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ABSTRACT

Although it is now well-known that self-reference processing benefits the episodic memory of laboratory material, studies have rarely investigated its influence on memory for specific episodes in a naturalistic context. We immersed 64 healthy young participants who were personally either very familiar or very unfamiliar with the Latin Quarter of Paris in a virtual environment resembling it. They all navigated using a joystick and memorized as many specific events as possible encountered in this environment, together with their perceptual details and spatial and temporal context. However, one group was assigned to a self-perspective condition (i.e., centered on their own interaction with the environment) and another to a condition requiring the mental simulation of an other-perspective (i.e., centered on the interaction of an avatar with the environment) during the period of navigation and the subsequent memory retrieval tasks. The main results showed that both high personal familiarity and a self-perspective (compared to low personal familiarity and an other-perspective) improved the recall and recognition of specific events and their spatiotemporal contexts and sense of remembering. Specifically, high personal familiarity was the most efficient condition for improving the memory of allocentric spatial context while, conversely, self-perspective was the most efficient for enhancing temporal context memory. An additive effect of self-perspective and high familiarity was observed regarding the memory of perceptual details and egocentric spatial context. These findings highlight the benefit of self-reference in episodic memory for specific events. They might help pave the way for the development of new perspectives for cognitive remediation of episodic memory encoding in daily life.

Keywords: episodic memory, self-reference effect, self-perspective, self-consciousness, personal familiarity, virtual reality

1. INTRODUCTION

One of the questions about episodic memory capacity in real life, for example during a walk in a city, is how detailed events are captured as a function of the self and retained in long-term memory and in what ways they are based on prior personal knowledge of the environment.

Episodic memory has been a focus of interest for many researchers studying the relation between the self and memory (James, 1890; Prebble, Addis & Tippett, 2012). This memory system records events experienced by the self that occurred at a particular time and place and which are consciously recollected through subjective mental time travel and autonoetic consciousness (Tulving, 1985, 2002). A vivid episodic memory involves the subject ("the traveler"), his or her subjectivity and the highly objective attempt to recollect all the details of the lived situation. The quality of memory encoding is modulated by the nature of the encoded events as well as by affective and cognitive states and body-centered physical experiences that define self-experience in the real world (Rugg, Otten, Henson, 2002; Makowski et al., 2017; Blanke et al., 2018). First-person experience is critical in determining the idiosyncratic nature of the self and defines the egocentric spatial frame of reference that is fundamental for episodic memory (Hommel, 2004; Bergouignan, Nyberg & Ehrsson, 2014). At the same time, the quality of episodic memory retrieval depends on the conscious recollection of these events situated in their spatio-temporal context - what happened as well as where and when it happened - and with intimate reference to oneself in the episode, i.e. "this happened to me". The essence of episodic memory thus lies in the specificity of the to-be-remembered information and in the fact that it binds together the diverse pieces of an episode via the hippocampal network (Kessels, Hobbel, & Postma, 2007), as well as in self-referential encoding and autonoetic consciousness at retrieval. The latter is defined as mental time travel which permits the reliving of a subjective first-person perspective that arises from the original encoding context (Suddendorf & Corballis, 1997; Wheeler et al., 1997). Thus, the sense of self is at the core of episodic memory at all stages of the memory process (from encoding to retrieval), allowing the individual to build a sense of temporal continuity and personal identity.

Many experimental studies have been designed to explore the role of the self in memory encoding. For 40 years, the best-known paradigm for studying this relationship has consisted in the manipulation of self-reference in a laboratory context. Self-reference processing consists in implicitly or explicitly linking the information to be remembered to the self, i.e. either to the narrative self (pre-stored personalized knowledge, autobiographical memories) or to the minimal self (the 'I' who is experiencing 'nowhere') (Gallagher, 2000). The self-reference effect refers to a tendency for individuals to encode information more effectively when this information is related in some way to themselves.

Most studies in the field of episodic memory have investigated the self-reference effect based on the narrative self. They have shown that processing new information that relates closely to oneself is the most effective strategy for stimulating the memorization of new material, such as lists of personality traits, and permits better encoding, structuring and retrieval (Symon & Johnson 1997 and Klein, 2012, for reviews). In the standard self-reference paradigm, subjects have to decide if a personality trait adjective describes them, as in Rogers et al.'s (Rogers, Kuiper, & Kirker, 1977) pioneering study, or are required to retrieve an autobiographical memory related to it (Klein & Loftus, 1988). Several studies have reported a spontaneous self-reference effect for items presented in the context of an individual's own face or name or date of birth compared with items seen in the context of another person, even in the absence of any explicit instruction to process information in a self-referential way (Turk, Cunningham, & Macrae, 2008; Rathbone & Moulin, 2010; Kesibir & Oishi, 2010). The conclusion drawn from such behavioural studies is that self-reference (compared to semantic processing or reference to other people), whether incidental or intentional, improves both factual and contextual remembering and the sense of remembering (Conway & Dewhurst, 1995; Lalanne et al., 2013; Leshikar & Duarte, 2012; Leshikar, Dulas, & Duarte, 2014; Serbun, Shih, & Gutchess, 2011). Thus, narrative self-reference during encoding seems to improve the objective as well as the subjective characteristics of episodic memory due its frequent use in information processing (Markus, 1977; Rogers et al., 1977). This efficiency has been ascribed to the fact that it depends on the intrinsic nature of the self, which operates as a hub (Sui & Humphreys, 2015) through dual elaboration-organization encoding processes and the organization of memory retrieval (Klein & Loftus, 1988). Neuroimaging research has shown that the self-reference effect is linked to cortical midline structures (Northoff et al., 2006). In this network, the medial prefrontal cortex appears to lie at the heart of self-referential processing (Fossatti et al., 2003; D'Argembeau et al., 2007; Martinelli et al., 2013; Kalenzaga et al., 2015; Sui & Gu, 2017).

Several other studies have focused on the role of self-perspective when experiencing or remembering an event. The first-person perspective is a fundamental feature of a minimal self as an embodied process that drives the pre-reflective feeling of being a subject of experience, differentiated from the environment (Vogeley & Finks, 2003; Blanke & Metzinger, 2009). Thus, the first-person perspective both at encoding and remembering is a prerequisite for rich episodic memory (Prebble et al., 2012). Since the seminal work of Nigro and Neisser (1983), a large body of studies has investigated self-perspective-taking in autobiographical memory retrieval. They have found evidence suggesting that the richness of episodic details and sense of remembering are enhanced when retrieval is associated with a first-person perspective rather than with a third-person memory perspective, i.e., when the participants keep the same viewpoint as in the encoded event (field memory) instead of adopting the viewpoint of an external observer (observer memory), (Robinson & Swanson, 1993; Crawley & French, 2005; Piolino et al., 2006; St Jacques et al., 2017). Some researchers have proposed that taking a third-person memory perspective acts as an effective mechanism for distancing one's current self from the remembered self (Libby & Eibach, 2002; Sutin & Robins, 2008). Accordingly, observer memories are associated with decreased activity in key regions involved in episodic memory processes and bodily self-consciousness, such as the hippocampus and the insular and motor cortices (e.g., Piolino et al., 2009 and Eich et al., 2009, respectively). More recently, studies tested the role of perspective-taking at encoding in the episodic memory of real-life scenes by means of virtual reality (the participants visualized the scene on a headset either from their own perspective or from an out-of-body perspective). The results suggested that a third-person perspective at encoding results in poorer episodic memory retrieval (Bergouignan et al., 2014; Iriye & St-Jacques, 2021).

