The effects of age on objective and subjective recollection after visiting a virtual apartment

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While aging has been associated with decreased retrieval of episodic memory details, subjective ratings about memory quality seem to remain stable. This suggests that subjective memory judgments are based on different information according to age. Here, we tested the hypothesis that older people would rather base their subjective judgments on the retrieval of personal elements (such as emotions and thoughts), whereas younger people would rather base their judgments on the retrieval of event-related elements (such as time, place, and perceptual details). Sixty participants (20 to 79 years old) performed eight actions in a virtual apartment and were then asked to verbally recall each action with a maximum of associated elements and to rate the subjective quality of their memories. The elements reported were classified into "person-related" and "event-related" categories. Executive functions, memory performance on traditional memory tasks, and subjects' perception of memory functioning were also evaluated. Results revealed that aging was associated with reduced retrieval of event-related elements, which was explained by decreasing executive resources. However, age did not affect the retrieval of person-related elements, and the subjective memory judgments of older people were not based on these elements to a greater extent than those of younger people. Finally, our results highlight the value of virtual reality (VR) in memory evaluations since subjects' perception of memory functioning was associated with their performance in the VR task but not in traditional memory tasks.

Keywords: episodic memory, recollection, subjective remembering, aging, virtual reality

Introduction

Episodic memory is the memory of personally experienced events that occurred at a particular time and place (Tulving, 1972, 1985). The retrieval of these events typically involves different details that were present at encoding. These details can be person-related (such as emotions or thoughts) or event-related (such as time, place, or perceptual details in the environment). Tulving (1985) also pointed out that the recovery of these details is accompanied by a phenomenological experience of recollection (e.g., the feeling of reliving the event while thinking about it), which can be evaluated using subjective memory judgments (for a review see McCabe et al., 2009).

Interestingly, there is no simple relationship between the objective recovery of details and the accompanying subjective judgments of remembering, which highlights the importance of assessing these two dimensions in both research and clinical settings. Aging is a clear example of this distinction between objective and subjective recollection (Duarte et al., 2006, 2008; Korkki et al., 2020; Robin & Moscovitch, 2017). Indeed, when memory performance is measured objectively (e.g., by determining the accuracy of memories in free recall or recognition tasks), older people show poorer performance than younger people (Bastin et al., 2013; Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000). However, when they have to give subjective ratings about the quality of their memories, they usually give similar or even higher judgments (Comblain et al., 2005; Folville et al., 2020a). This has been mainly demonstrated with discrete laboratory materials (i.e., lists of words or pictures). However, a similar dissociation between objective and subjective recollection in aging has recently been observed in a study where subjects had to recall real-world events that were recorded using a wearable camera, and then to judge the subjective quality of their memories with vividness and feeling of reliving judgments (Folville et al., 2020b). Overall, these findings suggest that older adults' subjective judgments are less dependent on the number of retrieved details (Folville et al., 2021; McDonough et al., 2014).

An alternative hypothesis, less quantitative and not mutually exclusive, could be that with age, the subjective sense of recollection becomes progressively based on qualitatively different information (Johnson et al., 2015). In support of this view, some studies suggest that young and older people do not focus their attention on the same elements when encoding stimuli in memory (Fredrickson & Carstensen, 1990; Labouvie-Vief & Blanchard-Fields, 1982). More specifically, older people would focus on social and emotional aspects, while younger people would focus on visual and perceptual aspects. This could be explained by the Socioemotional Selectivity Theory (SST; Carstensen, 2006), which postulates that the perception of decreasing time left to live leads to a focus on what is emotionally meaningful and less on the acquisition of new information. If older people give more importance to the emotional aspects of their experiences, they could rely more on these elements to determine the subjective quality of their memories. This is consistent with the proposal of Johnson et al. (2015), according to whom older people would rather base their memory vividness judgments on socio-emotional than visual aspects. However, to our knowledge, this specific assumption has only been studied with laboratory material (e.g., Mitchell & Johnson, 2009) and needs to be examined in situations closer to those encountered in daily life.

In clinical neuropsychology, several authors have therefore underlined the importance to evaluate the objective and subjective memory facets with more ecological material in order to understand the phenomenon of conscious retrieval and its evolution in aging (Becquet et al., 2017; Chaytor & Schmitter-Edgecombe, 2003; Spooner & Pachana, 2006). However, as applied in clinical settings, traditional memory evaluations tend to focus on the ability to recall decontextualized and personally insignificant information (e.g., word lists) that has been intentionally encoded repeatedly (Becquet et al., 2017). Therefore, evaluation of the content of objective recollection is strongly limited, and subjective components are usually completely absent. This is why efforts to develop more naturalistic assessment tools are still needed.

An evaluation such as the one proposed by Folville et al. (2020b), where participants engage in real-life activities, seems particularly interesting from an ecological perspective, but this type of task can be very complex to implement in a clinical situation. Therefore, tasks involving the simulation of real-life events through virtual reality seem more applicable (for a review, see Smith, 2019). Over the past several years, virtual reality (VR) has gained much popularity in assessing episodic memory (see Plancher & Piolino, 2017). By allowing the creation of situations close to daily life while keeping experimental control, it offers the possibility of a multisensorial experience, rich in perceptual and contextual details, lived from a first-person perspective and inducing personal involvement (Fuchs et al., 2006; Schultheis et al., 2002). These elements contribute to a sense of presence (the feeling of "being there"; Smith et al., 2019) and make VR particularly useful for studying the memorization of contextual and perceptual details, as well as the phenomenological aspects of memory.

Memory tasks involving events experienced in VR confirm that aging is associated with reduced binding capacities (e.g., Plancher et al., 2008, 2010). More interestingly, while performances on traditional memory tasks are not or only weakly correlated with participants' self-assessment of memory (e.g., Lannoo et al., 1998), binding scores obtained with VR are significantly correlated with subjective complaints in daily life (Ouellet et al., 2018). The interest of binding scores is further confirmed by their correlation with executive functioning (Plancher et al., 2008, 2010). These correlations highlight the role of the episodic buffer, a working memory sub-system depending on executive functions and allowing the association of the different details of specific events that elicit conscious recall (Baddeley, 2000; Piolino et al., 2010). This is also consistent with studies indicating that the decline in episodic richness of memories is largely mediated by executive function performance (el Haj & Allain, 2012; Isingrini & Taconnat, 2008; Salthouse et al., 2003). As executive functions decline with age (Calso et al., 2016), their involvement in memory processes can explain at least partly the age-related decline in binding abilities. However, with VR navigation tasks at encoding, the mediating effect of executive functions in the relationship between age and memory performance could in part result from the fact that participants have to learn how to use a new device while memorizing what they are doing (Plancher et al., 2008; Sauzéon et al., 2016), especially for older people who are often less familiar with new technologies (Selwyn, 2004). Therefore, when using a VR memory task, it is important to consider whether the mediating effect of executive functions in the relationship between age and memory performance is intrinsically due to the memory processes involved or whether it can be explained by the active navigation in VR.

