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The production of false recognition **and** the associated state of consciousness following encoding in a naturalistic context **in** aging

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Abstract

Using virtual reality, we implemented a naturalistic variant of the DRM paradigm in young and older adults to evaluate false recall and false recognition. We distinguished false recognition related to the highest semantic association (the critical lures), semantic similarity (i.e. items that belong to the same semantic category), and perceptual similarity (i.e. items that are similar, but not identical in terms of shape or color). The data revealed that younger adults recalled and recognized more correct elements than older adults did while the older adults intruded more critical items than younger adults. Both age groups produced false recognition related to the critical items, followed by perceptually and then semantically related items. False recognitions were highly recollective as they were mainly associated with a sense of remembering, even more so in older adults than in young adults. The decline of executive functions and working memory predicted age-related increases in false memories.

Keywords: False recognition; Intrusions; DRM; Episodic memory; Aging; Recollection; Semantic processing; Perceptual processing; source monitoring; virtual reality-based assessment; Remember/Know

1. Introduction

Episodic memory (EM) is the memory of personal events that occurred at a particular time and place, and that can be explicitly recollected with the internal and external contextual details of encoding (Tulving, 1972, 1985). One of the critical properties of EM recollection is autonoetic consciousness, which refers to a special kind of consciousness that accompanies the act of remembering and enables an individual to be aware of him/herself in subjective time. It is opposed to noetic consciousness that accompanies the act of just knowing an event without its encoding context. A myriad of research has shown that EM is not a passive device for the registering and literal reproduction of past events, but rather a dynamic system involving constructive processes (Bartlett, 1932; Clayton & Wilkins, 2018; Schacter & Addis, 2007; Schacter, Guerin, & St. Jacques, 2011; Schacter, Norman, & Koutstaal, 1998). Constructive processes are prone to errors, leading to the production of false memories. False memories refer to remembering events that never happened or misremembering details of an actual event (Gallo, 2006; Loftus, 1997). They can occur spontaneously during a free recall or recognition task and are revealed by intrusions or **false recognitions, respectively**, accompanied by a strong subjective feeling of remembering (Gallo, 2010; Jacoby & Rhodes, 2006; Lampinen, Neuschatz, & Payne, 1997).

1.1 False memories: experimental production and cognitive mechanisms

One of the most powerful paradigms used to produce false memories experimentally is the Deese–Roediger–McDermott (DRM) paradigm (Deese, 1959; Roediger & McDermott, 1995). In this method, participants view a list of semantically related words (e.g., candy, sour) that converge on a related semantic associate, the critical lure (e.g., a sweet). On a subsequent memory test, participants frequently recall, incorrectly, that the critical lure was present on the study list. In 1995, Roediger and McDermott extended this finding by administering a recognition task composed of the studied words, the non-presented critical words, and other non-studied words (Roediger et al., 1995). They also asked participants to make a “**Remember**” or a “**Know**” judgment associated to each response depending on whether their recognition was based on the recollection of specific encoding details or just on a sense of knowing without any remembering of specific details (Remember/Know paradigm, Tulving, 1985). The main finding highlighted a high rate of false recognition and that 48% of false recognitions of critical words were accompanied by a subjective sense of remembering.