Similarly, the mental adoption of another person's perspective instead of a self-perspective can affect episodic memory. To put oneself mentally in another person's shoes, it is necessary to transpose one's own egocentric experiential space onto another body, situated at different spatial coordinates, and model that person's mental state (Vogueley & Fink, 2003). Buckner and Carroll (2007) used the term self-projection to describe this capacity to shift our self-perspective from the present moment to alternative mental locations. This process has been studied in different contexts, such as personality trait judgement (Oschner et al. 2005; D'Argembeau et al., 2007) or theory of mind (Ruby & Decety, 2003). Different parts of the medial prefrontal cortex are engaged in self-referential processing (judgment about oneself) according to the self-perspective taken (adopting one's own or another person's perspective) (D'Argembeau et al., 2007). In the same way, they are concerned differently when participants are asked to re-experience their self-perspective or understand another person's perspective based on photos of their own or another individual's life taken with a wearable camera (St. Jacques et al., 2011).

A large body of data demonstrates that the engagement of the self at encoding has a positive effect on episodic memory. However, most research on episodic memory for new information, including studies on the self-referential effect, has generally investigated episodic memory of factual items using simplistic, non-ecological material such as words or images. The lack of ecological validity in the domain of memory psychology has been an issue ever since the seminal debate initiated by Neisser (Neisser & Winograd, 1988). Interestingly, some more ecological research has demonstrated the benefit of perceiving new items in personally familiar places (e.g., own university, own apartment, own city) on memory of these items (objects, names of street) (Kalakoski & Saariluoma, 2001; Donix et al., 2010). Unlike perceptually based familiarity (Thorndyke & Hayes-Roth, 1982), personal familiarity is also knowledge-based and comprises supplementary contextual information related to the self, namely personal habits, preferences, goals and autobiographical memories (Cloutier et al., 2011). The personal familiarity paradigm provides a way of investigating self-referential effects on real-life episodic memory.

In the present study, we examined the role of self-reference on the episodic memory of specific events in a naturalistic environment using virtual reality (VR) technology. VR is being increasingly used in neuroscience and psychology research to investigate cognitive processes in naturalistic environments and scenarios, while controlling experimental variables that are usually difficult to control in real life (Loomis, Blascovich, & Beall, 1999; Parsons, 2015; Shamay-Tsoory, & Mendelsohn, 2019). VR allows individuals to immerse themselves in and interact with "near-realistic" computer-generated three-dimensional environments in real-time and is capable of delivering a multisensory experience (Fuchs, 2017). The use of VR has been of great benefit to research on navigation skills and spatial memory (Landgraf et al., 2010; Cogné et al., 2016; Montana et al., 2019), and more recently to the study of episodic memory in naturalistic situations (Plancher & Piolino, 2017; La Corte et al., 2019; Smith, 2019; Tuena et al., 2019, for reviews). Interestingly, ever since the pioneering study by Burgess, Maguire and O'Keefe (2001), a number of VR tasks have been developed to allow a thorough evaluation of intentional or incidental episodic memories of experienced events (e.g., seeing a car accident; attending a hip-hop dancers' street show; receiving a book from a person) encountered during a real-life activity such as walking in a city. This VR paradigm provides a way of investigating episodic event memory in a naturalistic context while taking account of feature (What-Where-When) binding skills and recollection under rigorous experimental control (e.g., Abichou et al., 2019; Jebara et al., 2014; Plancher et al., 2010).

We created a VR simulation that made it possible to locate participants in a realistic urban environment (the Latin Quarter of Paris) and control all the static elements and events presented during a navigation task. The participants had to memorize as many specific events as they could from their navigation and were either personally unfamiliar or very familiar with the environment. They completed the navigation task from two different mental perspectives during the interaction with the environment, i.e. self vs. other (i.e., centered on their own self-perspective versus centered on the perspective of an avatar). Thus, we investigated episodic memory from four navigational conditions: 1) self-perspective and high-familiarity, 2) self-perspective and low-familiarity, 3) other-perspective and high-familiarity, and 4) other-perspective and low-familiarity. Furthermore, we sought to identify the retrieval performance for the different components of event memories, namely objective factual content and spatiotemporal context and subjective sense of remembering. Based on the literature on the self-reference effect and self-perspective, we expected that encoding in a personally familiar environment or adopting a self-perspective would contribute to the richness of episodic memory. Finally, we expected to observe additive effects of both high-familiarity and self-perspective conditions on episodic memory.

2. MATERIAL & METHODS

2.1. Participants

Sixty-four healthy volunteers (16 males and 48 females, aged from 20 to 34 years old, mean age 23.28 years ± 2.73) participated in the study. They were recruited from public announcements and a social network for the cognitive sciences. We based our sample size on a previous study assessing episodic memory of specific events in a virtual urban environment (Jebara et al., 2014). All the participants had normal or corrected-to-normal vision. They provided written informed consent and received financial compensation for their participation. The ethics committee of the National Center for Scientific Research approved the experimental protocol.

The volunteers were initially divided into two groups of 32 participants each depending on their personal familiarity with the Latin Quarter of Paris based on a questionnaire. This was based on previous studies which used criteria that made it possible to distinguish between individuals who were familiar or unfamiliar with a large-scale environment on the basis of objective pre-learned tests (place recognition and naming, Gale et al., 1990) and self-assessment (Prestopnik & Roskos-Ewoldsen, 2000).

Each participant had to specify 1) if he/she lived or worked in this Quarter, and how long they had lived/worked there (1: not at all to 5: a very long time); 2) their degree of familiarity with this Quarter (1: not at all familiar to 5: very familiar), 3) if he/she liked this Quarter (1: not at all to 5: very much) and 4) how many autobiographical memories he/she had linked to this Quarter (1: none to 5: very many). The participants then had to name 20 famous places in the Latin Quarter from photos (e.g., Café des Arts, Odéon Theater, Panthéon Square, Cluny Museum, Collège de France).

Based on this questionnaire, we used the median to build the two groups. Thus, the participants were divided into "high-familiarity" and "low-familiarity" groups. Finally, the participants in the two groups were randomly assigned to one experimental condition (self-perspective or other-perspective encoding, see the Procedure section below). The description of the population as a function of personal familiarity and self-perspective condition is presented in **Table 1**.

Table 1. Description of the population (means and standard deviations) as a function of experimental conditions and statistics (F, p value, η^2) depending on Familiarity and Self-perspective conditions.

	Experimental Conditions				**ANOVA**		
	High Familiarity		**Low Familiarity**		**Familiarity**	**Self-perspective**	**Interaction**
	Self	**Other**	**Self**	**Other**	F(1,60)	F(1,60)	F(1,60)
Participants N	(4M; 12F)	(4M; 12F)	(4M; 12F)	(4M; 12F)			
Age	23.94 (2.74) [2.02, 4.24]	23.56 (1.86) [1.37, 2.88]	22.25 (2.57) [1.90, 3.98]	23.37 (3.48) [2.57, 5.38]	1.89 η2=.03	0.30 η2=.00	1.21 η2=.02
Years of educations#	4.25 (.85) [0.63, 1.32]	4.25 (.69) [0.50, 1.06]	3.68 (.94) [0.70, 1.46]	4.31 (.87) [0.64, 1.35]	1.99 η2=.02	2.87 η2=.04	2.87 η2=.03
Familiarity Questionnaire (%)	65.31 (8.05) [5.95, 12.46]	66.56 (3.52) [2.60, 5.45]	35.00 (7.52) [5.56, 11.65]	30.31 (6.70) [4.95, 10.37]	**396.35*** η2=.87**	1.06 η2=.01	3.15 η2=.05

the number of years after the baccalaureate
( ) Standard Deviation ; [,] CI of SD 95%; *** p<.001