Finally, even if VR has allowed for a more comprehensive evaluation of episodic memory, phenomenological aspects are still understudied. To our knowledge, only Abichou et al. (2022) explored the link between the objective recollection of memories created in VR and the associated subjective memory judgments. They found that "remember" judgments of younger and older people were not associated with the same type of recalled information. Younger people's judgments were significantly more associated with correct retrieval of perceptual and spatio-temporal context than older people. However, only information about the what, where, when, and perceptual details were considered in this study. They did not evaluate the retrieval of person-related aspects of memories, such as feelings or thoughts. It would be interesting to determine whether the assumption of Johnson et al. (2015) postulating that older people base their subjective judgments on socio-emotional aspects is confirmed with ecological material.

The present study

The primary goal of the present study was to use a VR memory task to explore which elements of objective recollection influence subjective judgments and whether these influences evolve with age. More specifically, based on the SST, we examined if the retrieval of personal elements, such as thoughts or feelings (here referred to as “person-related elements”), and the retrieval of the other elements of memories, such as spatial and perceptual details (here referred to as “event-related elements”), differs with age. Moreover, following Johnson et al. (2015), we assumed that retrieving person-related elements would influence subjective judgments to a greater extent for older than younger people, while it would be the reverse for event-related elements. To test these hypotheses, people from 20 to 79 years of age were asked to perform several actions in a virtual apartment. For each action, they were subsequently asked to recall a maximum of associated elements and to evaluate the quality of their memory via vividness and feeling of reliving judgments (similarly to Folville et al. 2020b).

Secondly, we wanted to confirm the mediating effect of executive functions in the relationship between age and memory performance. A mediation analysis between age and memory score obtained with the VR task was therefore performed by introducing an executive function score as a mediator (calculated on flexibility, inhibition, and working memory performance, according to Miyake et al.’s model; Miyake et al., 2000). Moreover, to explore whether the intervention of executive functions is due to active navigation in VR, we added a score of computer experience level and frequency of computer use as a second mediator.

Third, we included a self-reported memory questionnaire (the Prospective and Retrospective Memory Questionnaire; Smith et al., 2000) to investigate whether subjects’ perception of memory functioning in daily life was more correlated with VR performance than with memory performance on traditional tasks (such as the California Verbal Learning Test; Poitrenaud et al., 2007). In addition, we wanted to explore whether subjects’ perception of their memory functioning depends on the subjective quality of their memories. More specifically, we hypothesized that the perception of memory functioning could be better explained by subjective quality judgments accompanying memories rather than by the objective accuracy of these memories.

Finally, because memory performance can be influenced by the sense of presence in virtual environments (Smith, 2019), we explored if this sense of presence (evaluated with the Sense of Presence Inventory; Lessiter et al., 2001) influenced the objective and subjective recollections of memories created in VR.

Method

Participants

Sixty healthy participants (34 women and 26 men) aged from 20 to 79 years (*M* = 48.87, *Mdn* = 49.50, *SD* = 17.15) voluntarily participated in this study. They were equally distributed in each 20-year age band (n = 20 for each of the 20-39, 40-59, 60-79 age bands). More detailed sample description (mean, median, SD, range, and gender) for each age band is provided in Table 1.

[Insert Table 1]

The sample size was determined a priori based on the expected correlation between VR memory score and the self-reported memory scale. In previous studies (Plancher et al., 2008, 2012), correlations between VR memory scores and self-reported global cognitive complaints varied between .30 and .80. An a priori power analysis indicated that a sample of 67 participants is necessary to detect a correlation of .30 with a statistical power of .80 and a p-value of .05 (one-tailed). However, we used a self-evaluation of memory rather than a measure of global cognitive functioning, so the expected correlation might be higher than .30. An a priori power analysis indicated that a sample of 49 participants was necessary to detect a correlation of .35 (again, with a power of .80 and p-value of .05). Based on these analyses, we decided to include 60 participants. They were all native French speakers living at home and screened for the absence of cognitive complaints and psychological or neurological history in the past 10 years. Their average years of education was 15.13 (*SD* = 3.19, *range* = 6–24). People who were at risk of cybersickness were excluded from the study. All participants provided informed consent, and the local ethics committee approved the study.

Participants had to perform the French version of the National Adult Reading Test (fNART; Bovet, 1991) as an estimation of their socio-economic status (SES) to ensure that an SES difference could not explain the age-related cognitive decline. They were also asked to define their level of computer experience (from no experience to expert) on a scale ranging from 0 to 3 and their frequency of computer use (from no computer use to daily use) from 0 to 4. Moreover, a battery of neuropsychological tests (see below) was administered to ensure that the elderly did not show cognitive deficits. After comparison to normative samples, 46 of the 60 subjects were above percentile 5 on all the neuropsychological tests administered, 13 were below the 5 percentile for a single task (4 subjects between 20 and 39 years, 4 between

40 and 59, and 5 between 60 and 79), which is quite common in healthy populations (Axelrod & Wall, 2007; Binder et al., 2009). Only one subject was under percentile 5 on 2 tasks and was consequently removed from the data to perform the statistical analyses.

Procedure and materials

Participants were tested individually in two sessions (Table 2). During the first session, they had to perform an incidental encoding activity in VR, followed by an immediate recall task and the completion of questionnaires about this experience and their perception of memory functioning in daily life. The second session, 2 to 7 days later, was dedicated to a delayed recall task and a classical evaluation of cognitive abilities. This delay was chosen because Conway et al. (2016) showed that the number of accessible event memories decreases rapidly over the first 2 days after the events occurred and seems to stabilize during the few days after.

[Insert Table 2]

Virtual environment

Participants were immersed in a virtual apartment created by the Canadian company IN VIRTUO (https://invirtuo.com/). This flat was composed of eight rooms (Figure 1) where different associated sounds were played (e.g., the sound of the drop of water in the kitchen or the receipt of an email in the office). Participants could move freely in these rooms using the oculus rift equipment, which includes a visuo-headset and “Touch” joysticks that recognize movements.