Two prominent theories attempt to explain the production of false memories within the DRM paradigm. The **Fuzzy-Trace Theory (FTT)** assumes that a **familiarity-based process** essentially supports memory errors (Brainerd & Reyna, 2002, 2015; Reyna & Brainerd, 1998). FTT considers that each memory contains two distinct traces: the (*gist*) trace corresponding to the general representation of meaning (which can incorporate preexisting perceptual and semantic knowledge), and the (*verbatim*) trace that represents the specific details of an experience such as its spatiotemporal context and perceptual characteristics (e.g., overall shape, color). During the memory test, items that are consistent with the gist of the list of related items (such as the critical item) will be highly familiar (sense of “déjà-vu”) and hence falsely recalled or recognized. Accordingly, the gist can sustain a strong sense of familiarity, which can cause people to erroneously believe that they recollect a memory (i.e., *phantom recollection*, Brainerd, Wright, Reyna, & Mojardin, 2001). An alternative explanation, **the Activation Monitoring Theory (AMT)** (Roediger & McDermott, 1995, 2000; Johnson, Hashtroudi, & Lindsay, 1993; Mitchell & Johnson, 2000), suggests that memory errors are derived from a **recollection based process** (Arndt, 2012). False memories arise as a consequence of the critical item's implicit mental activation by the encoding of related items, followed by a failure of the source monitoring process at retrieval (Johnson et al., 1993). AMT assumes that false recall or false recognition is associated with the recollection of an erroneous encoding context emerging from confusion in determining whether the critical item's salience in memory is due to its external presentation or rather due to an internal generation (Roediger & McDermott, 2000). Accordingly, false memories can be experienced in a way that mimics the recollection of authentic memory: they can be accompanied by retrieval of the encoding context of an element or event that was experienced but mistakenly used to validate a person's false memories experience (Arndt, 2012).

To sum up, while both theories emphasize the crucial role of semantic processing in producing false memories, FTT stresses the importance of reliance on gist, whereas AMT emphasizes the importance of the spread of semantic activation. Moreover, they differ in their claims about the mental process that underlies false recollection: FTT claims that the false recollection is a consequence of an erroneous attribution of familiarity whereas AMT claims that it is a consequence of a deficit in source monitoring, leading to an erroneous remembering of the encoding context.

1.2 False memories and aging: neurocognitive underpinnings

EM is highly age-sensitive. Older adults express a high vulnerability to false memories, accompanied by a high rate of false recollections (Devitt & Schacter, 2016; Gallo, 2010). An age-related increase in false memories has been reported in a wide range of tasks and conditions (Gallo, 2006; Jacoby, Bishara, Hessels, & Toth, 2005; Jacoby et al., 2006; McCabe, Roediger, McDaniel, & Balota, 2009; Norman & Schacter, 1997; Piolino et al., 2006; Schacter, Israel, & Racine, 1999; Taconnat & Rémy, 2006). In their review, Devitt and Schacter (2016) attributed age-related increases in false memories to neural changes and dysfunctions of the medial temporal lobes (MTL) and prefrontal cortex (PFC) (Buckner, 2004; Kim & Cabeza, 2007; West, 1996) which sustain a range of cognitive processes such as binding failure, deficits in strategic retrieval, overreliance on familiarity and gist-based processing. With advancing age, substantial changes in the hippocampus lead to an impairment in the distinctive encoding of new information, resulting in a *gist-based encoding* (Clemenson & Stark, 2015; Hunsaker & Kesner, 2013; Ly, Murray, & Yassa, 2013; Yassa & Stark, 2011). Electrophysiological and neuroimaging data report impaired discrimination of items in older adults, leading to greater overlap between feature memory representations (Wilson, Gallagher, Eichenbaum, & Tanila, 2006). In line with the **FTT**, favoring a gist-based encoding, the overreliance during retrieval on the extraction of information shared between events (gist) may support older adults' production of false memories based on familiarity. Besides, age-related changes in ventrolateral PFC have been linked to impaired strategic retrieval and inefficient source monitoring which, in line with **AMT**, have also been reported to increase the production of false memories based on recollection in older adults (Balota et al., 1999; Butler, McDaniel, Dornburg, Price, & Roediger, 2004; Gallo, Bell, Beier, & Schacter, 2006; Kensinger & Schacter, 1999).

1.3 False memories and aging: Varieties of false recognition production

Apart from emphasizing false memories related to the critical items, several studies showed that false recognitions concern other types of lures. In the DRM paradigm, the spread of associative activation has been extensively related to the production of false recognition of the critical lure (the strongest associate of the category), both in young (for a review, Brainerd & Reyna, 2005; Gallo, 2006) and older adults (Norman & Schacter, 1997; Schacter et al., 1999; Smith, Lozito, & Bayen, 2005). A body of studies suggests that semantic similarity (items that belong to the same semantic category, but are not the strongest associate) may also impact memory errors in older adults (Devitt & Schacter, 2016; Burnside, Hope, Gill, & Morcom,