2.2. Experimental VR episodic memory assessment (VR-EM test)

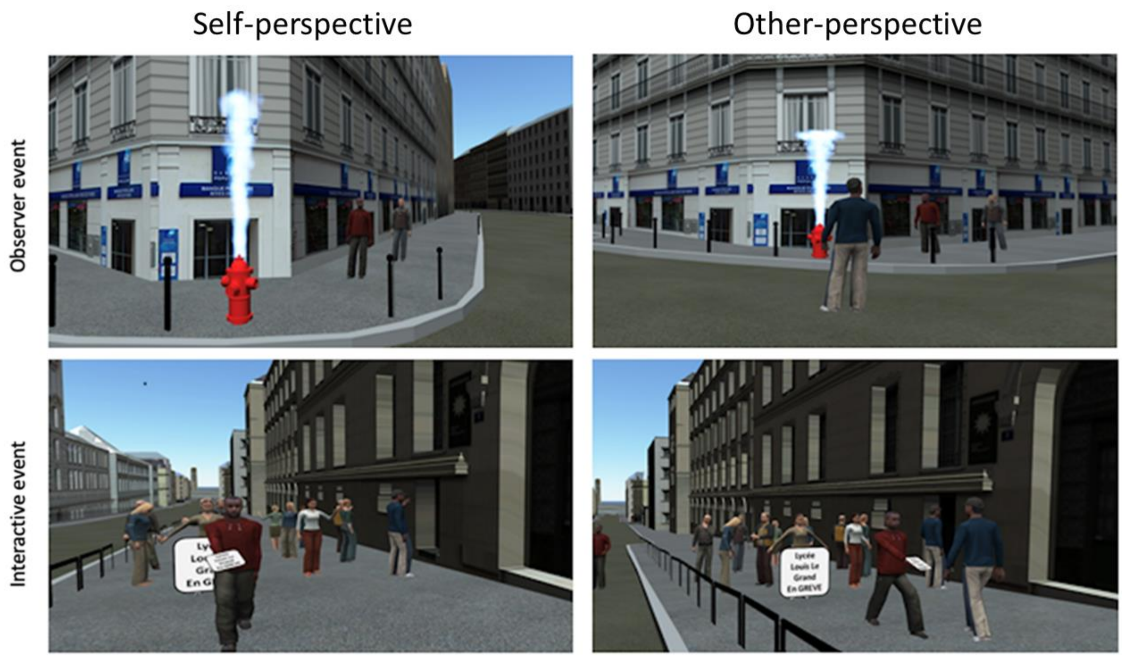
2.2.1. Material

A virtual town that realistically represented the Latin Quarter of Paris (see **Figure 1**) was built with 3DVIA Studio Pro in cooperation with professional designers. The environment was enriched with background sounds of the natural environment, such as noises of cars, voices, and 20 specific events observed during the navigation (e.g., seeing a car crash, street musicians, a group of joggers), or interactions with human avatars (e.g., a person holding out a teddy bear or an ice-cream or a placard).

The virtual town was projected via a PC (DELL PRECISION M6300) onto a large SONY screen (Resolution 1932*1080) covering 66 degrees of the visual field. All participants could move forward in the town by means of a joystick which controlled their speed of movement. However, the route was pre-determined and was the same for each participant.

In both the self- and the other- perspective condition, the camera field of view was similar, thus the participants had the same amount of information on the screen. The only thing that changed across the two perspectives was the initial position of the camera in the virtual environment: it was placed at the level of the avatar's eyes in the first-person mode and slightly raised and set back for the third person view.

Figure 1. Examples of a screenshot in the Self-perspective and in the Other-perspective for interactive and observer events.



2.2.2. Procedure

Participants were tested individually in a dark room. They were seated in front of the screen showing the virtual town. They had to navigate in the environment as a pedestrian. Before the test session, the participants underwent a training session to familiarize them with the equipment and the virtual paradigm but using a different environment from that used for the test. They were then informed that they would be immersed in a virtual environment representing the part of Paris situated around the *Collège de France*. All participants were asked to explore the environment by navigating along the route and paying attention to all the specific events together with their perceptual details and spatial and temporal ("where and when") contexts (intentional encoding). However, there was no explicit instruction to perform encoding in a self-referential way to allow us to identify any spontaneous self-reference effect for items presented in a self-relevant context.

Depending on the encoding condition, the interactions with the avatars in the virtual environment concerned the participants themselves or another virtual person. In the self-perspective condition, participants directly experienced events and interactions with avatars in the environment. They were told to pay attention to their interactions with the environment and their conscious self-awareness in the present moment. In the other-perspective condition, they followed an independent virtual human (an avatar) who walked through the virtual environment and experienced events and interactions with other avatars. In this condition, the participants had to decenter from themselves and mentally adopt the avatar's perspective instead of their own self-perspective ("put yourself mentally in the avatar's shoes").

2.2.3. VR episodic memory assessment (VR-EM test)

After participants had explored the virtual town, a delay of a few minutes (about 10 minutes) was proposed as a distractor period during which we administered a Trail Making Test (Reitan, 1979) and gave the explanations of the retrieval phase. Then, all participants underwent a series of memory tests previously validated by our team in other virtual reality episodic memory studies (Jebara et al., 2014; Picard et al., 2017; Plancher et al., 2010, 2012; Abichou et al., 2019, 2021).

Free recall test

First, participants had to verbally report all the different scenes/events, mentioning as many perceptual details as possible together with the associated "where and when" information for a maximum of 15 minutes. We chose this duration because it corresponded to the mean time spent in the town by participants. The participants in the self-perspective condition had to adopt their self-perspective to give their responses, unlike the participants in the other-perspective condition, who had to adopt the avatar's perspective except when judging their sense of remembering.

More precisely, to test the memory of the *content* information ("what"), participants had to remember the scenes/events (e.g., a car crash) that they/the avatar encountered during their/his exploration and to give the most salient *perceptual details* ("details") accompanying these events (one of the cars was gray). Regarding the *spatial context*, they had to indicate i) the place near which the event had occurred ("spatial location"), ii) if they/the avatar had turned to the left or the right after seeing it ("egocentric spatial reference") and iii) had to imagine themselves (or the independent avatar) flying over the town and try to give information about the spatial layout of the different elements ("allocentric spatial reference") that they remembered (e.g., the event was situated "Au vieux Campeur" store which was in front of the "Collège de France"). Regarding the *temporal context*, the participants had i) to situate each event roughly at the beginning, the middle, or the end of the circuit, and then ii) specify the events immediately preceding and following the target event, and iii) report the temporal order of the events in order to test recollection of the sequential order in which they/the avatar had encountered them.

Assessment of the Sense of Remembering

We used a supplementary subjective assessment based on the Remember/Know procedure that Tulving (1985) proposed to measure the state of consciousness involved during retrieval. A Remember response means that the persons consider that they recollect the subjective experience from the encoding context while a Know response means that retrieval is not accompanied by any recollection. A Remember response is an index of episodic memory retrieval via autonoetic consciousness (i.e., the capacity to mentally place oneself in past situations). To substantiate the Remember responses, participants can be asked for additional reports of phenomenological details from the encoding context (Piolino et al., 2006, 2009). Thus, at the end of the free recall phase, the participants' sense of remembering, i.e. *capacity to mentally relive the encoding phase*, was measured by asking them to what extent they were able to re-experience their virtual walk in the Latin Quarter, according to a similar procedure used by our group (Jebara et al., 2014). They responded on a scale from 0 to 5, corresponding to no re-experiencing (i.e., just knowing) and to very high re-experiencing, respectively. They were then asked to report some subjective internal details (up to 5 personal thoughts and feelings) associated with a specific event in the environment (noted from 0 to 5 number of internal details).