[Insert Figure 1]

To make an incidental encoding of the events, participants were not informed that their memory would be subsequently tested. Instead, we used a cover story explaining that the purpose of the study was to measure their feeling of realism in a virtual apartment where they will have to perform different actions. Total exposure time in the virtual environment was limited to 15 min to avoid cybersickness.

Familiarization

After a short familiarization phase with the device in a neutral environment, participants first visited the virtual apartment for about 5 min. They then received a blank plan of the apartment and had to write the name of the rooms on it while replacing them in the right place. Immediate feedback was provided to ensure all participants could find their way around the apartment before the encoding phase.

Encoding phase

Under cover of a story (the end of a weekend at sea), participants were instructed to perform eight actions in different rooms of the virtual apartment: feed the fish in one bedroom, take the food out of the oven and wash the dishes in the kitchen, take the bathrobe from the bathroom, put it in the suitcase in a second bedroom, check if the office garbage is not full, use a phone in the hallway to call the person who accompanies you to ensure he is downstairs, and put the keys on the living room table. They were also asked to physically mimic them to enhance multisensory encoding. The list of to-be-performed actions was memorized previously through a selective recall to avoid any interaction with the examiner during the encoding phase. This list presented the actions in a logical order to avoid useless displacements in the apartment, but subjects were not asked to retain this order and were free to modify it when they were in VR. If an action was omitted during encoding, cues were given to ensure that all subjects performed all actions.

Retrieval phase

Free recall: Immediately after performing the eight actions, participants were asked to verbally report all they could remember about the actions and their associated context. They were given these specific instructions: “Can you please recall all the actions you performed while giving the most details possible? For this, you are asked to specify the moment and the place where you performed these actions, give as many visual or auditory details as possible, situate these details in the environment (in relation to you and to each other), and give all the associated memories such as thoughts or emotions”. An example of a complete answer was also given to the participants (“After tidying up the playroom, I went to the garden to wash the barbecue which was disgusting with a leftover skewer on it, and I wondered how long it had been on it. I could also hear the sound of a lawnmower”).

Evaluation of phenomenological characteristics of memory: Just after the free recall, participants were asked, for each action, to rate on a visual analogical scale from 0 to 10 the vividness of their memory (i.e., how vivid the memory is in their mind) and their feeling of re-experiencing the scene when they think about it. They should also determine their point of view with a forced choice asking them if they re-experienced it in the first or third person.

Cued recall: As the objective was to evaluate participants' ability to recall, for each action, the associated object, place, and moment, but also associated visual, auditory, and internal details, questions were asked in case any of these elements were missing in free recall (e.g., "You told me about going to feed the fish, can you give me the room?").

Delayed recall: Two to 7 days later, a delayed recall took place and consisted of the same free recall, evaluation of phenomenological characteristics, and cued recall.

Scoring: Inspired by the coding proposed by Plancher et al. (2010), participants got one point for each action recalled and one point for each associated information (when, where, visual details, auditory details, and internal details), no matter how detailed this information was given (e.g., if participants said that they saw a blue and long bathrobe that seems very soft, they got only one point for the mention of visual information). The scoring of "where" information was divided into two categories assessing whether participants replaced elements relating to themselves (e.g. "it was in front of me") or to other elements in the environment (e.g. "the suitcase was next to the bed"). Two scores were calculated to examine whether subjective judgments were based on the retrieval of different elements of memories. The retrieval of the what, when, where, and perceptual details were summed to create what we called an "event-related elements" index, and the retrieval of internal details, such as feelings and thoughts, were summed to create a "person-related elements" index.

Prospective and Retrospective Memory Questionnaire (PRMQ)

The PRMQ (Smith et al., 2000) was administrated to assess subjects' perception of their memory functioning. This questionnaire is a 16-item self-report measure. Eight items concern prospective memory situations, and eight concern retrospective memory situations. Participants must choose their frequency of appearance among five answers (from never to very often). A high score means that memory difficulties are very frequent. This scale presents a good internal consistency (Cronbach's alpha = 0.89 for the total scale, 0.84 for the prospective scale, and 0.80 for the retrospective scale; Crawford et al., 2003).

Classical neuropsychological assessment

All participants had to perform several neuropsychological tests to evaluate episodic memory and executive functions. The former was evaluated with the California Verbal Learning Test

(CVLT; Poitrenaud et al., 2007), which implies learning a 16-word list corresponding to four semantic categories in five trials, followed by cued and delayed recalls. The entire Rivermead Behavioral Memory Test – 3rd edition (RBMT-III; Wilson et al., 2008) was also administrated to evaluate memory more ecologically. Indeed, the principle of this test is to put participants in situations similar to those encountered in their everyday life and includes visual, auditory, motor, and prospective memory tasks.

In addition, the Trail-Making Test (Lezak et al., 2004) was used to provide information about participants' shifting abilities. The Brown-Peterson (Peterson & Peterson, 1959) evaluates dual-task gestion and sensibility to interference, and the Stroop (Stroop, 1935) evaluates verbal inhibition capacity. An executive composite score was calculated from Z-scores on the three tests.

The Simulator Sickness Questionnaire (SSQ)

The SSQ (Kennedy et al., 1993; adapted by Bouchard et al., 2007) was used to evaluate the degree to which different unpleasant effects were felt during the use of virtual reality on a scale ranging from 0 to 3 (0 = not at all; 3 = extremely). It includes 16 items divided into two distinct but correlated factors: nausea and oculomotor difficulties ($r = .56$, $p < .001$). The Cronbach's alpha value for the SSQ is .87.

The Sense of Presence Inventory (ITC SOPI)

The ITC SOPI (Lessiter et al., 2001) was used to evaluate the degree of realism felt by the participants during their navigation on a Likert scale on 5 points ranging from "strongly disagree" to "strongly agree". A high score means a positive feeling concerning the degree of realism in virtual reality. This questionnaire includes 38 items divided into four subscales: spatial presence, engagement, ecological validity (naturalness), and negative effects. All subscales present a good internal consistency (respectively, Cronbach's alpha = .94; .89; .76; .77).

Analysis Plan

Before addressing our different hypotheses, preliminary correlational analyses were conducted to ensure that certain variables (i.e., ITC SOPI, SSQ, fNART, and educational level) were not impacted by age. We used spearman correlations because the distribution of some variables was not normal.

