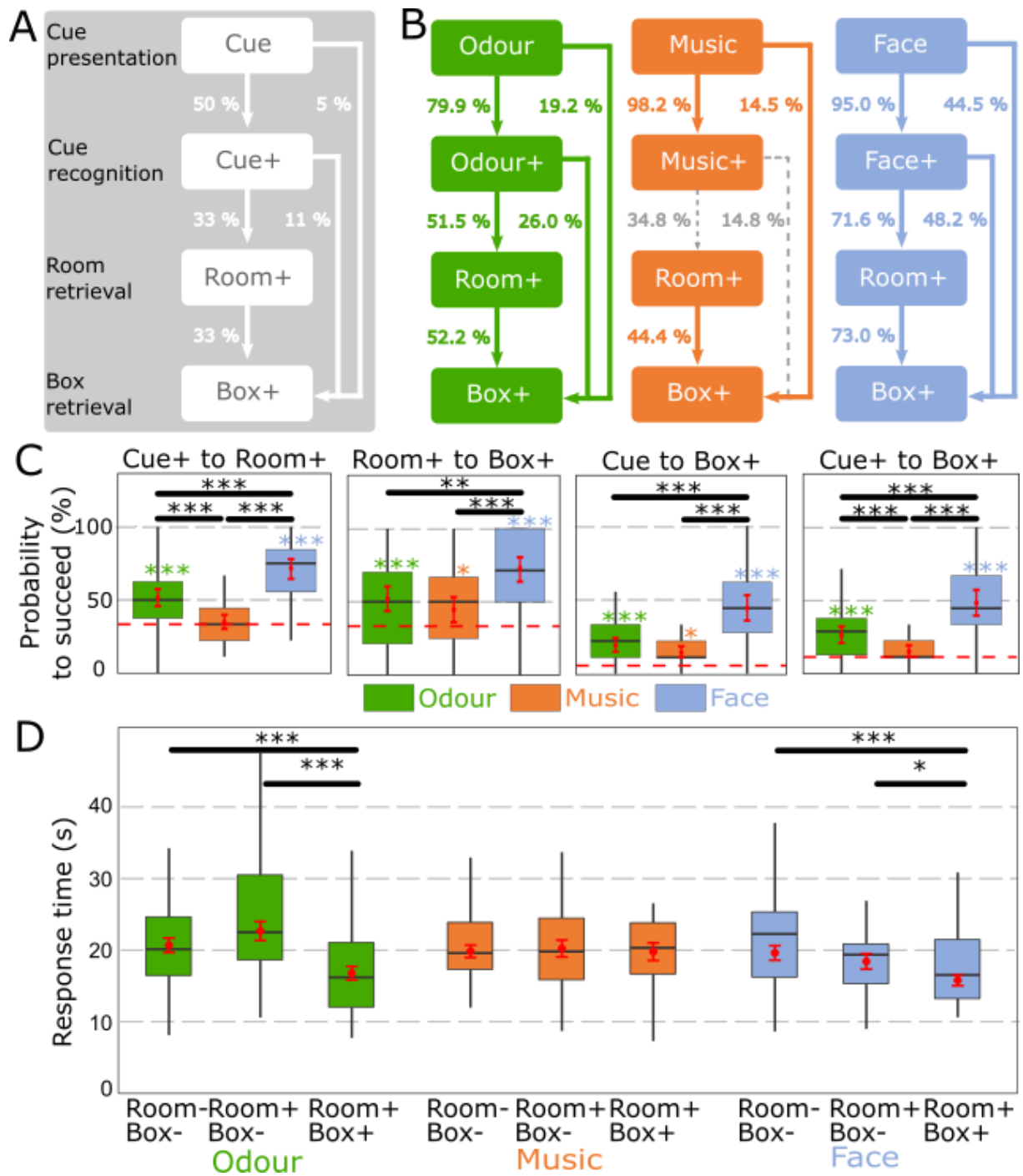


Figure 4

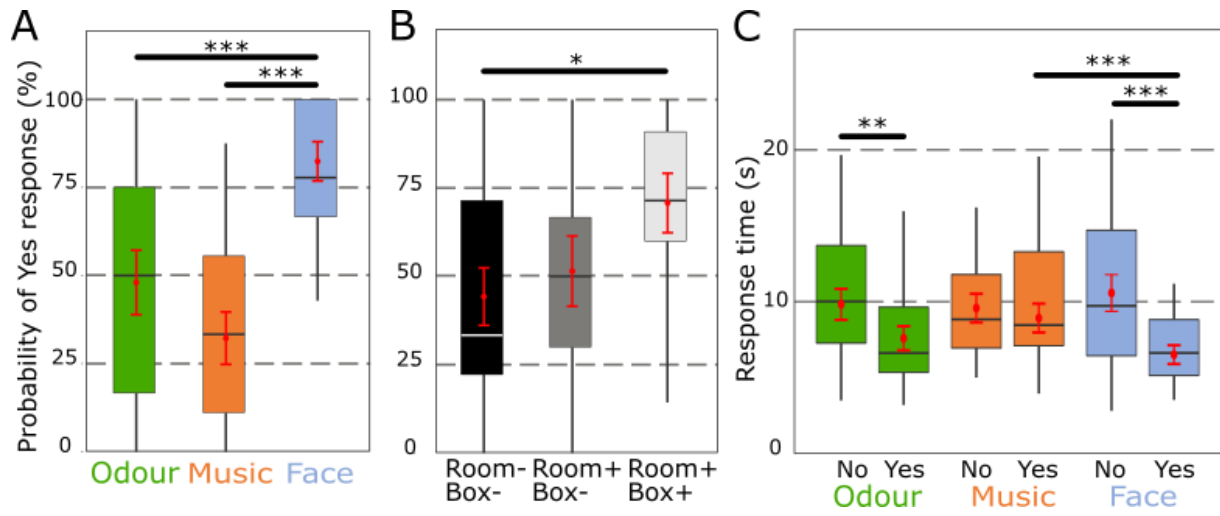


Figure captions

Figure 1. Experimental protocol. A, The three rooms of the virtual house. Yellow rectangles indicate the boxes in which the stimuli were presented (for demonstration here only). B, Details of an open box, delivering an odour, a piece of music, and a face. C, Examples of pictures of faces. D, The time course of the encoding and the retrieval sessions. During the encoding, participants discovered one episode per day over three days. On the fourth day, the memory of the episodes was tested across 54 trials (T1 to T54). E, Example of a retrieval trial. Participants click on the box allowed a stimulus, either an odour, a piece of music or a face, to be presented. Participants first had to decide whether they recognized the cue or not. In case of a ‘Yes’ response, for V2 only, they had to answer about their subjective recollection and then entered a room and selected a box. In V1, in case of a ‘Yes’ response, participants had to directly enter a room and select a box.

Figure 2. Cue recognition. A, Probability of correct responses (in %) as a function of Sensory Modality and Recognition Response Category. B, Response times (in s) from cue presentation to recognition response as a function of Sensory Modality and Recognition Response Category (for clarity purposes, only within-sensory modality comparisons were reported), and C, as a function of Subsequent Episodic Response for Hit responses only. D, Amplitude of inspiration (in arbitrary units (a.u.)) during the recognition period. The distribution of data is displayed with boxplots (minimum, first quartile, median, third quartile, maximum) in black. The model estimated means and their dispersion (SEM) are represented in red. $*p < .05$, $**p < .01$, $***p < .001$. When coloured, stars represent significant differences from chance level.