Visuo-spatial location test

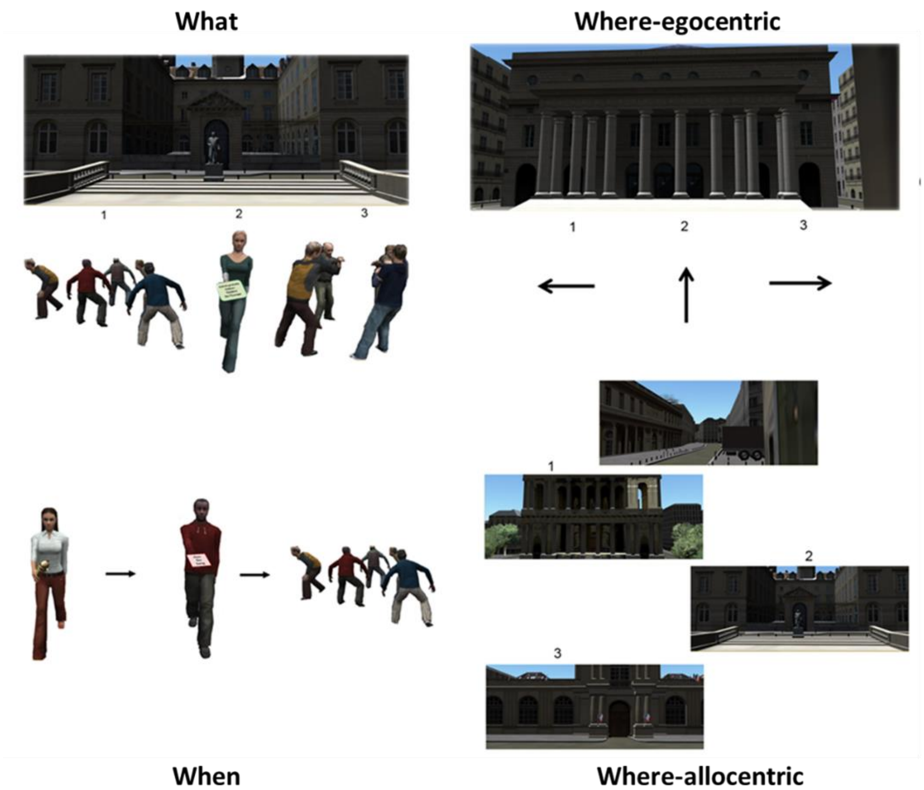
To test memory of the visuo-spatial combination of the "what", the "where" and the "when" components, participants were also asked to locate events and important places on a real map supplied by the experimenter for 10 minutes. (**Figure 2**).

Figure 2. Map of the visuo-spatial location test

Recognition test

Participants then performed a series of visual recognition tests on the different components of episodic memory. All the items displayed on the recognition tests were images taken from the virtual environment (see **Figure 3**). They were asked 20 questions for each component i.e., 20 questions, each focusing on the what component (recognition of the correct event out of three events associated with a place), the where-egocentric component (one scene was displayed and participants had to decide whether they (or the avatar) had turned to the left, to the right or gone straight on), the where-allocentric component (participants had to indicate which of three buildings was located near a target building), and the when component (three scenes were displayed, and participants had to decide whether the sequential order of the scenes was correct or not). To test spatial allocentric recognition, participants were asked to imagine that they (or the avatar) were flying over the town and locate the buildings.

Figure 3. Example of each component of the recognition task: What-Where egocentric-Where allocentric-When.



2.2.4. Scoring

Free recall test

Quantitative scoring of each event/scene resulted in a main score calculated on 20 points and expressed as a percentage (*"what"*). Each type of associated information was calculated on the basis of the number of events/scenes recalled and expressed as a percentage *("details", "where" and "when")*. One point was assigned for each correct response. For the spatial and temporal components, we recorded the mean scores on the sub-scores for each type of spatial and temporal information. We also calculated the mean percentage of associated information corresponding to the "what" recalls (*Total Binding*). Of note, the participant's ability to correctly label specific landmarks was not considered in the scores.

Sense of remembering assessment

We calculated a global score for the sense of remembering based on subjective re-experiencing and internal details (max. 10) corresponding to the addition of the intensity level of re-experiencing (max. 5) and the number of thoughts and feelings associated with specific events during navigation (max. 5). We expressed the score as a percentage of the maximum score. This subjective measure was independent of the other objective measures on correct recalls.

Visuo-Spatial test

We calculated a correct response percentage by dividing the number of correctly located items by the maximum number of elements, including the 20 events and 20 places (max. 40).

Recognition task

A total percentage was calculated by dividing the number of correct responses by the total number of questions (20) for each component.

2.2.5. Statistical analyses

We used STATISTICA 12 to conduct a series of two-way analyses of variance (ANCOVAs) on the encoding conditions, with self-perspective ("self" vs "other") and personal familiarity ("high" vs "low") as the between-subject factors for each score on the VR-EM test while keeping the exploration time, which differed between the groups (see below), constant. To determine the direction of the differences in the interactions between factors, we carried out post hoc Fischer LSD tests. The effect sizes were reported with partial eta squared (η^2). In line with Guéguen (2009), we considered effect sizes as small for η^2<.06, medium for .06 ≤ η^2 <.14, and large for $\eta^2 \geq 0.14$.

3. RESULTS

3.1. Participants

The participants were well matched across the four conditions on age and number of years of education after the baccalaureate. There was a sex ratio in favor of female which was balanced across the four conditions. As expected, the measure of personal familiarity was higher in the high-familiarity group. However, and importantly, there was no difference as a function of the self-perspective encoding condition (**see Table 1**). It should be noted that, compared to the high-familiarity participants (mean score of 66%, CI 95%: 64%-68%, min-max: 55%-75%), those in the low-familiarity group had little personal knowledge of the Latin Quarter of Paris (mean score of 32%, CI 95%: 30%-35%, min-max: 15%-40%). In fact, the high and low familiarity groups differed critically in their personal experiences with the Latin quarter more than in their cultural knowledge of the famous places of this Quarter.

3.2. VR-EM tests

Tables 2 and **3** present all the data in the form of means and standard deviations, together with confidence intervals and the statistical results of the ANCOVAs. As the navigation duration was longer ($p<.001$, $\eta 2 =.44$) in the other-perspective condition than in the self-perspective one, as is usually observed when comparing third-person versus first-person encoding in a virtual environment (e.g., Vogeley et al., 2004), all the subsequent analyses used ANCOVAs with navigation duration as a covariate.

3.2.1. Free recall

Table 2 presents all the descriptive data and the main results of the statistical analyses. Significant interactions between familiarity and self-perspective are indicated in **Figure 4**.

The familiarity x self-perspective ANCOVA showed significant simple effects on the percentages of events and their associated spatial and temporal contexts (*what %, mean where %* and *when %*, respectively), but no interaction. The participants in the self-perspective encoding condition (what 72%, where 68% and when 88%) or who were highly familiar (what 68%, where 74% and when 88%) performed better than the participants in the other-perspective encoding condition (what 56%, where 56% and when 78%) or those who were unfamiliar (what 60%, where 50% and when 79%). This profile was also found for the total *Binding* score when taking account of all the details and spatiotemporal information associated with the recall of each event. The binding score was best for the high-familiarity participants or self-perspective encoding (77.05% and 74.91% compared to 61.53% and 63.66% for low-familiarity participants or other-perspective encoding).

The detailed results on the spatial and temporal performance indicated simple main effects of both high-familiarity and self-perspective on all sub-scores, except for *spatial allocentric* and *temporal sequence (before/after)*. Indeed, there was no effect of the self-perspective condition on the allocentric score and no effect of familiarity on the temporal sequence score. Better performance was observed in the high-familiarity group than in the low-familiarity group on the *allocentric score*, (58% vs 26%), and better performance on the *sequential (before/after) temporal score* was found in the self-perspective condition than in the other-perspective condition (89% vs 78%).

However, the ANCOVAs revealed some significant interactions between familiarity and self-perspective (**see Figure 4**).

Regarding the *details score*, post hoc tests indicated that participants who had navigated in the self-perspective encoding condition performed better than those who had navigated in the other-perspective encoding condition (54.34 % vs 43.23%), but did so at a significant level only when they were in the high-familiarity group (64.61% vs 45.86%, $p<.01$ compared to 44.07% vs 40.59%, $p=.55$ in the low-familiarity group). Moreover, high-familiarity participants performed better than low-familiarity participants (55.24% vs 42.33%), but did so significantly only when they were in the self-perspective encoding condition (64.61% vs 44.07, $p<.001$ compared to 54.86% vs 40.59%, $p=.36$ in the other-perspective condition). In other words, self-perspective in the highly familiar environment was the best condition for recalling the perceptual details of events (all $p<.01$ to $p<.001$).