Similarly, in order to verify that age and interindividual differences in executive functioning did not affect the quality of encoding, we explored, first, the correlations of these two variables with the number of trials to learn the actions to be performed. Second, we explored using logistic regression the effect of these variables on the cueing needs to complete all the actions when participants omitted some of them during the encoding task in VR.

Then, we addressed our first research question by examining the effect of age on the retrieval of the different constituent elements of memories ("event-related elements" vs. "person-related elements") using mixed-effects models with subjects and actions introduced as random effects. We then examined if the retrieval of these different elements of memories influenced subjective memory judgments (i.e., vividness and feeling of reliving ratings) on a trial-by-trial basis and if this influence interacted with age. Subjects and actions were modeled as crossed random effects in these analyses. In two models, the sum of the event-related elements for each action was added as a first-level predictor, age as a second-level predictor, and the event-related elements × age cross-level interaction was added to investigate potential age differences in the relationship between the retrieval of event-related elements and subjective judgments. In the analyses of the delayed recall, we also added the delay between the two sessions as a second-level predictor. The dependent variable was vividness ratings in the first model and the feeling of reliving ratings in the second model. Two other models were similar, except that the first-level predictor was the person-related elements recalled. These analyses were performed with the lme4 package (Baayen et al., 2008) in R (R Team, 2015)

To investigate our second research question concerning the mediating influence of executive functions in the relation between age and memory performance, we planned to conduct mediation analyses according to the method proposed by Preacher and Hayes (2004) on IBM SPSS Statistics. In addition, to explore whether executive function recruitment could be explained by less familiarity with technology and thus effortful navigation in VR, we had originally planned to add computer experience level and frequency of computer use as a second mediator. However, this was neither feasible nor useful because mediation analyses require significant correlations between all variables included in the analysis (Preacher & Hayes, 2008), yet neither of these two variables was significantly correlated with age.

To address the question about the link between perception of memory functioning and memory performance, spearman correlations were conducted to compare the relation between subjects' answers to the PRMQ and memory performance at the VR task (i.e., immediate and delayed free recall of event and person-related elements and subjective judgments) and their relation with traditional memory tests (i.e., the Global Memory Index of the RBMT-III and the immediate free recall of the CVLT).

Finally, exploratory correlational analyses were conducted to determine the impact of the different factors of the ITC-SOPI on objective and subjective performance to explore if the sense of presence influenced these performances.

It should be noted that cued recall data of the VR task were not included in any analysis because they showed a ceiling effect. The mean number of correct elements of the 53 elements to be recalled at the immediate cued recall was 46.42 (*SD* = 4.13). At the delayed cued recall, participants recalled a mean number of 45.44 elements (*SD* = 4.76). For a more detailed description of the number of elements recalled and cues needed by each 20-year age band, see Table S1 in supplementary material.

Results

Preliminary analyses

Descriptive statistics (means, standard deviations, and ranges) for the different questionnaires, computer experience, frequency of computer use, fNART, and the classical neuropsychological assessment are listed in Table 3.

[Insert Table 3]

Correlations between these variables and age revealed that age correlated positively with the spatial presence factor of the ITC-SOPI (r_s = .33 ; p = .01) and negatively with the two factors of the SSQ (nausea: r_s = -.37 ; p = .004; oculo-motor difficulties: r_s = -.37 ; p = .003). PRMQ, level of computer experience, frequency of computer use, and fNART performance were not related to age (all r_s < .24 ; all p > .06 ; see Supplementary Table S2).

Given the absence of significant correlation between age and the level of computer experience or frequency of computer use, these two variables could not be included in the mediation analysis to explore if the intervention of executive functions was due to the lack of familiarity with technologies. However, it should be noted that both frequency of computer use and level of computer experience were significantly correlated with the recall of person-related elements at the immediate free recall (respectively r_s = .39 ; p = .002 and r_s = .43 : p <.001) but not with the recall of event-related elements. Concerning the delayed free recall, only the level of computer experience showed significant correlations with the recall of both event-related elements (r_s = .30 ; p = .02) and person-related elements (r_s = .39 ; p = .002).

Finally, concerning the encoding phase, age and executive functioning did not correlate with the number of trials to learn the actions to be performed (respectively $r_s = .09$; $p = .49$; $r_s = -.19$; $p = .15$) and did not influence the need of cues to perform all the actions in VR for participants who omitted some of them at the encoding task (respectively *Wald* = 0.07; *df* = 1; *p* = .79; *OR* = 1.00; and *Wald* = 0.36; *df* = 1; *p* = .55; *OR* = .56). This need of cues to complete all the actions concerned 39 subjects.

Effect of age on objective and subjective recollection

Table 4 presents the results from the mixed-effects models exploring the influence of age on the retrieval of event-related and person-related elements, and then the influence of these two categories of memories' elements on vividness and feeling of reliving ratings.

[Insert Table 4]

These analyses revealed a significant effect of age on the retrieval of event-related elements (showing that fewer elements were recalled with increasing age) but not on person-related elements. In addition, the score of recalled event-related elements was a significant predictor of subjective judgments for both vividness and reliving judgments. On the other hand, retrieving person-related elements was a significant predictor of reliving judgments but not of vividness judgments. The effect of age and interaction were significant in neither of the analyses, indicating no influence of age on subjective recollection.

Similar results were obtained at the delayed free recall with event-related elements significantly predicting both subjective judgments (all $p < .02$). However, the effect of person-related elements was not significant for both vividness and reliving ratings (all $p > .59$). Age and interaction effects were not significant in all analyses. The interval between the encoding and delayed recall had no effect either ($p > .34$) (see Supplementary Table S3).

Relationship between age, executive functions, and objective performance

Mediation analyses were made according to Preacher and Hayes's (2004)' recommendations to determine if the effect of age on the score of event-related elements could be explained by executive abilities (Figure 2). The [a] coefficient estimates the strength of the direct link between the independent variable and the mediator. The [b] coefficient estimates the strength of the direct link between the mediator and the dependent variable. The [c] coefficient estimates the strength of the link between the independent and dependent variables. Finally, the [c′] coefficient estimates the effect of the independent variable on the dependent variable when the mediator's influence is considered.