Figure 3. Episodic memory. A, Experimental conditions with the chance-level value of probability to go from one step to another. B, Sensory modality-specific probabilities to go

from one step to another (in %). Solid lines represent significant probability; dashed lines represent non-significant probability. C, Probability to succeed as a function of Sensory Modality for all episodic steps. Red dashed lines represent chance-level. D, Response times (in s) from the presentation of the cue to the click on a box as a function of Sensory Modality and Episodic Response Category (for clarity purposes, only within-sensory modality comparisons were reported). The distribution of data is displayed with boxplots (minimum, first quartile, median, third quartile, maximum) in black. The model estimated means and their dispersion (SEM) are represented in red. $*p < .05$, $**p < .01$, $***p < .001$. When coloured, stars represent significant differences with chance level.

Figure 4. Subjective recollection. Probability to give a “Yes” response (in %) as a function of A, Sensory Modality of the cue, and B, Subsequent Episodic Response. C, Response times from the presentation of the cue to the subjective recollection response, as a function of the Sensory Modality of the cue and the Yes/No subjective recollection response. The distribution of data is displayed with boxplots (minimum, first quartile, median, third quartile, maximum) in black. The model estimated means and their dispersion (SEM) are represented in red. $*p < .05$; $**p < .01$; $***p < .001$.