Regarding the *egocentric spatial score*, post hoc tests indicated that high-familiarity participants performed better in the self-perspective encoding condition than those who had navigated in the other-perspective encoding condition (93.53% vs 86.35%, $p=.05$ compared to 76.37% vs 74.42%, $p=.61$ in the unfamiliar group). The high-familiarity participants performed better than low-familiarity participants, and performance was better in the self-perspective encoding group 93.53% vs 76.37%, $p<.001$) than in the other-perspective encoding group (86.35% vs 74.42%, $p<.05$).

3.2.2. Sense of remembering

There were main effects of self-perspective encoding and familiarity and an interaction between them (**Table 3, Figure 5**). High-familiarity participants obtained a higher sense-of-remembering score than unfamiliar participants (72.18% vs 55.15%), but did so at a significant level only in the other-perspective condition (69.37 vs 44.06%, $p<.001$ compared to 75% vs 66.25, $p=.06$ in the self-perspective condition). Moreover, self-perspective participants obtained higher scores than other-perspective ones (70.62% vs 56.72%), but the difference was only significant for the low-familiarity participants (66.25% vs 44.06, $p<.001$ compared to 75% vs 69.37, $p=.23$ when highly familiar). In other words, the sense of remembering was not impacted by the other-perspective or the low-familiarity condition when the participants were highly familiar or in the self-perspective condition, respectively. Other-perspective in an unfamiliar environment reduced the sense of remembering compared to all the other conditions (all $p<.001$).

Table 2. Navigation duration and free recall of specific events according to the experimental conditions (Familiarity x Self-perspective)

	Experimental Conditions				**ANCOVA**		
	High Familiarity		**Low Familiarity**		**Familiarity**	**Self-perspective**	**Interaction**
	Self	**Other**	**Self**	**Other**	F(1,59)	F(1,59)	F(1,59)
Duration of the navigation (s)	804.12 (59.52) [43.87, 92.12]	914.62 (50.25) [37.12, 77.78]	833.19 (76.42) [56.45, 118.28]	925.75 (45.24) [33.42, 70.02]	1.85 η2=.03	**47.27*** η2=.44**	.37 η2=.01
Free recall What (%)	78.25 (9.59) [7.08, 14.84]	58.59 (10.86) [8.02, 16.81]	68.36 (13.27) [9.80, 20.53]	52.47 (9.13) [6.75, 14.14]	**7.94** η2=.12**	**21.06*** η2=.26**	.43 η2=.00
Free recall Details (%)	64.61 (11.23) [8.30, 17.39]	45.86 (13.19) [9.74, 20.42]	44.07 (18.74) [13.85, 29.01]	40.59 (20.44) [15.10, 31.64]	**10.27** η2=.15**	**6.00* η2=.09**	**3.96*a** η2=.06

Free recall Where (mean%)	81.20 (12.07) [8.92, 18.68]	66.06 (13.53) [10.00, 20.95]	55.03 (8.77) [6.48, 13.57]	45.63 (9.66) [7.14, 14.95]	**74.72*** η2=.56**	**20.02*** η2=.25**	1.37 η2=.02
Spatial location	84.38 (9.51) [7.03, 14.73]	62.12 (17.45) [12.89, 27.02]	60.86 (15.83) [11.69, 24.50]	38.30 (14.29) [10.56, 22.12]	**45.48*** η2=.43**	**32.43*** η2=.35**	0.01 η2=.00
Egocentric	93.53 (11.31) [8.36, 17.51]	86.35 (13.04) [9.63, 20.19]	76,.37 (10.44) [7.72, 16.17]	74.42 (10.15) [7.50, 15.71]	**33.54*** η2=.36**	**6.28* η2=.10**	**3.91*b** η2=.06
Allocentric	65.69 (27.94) [20.63, 43.24]	49.71 (15.66) [11.57, 24.23]	29.81 (14.97) [11.06, 23.18]	22.20 (20.74) [15.32, 32.31]	**37.04*** η2=.38**	3.49 η2=.05	0.68 η2=.01
Free recall When (mean%)	92.44 (9.22) [6.81, 14.27]	83.02 (16.15) [11.94, 25.00]	84.68 (15.20) [11.23, 23.53]	73.57 (10.93) [8.07, 16.92]	**7.64** η2=.11**	**9.41** η2=.14**	.03 η2=.00
Parts of the VE	90.56 (12.09) [8.93, 18.71]	85.42 (12.51) [9.24, 19.37]	83.11 (25.26) [18.66, 39.10]	70.51 (19.65) [14.52, 30.42]	**7.33** η2=.11**	**6.15* η2=.09**	0.50 η2=.00
Before/after	93.27 (9.46) [6.99, 14.65]	80.91 (19.55) [14.44, 30.26]	85.77 (13.57) [10.03, 21.01]	75.77 (12.47) [9.21, 19.31]	3.52 η2=.05	**8.18** η2=.12**	0.15 η2=.00
Temporal order	93.47 (9.30) [6.87, 14.40]	82.72 (17.25) [12.75, 26.71]	85.16 (15.46) [11.42, 23.93]	74.24 (11.90) [8.79, 18.42]	**5.83* η2=.09**	**6.56* η2=.10**	0.01 η2=.00
Free recall Binding (mean%)	83.65 (8.76) [6.47, 13.55]	70.45 (12.60) [9.30, 19.50]	66.18 (10.41) [7.69, 16.11]	56.88 (7.86) [5.81, 12.18]	**41.26*** η2=.41**	**19.72*** η2=.25**	0.82 η2=.01

Note. Mean scores and results of the ANCOVAs (navigation time controlled for)
() : Standard deviation; [,]:95% CI of SD.
F-values in bold are significant: *p <0.05; **p <0.01; ***p <0.001.
Post hoc of interactions:

a) (High Fam: Self > Other, p<.01; Low Fam: Self=Other; Self: High Fam>Low Fam, p<.001; Other: High Fam=Low Fam);
b) (High Fam: Self> Other, p<.05; Low Fam: Self=Other; Self: High Fam>Low Fam, p<.001; Other: High Fam>Low Fam, p<.05).

Figure 4. Interaction between self-perspective and high personal familiarity on event memory: Egocentric spatial context and perceptual details (mean and standard deviation).