[Insert Figure 2]

The results revealed a significant effect of age on executive functions (path [a]) and on the score of event-related elements (path [c]), demonstrating that both binding abilities and executive performance decline with age. Moreover, results also revealed a significant effect of executive performance on the score of event-related elements (path [b]), indicating that participants with better executive functioning had higher binding scores. The global model was significant ($R^2 = .17$, $F(1,57) = 12.16$, $p < .001$). Furthermore, there was no evidence that age still affected binding scores when executive functions' influence was taken into account (path [c']), demonstrating the mediating effect of executive functions on the relationship between age and binding scores.

Relationship between memory performance and subjects' perception of memory functioning

Results of the correlational analyses between memory performance and answers to the PRMQ are presented in Table 5.

[Insert Table 5]

We detected significant correlations between memory complaints and the retrieval of event-related elements from the VR task but no significant correlation with the recall of person-related elements and the performance at the traditional memory tasks. Concerning the phenomenological aspects, only the first-person view after the immediate free recall was significantly correlated with memory complaints.

Relationship between memory performance and the immersive experience

Exploratory correlational analyses investigating the link between the ITC-SOPI and objective and subjective memory performance revealed that only the engagement factor was significantly correlated to the feeling of reliving after the immediate free recall (r_s = .27 ; p = .04) (see supplementary material, table S4).

Discussion

Relationship between objective and subjective recollection

The primary goal of this study was to investigate the link between objective and subjective recollection with a VR memory task. The contrast between these two kinds of recollection in older people has been mainly demonstrated with discrete laboratory materials, such as lists of words or pictures (Duarte et al., 2006, 2008; Korkki et al., 2020; McDonough et al., 2014). The advantage of using VR is that it offers a greater ecological validity, thanks to the richness and complexity of the environment, while keeping an experimental control (Plancher & Piolino, 2017). Our results confirm the contrast between objective and subjective recollection in older people. While subjective judgments about the quality of memories were similar, the objective amount of event-related details recalled decreased with age. These results are consistent with what McDonough et al. (2014) called the recollection quantity hypothesis, postulating that even if older people retrieve less information, they recalibrate their subjective judgments on this lower amount of details.

However, the present study aimed at testing another explanation, according to which people do not base their subjective judgments on the same type of information as they get older. Abichou et al. (2022) have already highlighted that subjective judgments of older people were less associated with retrieving spatio-temporal and perceptual elements than younger people's judgments. Based on the results of Johnson et al. (2015), we hypothesized that subjective judgments of older people were more associated with the retrieval of personal elements, such as emotions or thoughts.

Even if our results revealed that the retrieval of personal elements did not decline with age, we failed to confirm this hypothesis. Indeed, age had no main or interaction effect on subjective recollection. However, the absence of the expected interaction between age and the emotional elements of memories could be explained by a weak emotional involvement during the VR task. As the actions performed in VR were very neutral and probably induced few emotions and thoughts, the emotional involvement may not have been strong enough to allow older people to rely more on this information than younger people when judging the subjective quality of their memories. This interpretation of a low personal engagement during the VR task is congruent with the absence of the effect of person-related elements on both subjective judgments at the delayed recall. In future studies, it would be interesting to use a task inducing stronger emotional involvement to see whether older people base their vividness and feeling of reliving ratings on these emotional aspects. To achieve this, we could simply modify the cover story in a way that subjects can establish a link with their personal life and thus be more involved in the task (e.g., “you are organizing a surprise party for your partner and you have 5 min to finish cleaning the apartment before he or she arrives”). Another possibility would be to propose another virtual environment supposed to induce stronger emotional involvement (e.g., an emergency room, simulation of a car accident, etc.).

However, it is still possible that it is not – or at least not only – the retrieval of emotional aspects that influence the subjective memory judgments of older people. As subjects were not given any information concerning how to define “vividness” or “feeling of reliving”, we do not know on what basis they made their subjective judgments. It is therefore possible that these judgments are based neither on the recall of event-related elements nor person-related elements. Johnson et al. (2015) suggested that the elderly could base their subjective judgments on conceptual or semantic aspects. Their judgments have also been associated with the activation of brain regions related to self-referencing (Mitchell & Johnson, 2009). This suggests that the retrieval of personal information could also determine the memory judgments of elderly participants (Mitchell & Hill, 2019). Therefore, instead of categorizing the different constituent features of memories, as we did in the current study, it would be interesting to investigate other features of memories, such as the ability of older people to link their memories with semantic or personal information. Aspects related to the narrative coherence of memories could also be interesting, such as their ability to replace events in their temporal context within the continuous flow of events (Radvansky, 2012). If older people base their subjective judgments on these elements, it could explain why they make similar subjective judgments while retrieving lower objective details. Future studies should further investigate which aspects of memories young and older people rely on to determine the subjective quality of their memories created in natural settings.

In addition, our results show that both event- and person-related elements predict the feeling of reliving ratings, but only the event-related elements predict the vividness ratings. These two subjective judgments are often studied together, but researchers make little difference between them. However, our results demonstrate that they have their specificities. More specifically, they suggest that retrieving emotions and thoughts is only important to provide a feeling of reliving but not to make memories vivid. This is not surprising since vividness is defined as a personal evaluation of a mental image's degree of richness and clarity (D'Angiulli & Reeves, 2007; Mitchell & Johnson, 2009). Vividness ratings thus focus on retrieving a mental representation of the original scene well-located in space (Rubin et al., 2019). Consequently, person-related elements of memories may have little weight in vividness judgments. On the other hand, the feeling of reliving judgments depends not only on the ability to reconstruct the scene (Rubin & Umanath, 2015) but also on the retrieval of emotions, as already highlighted by Rubin et al. (2003).

Mediating effect of executive functions between age and objective recollection

Beyond confirming the well-documented mediating effect of executive functions in the relationship between age and memory performance (Bouazzaoui et al., 2010; Piolino et al., 2010; Salthouse et al., 2003; Taconnat et al., 2007), our interest in the current study was to explore whether the involvement of executive functions in the VR memory task was due to active navigation. Indeed, learning how to use a VR device while doing the task may have recruited more executive functions than usual memory tasks, thus reducing the number of resources allocated to encode information properly. As older people are often less familiar with technologies (Corriveau Lecavalier et al., 2020), we hypothesized that subjects' level of computer experience or the frequency of computer use could be a second mediator between age and memory performance as it reflects the level of familiarity with technology and consequently the ability to handle the VR device. However, we could not verify this assumption because mediation analysis requires significant correlations between all the independent and dependent variables included in the analysis (Preacher & Hayes, 2008) and there was no correlation between age and the level of computer experience or the frequency of computer use. Although subjects' ability to handle the VR device should be measured more objectively, these results suggest that the involvement of executive functions in VR memory performance (already shown in other VR studies; Plancher et al., 2008, 2018; Sauzéon et al., 2016) is not explained by learning how to use a new device. Consequently, executive functions seem intrinsically involved in binding abilities. Theoretically, this could be explained by the episodic buffer, a working memory system allowing the creation of multimodal representations and sending them to long-term memory (Baddeley, 2000). This system, at the basis of the binding process, is dependent on executive functions to integrate different types of information together (Baddeley, 1886). By affecting the episodic buffer, the age-related executive decline may thus explain why older people have difficulties creating integrated episodes. However, it is important to remember that we cannot conclude that active navigation in VR does not involve any executive resources as we only indirectly evaluate this involvement. Despite the absence of correlations with age, computer experience still showed significant correlations with some VR memory scores. Future studies should explore more directly the executive and attentional resources devoted to active navigation and their impact on memory performance when encoding is done in VR.