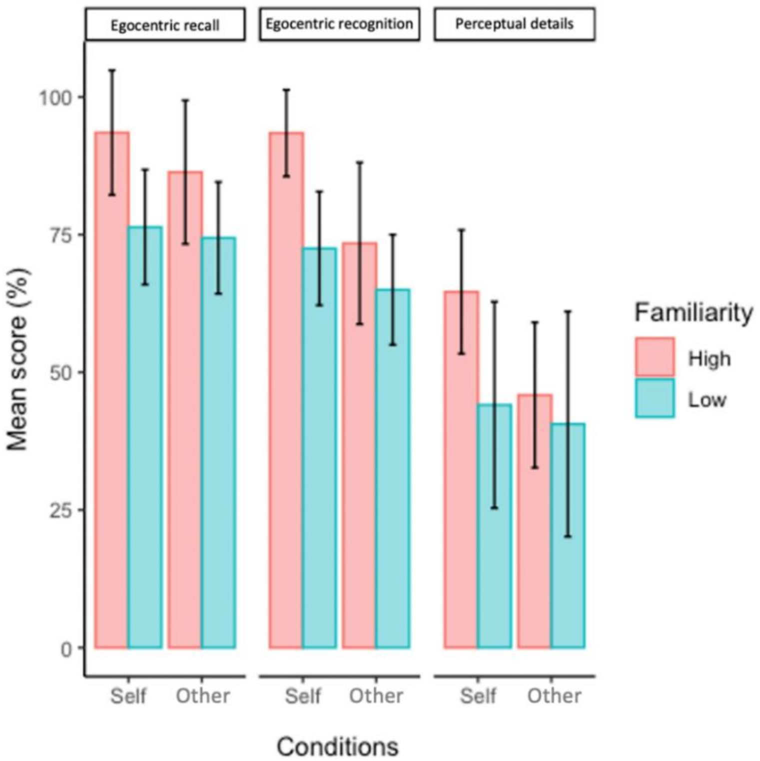


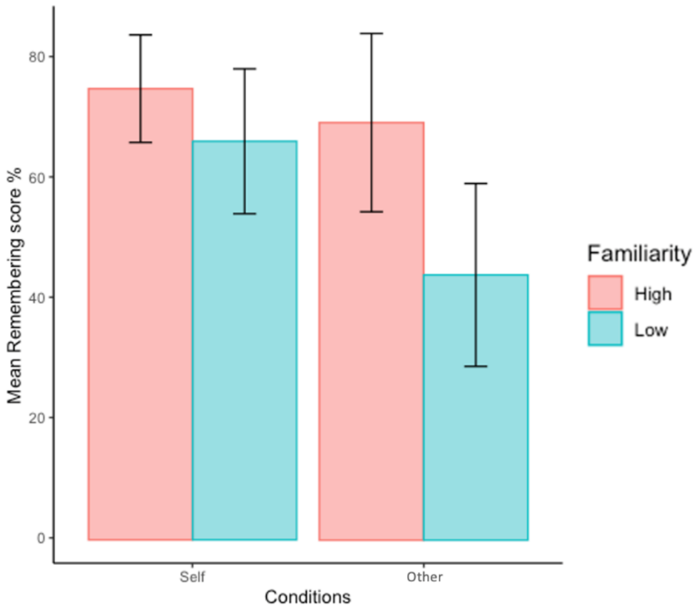
Table 3. Sense of Remembering, visuospatial cued recall and recognition tests according to the experimental conditions (Familiarity x Self-perspective)

	Experimental Conditions				**ANCOVA**		
	High Familiarity		**Low Familiarity**		**Familiarity**	**Self-perspective**	**Interaction**
	Self	**Other**	**Self**	**Other**	**F(1, 59)**	**F(1, 59)**	**F(1, 59)**
Remembering (%)	75.00 (8.94) [6.61, 13.84]	69.37 (14.81) [10.94, 22.93]	66.25 (12.04) [8.89, 18.63]	44.06 (15.19) [11.22, 23.51]	**20.98*** η2=.31**	**11.81** η2=.16**	**6.21*a η2=.09**
Visuospatial recall (%)	63.90 (10.60) [7.83, 16.41]	42.03 (21.95) [16.21, 33.97]	43.12 (21.02) [15.53, 32.54]	22.50 (10.49) [7.75, 16.23]	**22.17*** η2=.27**	**15.45*** η2=.21**	0.3 η2=.00
Recognition (Total %)	81.56 (8.14) [6.02, 12.61]	69.45 (13.54) [10.00, 20.96]	72.73 (10.70) [7.91, 16.57]	59.06 (6.41) [4.74, 16 .23]	**19.40*** η2=.25**	**33.45*** η2=.36**	0.01 η2=.00

What	91.56 (5.39) [3.98, 8.34]	77.18 (13.78) [10.17, 21.32]	84.37 (9.81) [7.25, 15.18]	71.56 (9.78) [7.23, 15.14]	**9.60** η2=.14**	**36.60*** η2=.38**	0.29 η2=.00
Where egocentric	93.44 (7.68) [5.68, 11.89]	73.43 (14.68) [10.85, 22.73]	72.50 (10.32) [7.63, 15.98]	65.00 (10.00) [7.38, 15.47]	**38.98*** η2=.40**	**38.42*** η2=.39**	**7.29**b η2=.11**
Where allocentric	62.18 (17.31) [12.79, 26.80]	55.00 (15.05) [11.12, 23.30]	60.31 (17.17) [12.68, 26.58]	40.93 (11.72) [8.66, 18.14]	**9.91** η2=.14**	**4.74* η2=.07**	2.24 η2=.03
When	79.06 (13.81) [10.20, 21.37]	72.18 (19.91) [14.27, 29.90]	73.75 (14.54) [10.75, 22.51]	58.75 (12.44) [9.19, 19.27]	**7.89** η2=.12**	**12.06*** η2=.17**	0.87 η2=.01

Note. Mean scores and results of the ANCOVAs
() : Standard deviation; []:95% CI. F-values in bold are significant: *p <0.05; **p <0.01; ***p <0.001.
Post hoc of interactions :
a) (High Fam: Self = Other; Low Fam: Self>Other, p<.001; Self: High Fam=Low Fam; Other: High Fam>Low Fam, p<.001) ;
b) (High Fam: Self> Other, p<.001; Low Fam: Self>Other, p<.05; Self: High Fam>Low Fam, p<.001; Other: High Fam>Low Fam, p<.05)

Figure 5. Interaction between self-perspective and high personal familiarity on sense of remembering (mean and standard deviation).



3.2.3. Visuo-spatial location

The ANOVA on the score concerning the location of elements on a map (see **Table 3**, **Figure 4**) indicated better performance in the self-perspective and high-familiarity conditions (53.5% and 52.9%) compared to the other-perspective and the low-familiarity conditions (32.2% and 32.8%).

3.2.4. Recognition

The ANCOVA showed significant main effects of the self-perspective encoding and familiarity conditions on all the recognition scores, namely *What*, *egocentric* and *allocentric Where*, *When* and *Total*. The participants who performed self-perspective encoding or were highly familiar performed better than those in the other-perspective condition or who were unfamiliar (**Table 3**).

Regarding the *egocentric Where* recognition score, the interaction between the two conditions was significant (**Figure 4**). Post hoc tests indicated that participants who had navigated in the self-perspective condition performed better than those who had navigated in the other-perspective condition (82.97% vs 69.22%), and did so to a greater extent in the high-familiarity group (93.44% vs 73.44%, $p<.001$) than in the low-familiarity group (72.50% vs 65%, $p<.05$). At the same time, post hoc tests indicated that participants who had navigated in the high-familiarity group performed better than those who had navigated in the low-familiarity group, and especially so in the self-perspective condition (93.44% vs 72.50% $p<.001$ compared to 73.44% vs 65%, $p<.05$ in the other-perspective condition).

4. DISCUSSION

The present study aimed to examine the influence of self-reference processing on episodic memory encoding of specific events in a naturalistic environment. To this end, we implemented an encoding phase set in a virtual version of the Latin Quarter of Paris in which a series of specific events took place. The second original feature of our study lay in the fact that it teased apart the impact of two dimensions related to the self on memory encoding, namely personal familiarity with the explored environment and the mental self-perspective adopted for encoding during navigation. Finally, we assessed the effect of these two dimensions on the multiple components of episodic memory, including objective and subjective measurements at retrieval.

Our key findings showed that both personal familiarity and self-perspective during navigation not only enhanced common aspects of episodic memory (event recall and recognition, spatiotemporal context, binding, location on a map, sense of remembering), but also had specific benefits (self-perspective in the temporal context and high familiarity in the spatial context) or certain additive beneficial effects (perceptual details, egocentric spatial context). It should be remembered that these effects were not attributable to differences in the duration of navigation or virtual immersion in or sensorimotor interaction with the environment since in all the analyses, we controlled for differences in navigation duration, and the virtual device installation was identical across all the conditions.

4.1. The mnemonic impact of personal familiarity on episodic memory of naturalistic specific events

Personal familiarity with the environment was the first aspect of self-reference investigated for its effect on the memorization of new events to try to identify a spontaneous self-reference effect for events presented in a self-relevant context. The high and low familiarity conditions differed critically in the extent of personal experiences and autobiographical memories related with the Latin quarter of Paris more than in the cultural knowledge of the famous places of this Quarter. To our knowledge, there are only a few studies that have sought to quantitatively assess how personal familiarity with a given environment contributes to the pattern of episodic memory (Kalakoski & Saariluoma, 2001; Donix et al., 2010), and none on the effect on event memory capabilities.

We found, regardless of the perspective taken at encoding, that the participants with high personal familiarity performed better than those unfamiliar with the Latin Quarter in terms of the number of recalled and recognized specific new events and their spatiotemporal context, and that they performed better when asked to indicate the location of events on a map. The benefit of personal familiarity concerned both allocentric and egocentric spatial dimensions. This finding is in keeping with previous evidence that the better spatial performance of high-familiarity participants derives from their knowledge of the overall itinerary and their capacity to associate new items with each known location already present in memory (Kalakoski & Saariluoma, 2001; Epstein et al., 2007). Greater personal familiarity with an environment can promote allocentric referencing (landmarks, direction, and distance information) in addition to egocentric referencing (Burgess, 2006; Ekstrom, Arnold & Iaria, 2014).

In the present study, the advantage of high familiarity may result from spatial knowledge of the environment (names of places, map, route) and strategies implemented to mentally simulate walking in the Latin Quarter during the memory tasks. However, the benefits extended to many specific details of the recalled new events and a greater subjective sense of remembering, and thus were not restricted to factual and spatial information. Thus, additional links with pre-stored personal information (having a more precise memory of an event that occurred in front of a coffee shop in the Latin Quarter that one frequents) and the self-relevance and emotional value of the environment (the location of “my” university, “my” favorite restaurant, the place where “I” married), all contributed to the benefit of personal familiarity in the memorization of rich new events, thus bringing about a self-reference effect (Klein, 2012). Thus, the present self-referencing allowing participants to better encode and retrieve new experiences resulted in a high level of elaboration of new events (item-specific processing, i.e., trace distinctiveness as shown by enhancement of the perceptual recalls), together with a greater level of organization, which consists in relational processing between the events (embedding a memory in a network of cues as shown by the enhancement of contextual recalls). This finding extends the dual-process proposed by Klein and Loftus (1988) for the self-referential effect to include the episodic memory of specific events in a naturalistic context. Additionally, the benefit of personal familiarity has been found to be related to increased brain activity either in the medial prefrontal/anterior cingulate regions (Cloutier et al., 2011; Donix et al., 2010) or in the posterior cingulate and retrosplenial areas (Shah et al., 2001; Epstein et al., 2007; Sugiura et al., 2005, 2009). The benefit could also result from the reactivation of a large network, including the hippocampus, which depends on the specificity of the reactivated autobiographical memory (Martinelli et al., 2013; Moscovitch et al., 2005). Further research should investigate this issue while taking into account the nature of pre-stored personal representations.

Basically, the differences in memory performance between high and low familiarity could result from cognitive load processing. Regular compared to occasional travelers in a real train station or its virtual simulation (in terms of frequency of use), considered as experts and novices respectively, have demonstrated a lower cognitive load based on physiological, subjective and behavioral measures and better episodic memory performance (Armougum et al., 2019). Indeed, participants who were highly familiar with the environment may have benefited from previous knowledge of the environmental regularities, thereby freeing up a more significant amount of cognitive resources to encode the new events than participants in an unfamiliar environment. Nevertheless, our two familiarity conditions did not differ in terms of time duration unlike what was observed when comparing two navigation conditions differing in cognitive resources (e.g., Vogeley et al., 2004; Armougum et al., 2019). This seems to substantiate the claim that cognitive load did not account for all the present findings. Still, the issue needs further consideration to investigate further the differential impact of cognitive load and self-reference in personal familiarity benefits.

4.2. The mnemonic impact of self-perspective in episodic memory of naturalistic specific events

Self-perspective during navigation was the second aspect of self-reference investigated in the memorization of new events. In this condition, the participants had to encode and retrieve new specific events from a first-person perspective. This aspect is more closely associated with a minimal component of the self (Gallagher, 2000) and is critically involved in the episodic memory system (Prebble et al., 2012). As expected, the conscious self-perspective encoding enhanced episodic memory performance on most of the scores, whatever the level of familiarity. In other words, the self-perspective boosted episodic memory of specific new events even if encountered in a personally unfamiliar environment, thus suggesting that it enhances the encoding of the features of lived experiences and the structuring of retrieval cues (Hommel, 2004; Bergouignan et al., 2014).

In particular, self-perspective encoding was the most effective way to recall events together with their temporal context, both localization of time of occurrence of an event and temporal order of the events. By definition, episodic memory relates primarily to events located at a specific time and place and in subjective time (Tulving, 2002). However, the measurement of temporal information during navigation is less frequent than that of spatial information (Iglói et al., 2010; Bellassen et al., 2012). A study evaluating the judgments of spatial and temporal distances between events staged in a large-scale virtual city provided evidence of a common coding mechanism underlying the spatiotemporal aspects of episodic memory in the hippocampus (Deuker et al., 2016). Other studies have shown that recall of the precise temporal order of new personal experiences is directly derived from first-person (sequential egocentric) experience (Fabiani & Friedman, 1997; Howland et al., 2008). One interpretation is that, compared to the mental simulation of an other-perspective, the conscious self-perspective drove the process of segmentation during navigation based on the chronology of a set of goal-directed actions, thereby possibly improving the identification of the events themselves and the perceived transitions between events (Zacks & Tversky, 2001; Zacks, 2020).

The self-perspective adopted at encoding also improved memory of the perceptual details and spatial egocentric context in keeping with the role of egocentric frames of reference in large scale ecological environments in episodic memory (Iachini & Ruggiero, 2006; Iachini, Ruggiero, & Ruotolo, 2009; Riva et al., 2020). Self-perspective specifies the knowledge of the spatial layout of the route from the first-person point of view (e.g., encoding of the eye and body movements associated with a specific time point) when navigating the environment and memorizing sequences or combinations of scenes. Thus, egocentric frames of reference promoted by a self-perspective specified both the temporal sequence of the scenes and directional route knowledge related to the specific events.

Similarly, the self-perspective (irrespective of the level of familiarity) generated a high sense of remembering at retrieval (i.e., subjective re-experiencing and report of internal details). Thus, it facilitated the retrieval based on a mental time travel in the past with a subjective feeling of re-experiencing the earlier virtual walk seeing new events from the original first-person perspective (Tulving, 1985, 2002). This result confirms that adopting a conscious self-perspective, both at encoding and retrieval, constitutes the essence of episodic memory (Prebble et al., 2012). In line with neuroimaging research, it can be suggested that self-perspective during navigation is a process which, thanks to the interaction between the medial prefrontal cortex and the limbic system, facilitates the activity of binding sensory, bodily, cognitive, and emotional information (Hommel, 2004; Zimmer, Mecklinger, & Lindenberger, 2006) into coherent representations at encoding and permits their reactivation at retrieval (Bergouignan et al., 2014; St. Jacques et al., 2011).