Another important point to discuss is the absence of age effect on memory performance in the delayed free recall task, which was quite surprising. This could be explained by the recall tasks being repeated after a short interval. Indeed, we observed an improvement in memory performance between the two recall tasks, probably because at the delayed recall, participants remembered the information they had to give at the cued recall task that took place a few days before. The immediate recall task may thus have reinforced the encoding of the information already highly memorable, which may have led to a better performance at the delayed recall. This suggests that when the material is sufficiently memorable, such as when using ecological and immersive material, the immediate recall could be removed, and future studies could be limited to a delayed recall.

Relation between the perception of memory functioning in everyday life and memory performance

Another goal of this study was to determine whether subjects' perception of their memory functioning depends on their objective performance or the subjective quality of their memories. Only binding measures obtained with the VR task for the event-related elements turned out to be related to participants' perception of their memory functioning in everyday life. There was no correlation with traditional tasks. This is in line with previous studies that obtained the same results (Ouellet et al., 2018; Plancher et al., 2008) and could be explained by the fact that VR offers the possibility to create situations close to those encountered in daily life, allowing an incidental and multidimensional encoding that can facilitate the retrieval of information by reactivating more distributed memory traces, which is less the case of traditional memory tasks. These findings demonstrate again the ecological validity of VR memory tasks and their ability to predict everyday memory functioning (Ouellet et al., 2018).

Sense of presence and memory performance

Finally, we explored whether objective and subjective recollection were influenced by the sense of presence in the VR environment. The sense of presence is a multidimensional construct corresponding to several factors (Lessiter et al., 2001). In the current study, we used the ITC-SOPI, which considers four factors. Participants reported moderate spatial presence, engagement, and naturalness of the environment and few negative effects, which confirm our virtual environment's small amount of inconvenience. The moderate scores could be explained by the already mentioned low emotional inducement of the task, as several studies have demonstrated that emotional activation is an important factor in inducing a sense of presence (Baños et al., 2004, 2008; Riva et al., 2007). However, in the current study, almost none of the presence factors were linked with objective or subjective memory performance. The link between the sense of presence and memory performance is not well established in the literature (for a review, see Smith, 2019). For example, Makowski et al. (2017) found positive correlations between the sense of presence and memory for factual information but not with memory for temporal order. This is probably due to the location of the attentional focus. Attentional engagement seems to be a critical variable underlying the sense of presence (Darken et al., 1999; Kober & Neuper, 2012). But even if increasing attention could appear as an advantage for memory encoding, it could lead to lower memory performance if attention is allocated to irrelevant details. Consequently, even if participants reported a similar sense of presence, the differences between where they placed their attention (relevant vs. irrelevant details) could explain the absence of correlation with memory performance.

Conclusion

This study investigated age-related changes in objective and subjective recollection in episodic memory when using a VR memory task. Our findings confirm that age is associated with decreased objective memory performance, at least for retrieving event-related elements, and this can be explained by a decline in executive functions. However, age did not influence subjective memory judgments. Vividness and feeling of reliving judgments were influenced by the number of objective event-related elements recalled (at any age), whereas the retrieval of person-related elements only influenced the feeling of reliving. This highlights the importance of assessing both objective and subjective recollection when evaluating episodic memories. Finally, this study confirms the advantage of using VR for studying episodic memory by showing the correlation between memory performance and subjects' perception of memory functioning (contrary to traditional memory tasks) and the absence of interference generated by the immersive environment.

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The authors have no conflict of interest to declare.

The data that support the findings of this study are available upon request from the corresponding author (M.B.).

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Table 1. Sample description by each 20-year band.

	20 – 39 year (n = 20)	40 – 59 year (n = 20)	60 – 79 year (n = 20)
Mean age	29.10	49.35	68.15
Median age	27.00	49.50	67.50
SD	6.90	5.05	6.14
Range	20 – 39	40 – 58	60 – 79
Gender	11 men – 9 women	5 men – 15 women	10 men – 10 women

Table 2. Content of the two sessions.

Session 1	Familiarization with VR Encoding phase in VR Immediate free recall Immediate phenomenological evaluation Immediate cued recall SSQ ITC-SOPI PRMQ
Session 2	Delayed free recall Delayed phenomenological evaluation Delayed cued recall CVLT Trail Making Test Stroop Brown-Peterson fNART RBMT-III

Table 3. Mean scores, standard deviations, and ranges for the questionnaires, computer use and fNART by age groups.