4.3. The mnemonic impact of other-perspective in episodic memory of naturalistic specific events

While navigating, the other-perspective condition required the participants to shift from the naturally adopted self-perspective to a simulated mental projection into an other-perspective for encoding. Contrasting with self-perspective encoding, adopting an other-perspective was detrimental to episodic memory performance regardless of the level of familiarity (see below for some exceptions). It increased the navigation duration (which was thus controlled in all analyses) and reduced all objective memory performances as well as the subjective sense of remembering. This is in keeping with the finding that adopting an other-perspective instead of a self-perspective in a virtual environment increases reaction times and decreases the percent of correctness scores while relying on differential neural processes that engage the parietal and premotor cortex (Vogeley et al., 2004). Some other VR studies exploring the mechanisms of change of perspective when interacting with others in virtual reality (e.g., Thirioux et al., 2009) have demonstrated that subjects spontaneously take the visuospatial perspective of the avatar, thus adopting a mental transformation of their body. Interestingly, St. Jacques et al. (2011) showed that simulation of an other-perspective is related to the frontoparietal network, which is engaged in cognitive load processes while adopting self-perspective is linked to the ventral part of the medial prefrontal cortex in connection with the medial temporal lobe, including the hippocampus, which favors episodic memory processes. Following this reasoning, we suggest that mentally adopting an other-perspective at encoding increased the cognitive load during navigation and was thus detrimental for subsequent memory performance. Indeed, the participants were mentally decentered from their self-perspective during navigation and need to cope with the multiple demands of complex world space, especially when the environment was unfamiliar (Burgess, 2006; Landgraf et al., 2010; Blondé et al., 2021). Bergouignan and colleagues (Bergouignan et al., 2014) found that encoding memory from a third person perspective disrupts hippocampal binding, suggesting that memory deficits seen during third person memories are related to the initial encoding of the scene rather than to retrieval. The challenge of learning in this navigation situation is likely related to engagement of the attentional network and disengagement of medial prefrontal structures and the limbic system. Finally, it does not seem possible to attribute our other-perspective condition effects to a deficient transfer appropriate processing (TAP). TAP states that "the likelihood of successful episodic memory depends on the extent to which the processing engaged by a retrieval cue overlaps with that engaged at encoding" (Bramao & Johansson, 2021). Thus, the participants' better performance in the self-perspective condition may have benefited to recall from a first-person perspective. However, their poorer performance in the other-perspective did not seem to result from a discrepancy of perspective between encoding and retrieval. In the present study, simulation of the other-perspective at encoding required the participants to project themselves mentally into the avatar's place and then perform the event retrieval tasks from the avatar's viewpoint.

Nevertheless, when the environment was highly familiar compared to unfamiliar, the egocentric spatial recall was relatively better preserved. Given that spatial knowledge about a familiar environment is stored in a cognitive map of the environment that contains landmarks and knowledge about metrics and directions between places (Jeffery, 2017), one possible explanation is that high-familiarity participants benefited from this knowledge, which helped them to accurately reconstruct the egocentric space around the avatar's body. In the same line, when the environment was highly familiar, the other-perspective condition did not reduce the subjective sense of remembering. While all the memory performance in the other-perspective condition resulted from adopting the avatar's perspective both at encoding and retrieval, assessing the subjective sense of remembering involved adopting a self-perspective, thus a change of perspective from encoding to retrieval. It seems possible, in our case, that pre-existing personal knowledge and memories associated with the Latin Quarter had supported the self-perspective and thus the capacity of re-experiencing the virtual walk with internal detail. In the same line. In addition, the high familiarity with the environment is likely to have reduced the amount of cognitive load when mentally adopting other-perspective and thus be less detrimental for self-referential effect on memory.

4.4. The mnemonic additional benefit of high familiarity and self-perspective on episodic memory of naturalistic specific events

The present study highlighted the fact that two dimensions related to the self, either by adopting a conscious self-perspective during navigation or through personal familiarity with the environment, are encoding processes that are effective in boosting the quantitative and qualitative features of episodic memory. The additive effect resulting from adopting both dimensions was particularly efficient for the recall of perceptual memory details and egocentric spatial direction which are important characteristics of the episodic memory trace (Prebble et al., 2014). Interestingly, perceptual memory details give the distinctive feature of items which also contribute to enhancing correct recollection and reducing the creation of false memories (Brainerd et al., 2002; Abichou et al., 2021). In turn egocentric spatial details are important aspects of episodic long-term feature binding and self-focused frame of reference (Hommel, 2004; Bergouignan, Nyberg & Ehrsson, 2014). Remarkably, as mentioned above, the results also highlighted that personal familiarity could overcome or reduce the detrimental effect of encoding conditions that impose a high cognitive load, such as other-perspective encoding. These findings increase our understanding of how two routes of self-reference can enhance the memory of new complex events in a naturalistic context by facilitating the integration of multimodal self-experienced information. More specifically, adopting both dimensions in a naturalistic context seems to play a crucial role in increasing episodic mnemonic efficiency by combining elaboration (the encoding of individual characteristics of events, i.e., perceptual information) and organization (the encoding of relationships between events, i.e., spatial information) processes, and then strengthening the recollection.

It opens new avenues for managing learning disabilities in daily life by promoting first person-perspective and personal familiarization with environments to reduce cognitive load and improve encoding depth. Therefore, first-person memory training in familiar virtual environments could help people better memorize new situations in their real environments and thus increase their autonomy in everyday activities. This avenue of VR research, which is based on the benefit of self-reference for episodic memory, may be very pertinent due to the ecological validity of VR (Loomis et al., 1999; Armougum et al., 2019) and high level of transfer to real-life (Bohil et al., 2011; Rose et al., 2005; Smith, 2019; Serino et al., 2017). This issue is particularly relevant in aging, given the relatively high level of preservation of the self-reference effect on memory (Glisky & Marquine, 2009; Gutchess et al., 2010, 2007; Lalanne et al., 2013; Kalenzaga et al., 2015, 2019).

4.5. Limitations and conclusion

We acknowledge that the present study has some limitations and that future studies are needed to resolve certain issues and allow us to move forwards in our investigations. First, even if the sex ratio was balanced across conditions, the findings are based more on women's performance than men's. It could be interesting to increase the number of participants and examine the sex-related differences. Previous studies have revealed that men and women use different cognitive strategies and neural networks related to episodic memory (Piefke & Fink, 2005; Compère et al., 2019). Second, the findings emanate from a navigation task using a joystick and a virtual environment presented on a large screen, thus with a relatively low level of immersion and interaction. Virtual presence is generally defined as the feeling of "being here" and refers to the psychological immersion of participants inside the virtual environment (Slater, 2003). Sense of presence was not assessed in our experiment, but several studies have already shown that first person perspective is associated with a greater level of presence than third person perspective in a virtual environment. Nevertheless, the correlation between sense of presence and episodic memory performance is not systematic (Smith, 2019; Iriye & St-Jacques, 2021; Makowski et al., 2019). Third, the present study investigated intentional encoding and navigation was directed to ensure that all participants were able to see the same situations during navigation. In contrast, in real-life, walkers generally choose their own routes and encoding is incidental, guided by the motivated aspects of self (Conway, Singer & Tagini, 2005). Therefore, future research would benefit from using incidental encoding with a more immersive and interactive virtual device and controlling for sense of presence and attention to each event (e.g., via a head-mounted display with eye-tracking) to further increase the resemblance to real-life. In particular, high levels of immersion and interaction with the virtual environment will be crucial in further examining the distinct role of the multiple components of self-referencing in the memorization of real-world events, including the different aspects of the minimal self (Gallagher, 2000; Prebble, 2012) linked to bodily self-consciousness (Blanke, 2012). A new line of research is being developed using VR embodiment techniques involving avatars to explore the role played by the integration of multimodal bodily signals in peripersonal space in structuring episodic memory (Tuena et al., 2017; Blanke et al., 2018; Bréchet et al., 2019, 2020).

To conclude, episodic memory is highly related to the self and, crucially, is involved in the learning and distinctiveness of memory traces and thus contributes to both autonomy and well-being. Despite this, many studies have abandoned the idea of observing it in natural contexts. Using an ecological approach based on VR technology, we demonstrated the beneficial effects of conscious self-perspective during navigation and personal familiarity with the environment on the richness of episodic memory. We suggest that VR holds great promise for extending research in the field of self-referential processing on episodic memory and may pave the way toward the development of remediation methods based on self-reference to support episodic memory encoding in daily life.

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