	Mean (SE) Range		
	20-39 year	40-59 year	60-79 year
Prospective and Retrospective Memory Questionnaire (1 = no complaint ; 5 = lots of complaints)			
Prospective items	2.62 (0.47)	2.35 (0.34)	2.29 (0.47)
	1.75 – 3.75	1.50 – 2.87	1.50 – 3.00
Retrospective items	2.30 (0.52)	2.16 (0.40)	2.27 (0.50)
	1.50 – 3.37	1.62 – 3.12	1.37 – 2.87
Sense of Presence Inventory (1 = low ; 5 = high)			
Spatial Presence	3.06 (0.42)	3.37 (0.59)	3.47 (0.48)
	2.17 – 3.57	1.47 – 4.10	2.57 – 4.26
Engagement	3.64 (0.43)	3.61 (0.47)	3.73 (0.49)
	2.46 – 4.15	2.54 – 4.23	3.00 – 4.92
Ecological Validity/Naturalness	3.20 (0.66)	3.41 (0.73)	3.64 (0.75)
	1.80 – 4.20	1.00 – 4.40	2.20 – 5.00
Negative Effects	2.53 (1.12)	1.85 (0.96)	1.88 (0.73)
	1.16 – 4.83	1.00 – 3.83	1.00 – 3.33
Simulator Sickness Questionnaire (0 = no unpleasant effect ; 3 = lots of unpleasant effects)			
Nausea	0.38 (0.42)	0.32 (0.35)	0.13 (0.15)
	0.00 – 1.78	0.00 – 1.11	0.00 – 0.44
Oculo-motor difficulties	0.37 (0.37)	0.20 (0.21)	0.18 (0.27)
	0.00 – 1.57	0.00 – 0.86	0.00 – 0.86
Level of computer experience (0 = none ; 3 = expert)	1.85 (0.67)	1.53 (0.70)	1.65 (0.87)
	1 – 3	0 – 3	0 – 3
Frequency of computer use (0 = never ; 4 = every day)	2.00 (1.62)	3.00 (1.20)	2.65 (1.56)
	0 – 4	0 – 4	0 – 4
fNART performance (on 33 points)	23.55 (3.99)	26.00 (3.03)	22.95 (4.91)
	15 – 30	19 – 31	14 – 30
CVLT (maximum of correct words recalled = 16)			
Immediate free recall	13.40 (2.60)	13.95 (2.61)	12.80 (2.53)
	7 – 16	8 – 16	8 – 16
Immediate cued recall	13.45 (2.54)	13.95 (2.63)	13.15 (2.21)
	8 – 16	8 – 16	9 – 16
Delayed free recall	14.00 (2.55)	14.10 (2.31)	13.10 (1.94)

	6 – 16	10 – 16	9 – 16
Delayed cued recall	14.25 (2.02)	14.42 (2.22)	13.25 (1.97)
	9 – 16	9 – 16	10 – 16
RBMT-III			
Global memory index	100.05 (15.56)	107.79 (12.91)	111.65 (12.57)
	72 – 121	89 – 131	81 – 128
Stroop			
Denomination time (sec.)	57.05 (8.22)	64.21 (13.89)	69.75 (11.30)
	39 – 75	47 – 109	56 – 107
Denomination errors	0.05 (0.22)	0.05 (0.23)	0.30 (0.57)
	0 – 1	0 – 1	0 – 2
Lecture time (sec.)	39.65 (4.57)	45.16 (7.42)	47.70 (9.19)
	30 – 48	32 – 63	37 – 75
Lecture errors	0.05 (0.22)	0.00 (0.00)	0.00 (0.00)
	0 – 1	0 – 0	0 – 0
Interference time (sec.)	94.25 (18.76)	105.11 (21.57)	127.35 (32.91)
	59 – 135	73 – 155	90 – 223
Interference errors	0.20 (0.69)	0.47 (1.23)	1.40 (4.69)
	0 – 3	0 – 5	0 – 21
Brown Peterson (percentage of correct ordered consonants recalled)			
5 seconds interval	0.95 (0.10)	0.97 (0.05)	0.81 (0.21)
	0.56 – 1.00	0.83 – 1.00	0.28 – 1.00
10 seconds interval	0.91 (0.14)	0.88 (0.09)	0.73 (0.24)
	0.44 – 1.00	0.72 – 1.00	0.11 – 1.00
20 seconds interval	0.91 (0.11)	0.89 (0.15)	0.75 (0.21)
	0.67 – 1.00	0.50 – 1.00	0.11 – 1.00
Trail Making Test			
Part B time (sec.)	31.55 (18.47)	30.89 (8.18)	52.65 (29.44)
	14 – 82	21 – 51	25 – 137
Part B errors	0.45 (1.00)	0.16 (0.50)	0.50 (1.00)
	0 – 4	0 – 2	0 – 4

Table 4. Mixed-effects models assessing the relationship between age, objective memory performance, and subjective judgments.

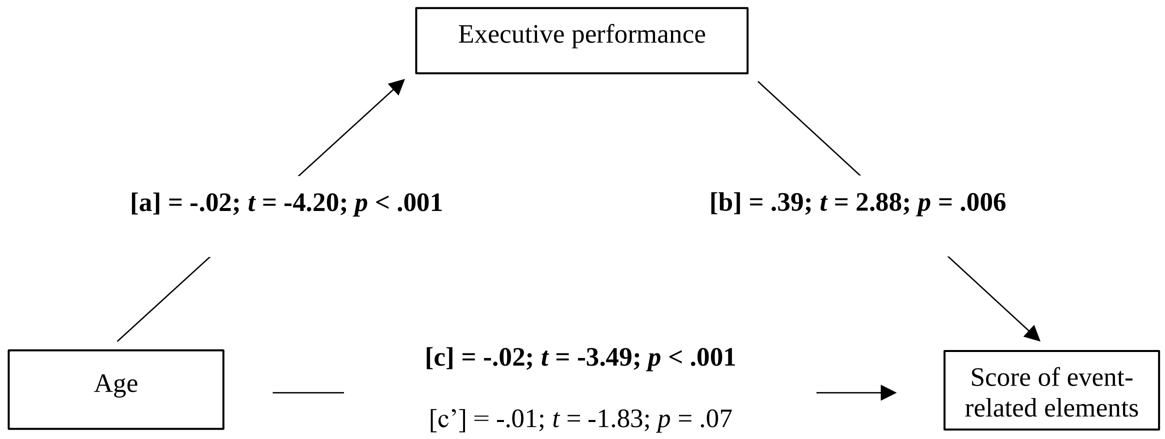
Outcome variable	Predictor	β	SE	t	*P*
Event-related elements	Age	**-0.01**	**0.005**	**-2.88**	**0.005**
Person-related elements	Age	-0.02	0.01	-1.17	0.25
Vividness ratings	Event-related elements	**0.19**	**0.05**	**3.75**	**< .001**
	Age	-0.01	0.01	-0.87	0.39
	Event-related × Age interaction	0.004	0.003	1.36	0.17
	Person-related elements	0.07	0.12	0.53	0.60
	Age	-0.01	0.01	-0.87	0.39
	Person-related elements × Age interaction	0.01	0.01	0.99	0.32
Feeling of reliving ratings	Event-related elements	**0.15**	**0.04**	**3.46**	**< .001**
	Age	0.002	0.01	0.23	0.82
	Event-related × Age interaction	-0.001	0.002	-0.51	0.61
	Person-related elements	**0.87**	**0.40**	**2.20**	**0.03**
	Age	0.10	0.47	0.23	0.82
	Person-related elements × Age interaction	-0.05	0.32	-0.01	0.99

Table 5. Spearman correlations between the PRMQ and the different memory performances.

	Memory complaints (PRMQ)
RBMT-III	$r_s = -0.20$; $p = 0.13$
CVLT	$r_s = -0.06$; $p = 0.63$
VR – Immediate free recall	
Recall of event-related elements	**$r_s = -0.38$; $p = 0.002$**
Recall of person-related elements	$r_s = -0.14$; $p = 0.30$
Vividness	$r_s = -0.02$; $p = 0.89$
Reliving	$r_s = -0.05$; $p = 0.68$
1st person view	**$r_s = -0.28$; $p = 0.03$**
VR – Delayed free recall	
Recall of event-related elements	**$r_s = -0.52$; $p < .001$**
Recall of person-related elements	$r_s = -0.16$; $p = 0.23$
Vividness	$r_s = -0.21$; $p = 0.11$
Reliving	$r_s = -0.16$; $p = 0.23$
1st person view	$r_s = -0.16$; $p = 0.21$

Figure 1. Illustration of the virtual flat.

Figure 2. Mediating effect of executive functions on the relation between age and memory performance.



Supplementary materials

Table S1. Means and standard deviations of correctly reported elements of the actions carried out in VR and the number of cues needed at the different recall phases.

	All participants	20-39 years	40-59 years	60-79 years
Number of correct recall elements (/53) – Immediate free recall	M = 32.85 SD = 6.03	M = 34.95 SD = 5.11	M = 34.00 SD = 5.04	M = 29.65 SD = 6.63
Number of cues needed	M = 20.15 SD = 6.03	M = 18.05 SD = 5.11	M = 19.00 SD = 5.04	M = 23.35 SD = 6.63
Number of correct recall elements (/53) – Immediate cued recall	M = 46.42 SD = 4.13	M = 47.70 SD = 2.96	M = 47.00 SD = 3.07	M = 44.60 SD = 6.63
Number of correct recall elements (/53) – Delayed free recall	M = 34.47 SD = 7.99	M = 36.50 SD = 7.72	M = 33.42 SD = 6.89	M = 33.45 SD = 9.17
Number of cues needed	M = 18.52 SD = 7.99	M = 16.50 SD = 7.72	M = 19.58 SD = 6.89	M = 19.55 SD = 9.17
Number of correct recall elements (/53) – Delayed cued recall	M = 45.44 SD = 4.76	M = 47.00 SD = 4.51	M = 45.10 SD = 4.03	M = 44.20 SD = 5.41

Table S2. Spearman correlations between age and the questionnaires, computer use, and fNART.

	Correlation with age
Prospective and Retrospective Memory Questionnaire (1 = no complaint ; 5 = lots of complaints)	
Prospective items	r_s = -.24 (*p* = 0.06)
Retrospective items	r_s = .02 (*p* = 0.87)
Sense of Presence Inventory (1 = low ; 5 = high)	
Spatial Presence	**r_s = .33 (*p* = 0.01)**
Engagement	r_s = -.05 (*p* = 0.72)
Ecological Validity/Naturalness	r_s = .24 (*p* = 0.07)
Negative Effects	r_s = -.24 (*p* = 0.06)
Simulator Sickness Questionnaire (0 = no unpleasant effect ; 3 = lots of unpleasant effects)	
Nausea	**r_s = -.37 (*p* = 0.004)**
Oculo-motor difficulties	**r_s = -.37 (*p* = 0.003)**
Level of computer experience (0 = none ; 3 = expert)	r_s = -.21 (*p* = 0.10)
Frequency of computer use (0 = never ; 4 = every day)	r_s = .18 (*p* = 0.16)
fNART performance (on 33 points)	r_s = .06 (*p* = 0.67)

Table S3. Mixed-effects models assessing the relationship between age, objective memory performance at the delayed free recall, delay, and subjective judgments.

Outcome variable	Predictor	β	SE	t	*P*
Event-related elements	Age	-0.01	0.01	-1.87	0.06
Person-related elements	Age	-0.005	0.02	-0.28	0.78
Vividness ratings	Event-related elements	**0.21**	**0.05**	**3.87**	**< .001**
	Age	0.003	0.01	0.35	0.73
	Delay	-0.07	0.08	-0.92	0.36
	Event-related elements × Age interaction	0.005	0.003	1.48	0.14
	Event-related elements × Age × Delay interaction	-0.001	0.001	-0.80	0.42
	Person-related elements	0.07	0.14	0.54	0.59
	Age	0.003	0.01	0.35	0.73
	Delay	-0.07	0.08	-0.92	0.36
	Person-related elements × Age interaction	0.001	0.01	0.20	0.84
	Person-related elements × Age × Delay interaction	0.002	0.004	0.61	0.54
Feeling of reliving ratings	Event-related elements	**0.43**	**0.68**	**2.32**	**0.02**
	Age	0.33	0.15	0.58	0.56
	Delay	-1.26	1.31	-0.97	0.34
	Event-related elements × Age interaction	0.09	0.15	0.61	0.54
	Event-related elements × Age × Delay interaction	-0.15	0.07	-0.59	0.56
	Person-related elements	-0.47	0.47	-0.07	0.94
	Age	0.33	0.15	0.58	0.56
	Delay	-1.26	1.31	-0.97	0.34
	Person-related elements × Age interaction	0.05	0.37	0.15	0.88
	Person-related elements × Age × Delay interaction	0.07	0.17	0.43	0.66

Table S4. Spearman correlations (p-value) between factors contributing to the sense of presence and memory scores.

	Number of correctly reported elements (immediate recall)	Vividness	Feeling of reliving	Number of correctly reported elements (delayed recall)	Vividness	Feeling of reliving
Spatial presence	-0.09 (0.48)	-0.09 (0.50)	0.14 (0.30)	-0.06 (0.67)	0.11 (0.39)	0.20 (0.13)
Engagement	0.09 (0.51)	0.05 (0.71)	**0.27 (0.04)**	0.18 (0.16)	0.17 (0.21)	0.22 (0.09)
Naturalness	-0.23 (0.08)	-0.09 (0.51)	0.23 (0.07)	-0.14 (0.29)	0.18 (0.18)	0.22 (0.09)
Negative effects	0.10 (0.44)	0.11 (0.42)	0.02 (0.87)	-0.07 (0.60)	0.06 (0.67)	0.08 (0.56)