2017; Koutstaal et al., 2003; Koutstaal & Schacter, 1997; Tun, Wingfield, Rosen, & Blanchard, 1998; Webb & Dennis, 2018). Older adults appear to be particularly vulnerable to false recognition of items with preexisting semantic representations. Koutstaal and colleagues (2003) reported such vulnerability for categorically related pictures of common objects. Using the same stimulus, Pidgeon and Marcom (2014) confirmed the findings of Koutstaal et al. (2003) by reporting a greater increase in false recognition for concrete items sharing semantic similarities in older adults (experiment 1). They proposed that older adults' propensity to make false recognitions related to semantic similarities was favored by reliance at encoding and retrieval on gist processing to the detriment of item-specific (verbatim) information.

Several studies have recently evidenced the involvement of perceptual similarity in producing false memories in young adults and even more so in older adults (Burnside, Hope, Gill, & Morcom, 2017; Dennis & Turney, 2018; Ly et al., 2013; Pidgeon & Morcom, 2014). Interestingly, some of them suggested that failure in perceptual similarity rather than semantic similarity may produce false memories. Using a verbal DRM paradigm, Ly and colleagues (2013) reported a selective impairment in older adults compared to younger ones in the recognition of perceptually similar (phonologically related) verbal stimuli compared to conceptually similar (semantically related) verbal stimuli. In the same vein, Burnside and colleagues (2017) used a verbal DRM paradigm involving conceptual similarity (semantically associated words) and perceptual similarity (words sharing a similar font). Their results suggested that compared to younger adults, older adults are more prone to perceptually related than to semantically related false recognition. Furthermore, this study was one of the few that addressed the phenomenology associated with these types of false recognitions in both age groups by using a Remember / Know paradigm. The authors found that perceptually related false recognitions among older adults were highly recollective. The propensity of older adults to produce false recognitions related to perceptual similarities has been explained by a decline in pattern separation mediated by impaired discrimination of perceptually similar items (Clemenson & Stark, 2015; Hunsaker & Kesner, 2013; Stark, Yassa, Lacy, & Stark, 2013; Wilson et al., 2006; Yassa et al., 2010; Yassa & Stark, 2011).

In sum, using a plethora of material ranging from verbal to pictorial tasks, critical lures and semantic similarity are reported to be significantly involved in producing false recognitions in aging. Recently, an increasing number of studies highlighted the involvement of perceptual similarity in the production of false recognitions in young and older adults. To our knowledge,

no study has yet distinguished, in the same task, the production of false recognitions related respectively to the critical item, to semantic similarity, and to perceptual similarity in aging. Besides, no study has simultaneously investigated the phenomenology associated with producing these three types of false recognition. A final important consideration is whether the production of false memories arising from the incorrect recognition of critical lures and items with semantic and perceptual similarities is observable in situations close to those of daily life (Neisser & Winograd, 1988).

1.4 Virtual reality validity in episodic memory studies

The value of using virtual reality (VR) to study everyday memory is now well established (Smith, 2019), and studies have demonstrated that the performance of episodic memory, particularly what-where-when binding, in a real environment and in its virtual version is comparable (Armougum et al., 2019). Performance in a virtual environment close to daily life is more sensitive to episodic memory age-related deficit detection than standard tasks and is more related to subjective complaints in everyday life (Plancher et al., 2010, 2012). VR is thus an excellent complement to the traditional study of true and false memory (Abichou, La Corte, Nicolas, & Piolino, 2020), as it allows complex naturalistic situations, close to those that participants may encounter in daily life and thus close to the challenge imposed by everyday demands, all the while maintaining a high level of experimental control which may be difficult in a real context (Abichou, La Corte, & Piolino, 2017; La Corte et al., 2019; Loomis et al., 1999; Plancher and Piolino, 2017; Smith, 2019). Finally, using VR in young adults, Flannery and Walles (2003) showed that the level of associative false recognition induced by virtual material was similar to that induced by real material (i.e., items displayed in a virtual or a real office), confirming the ecological validity of VR to study false memories.

1.5 Current study

To study both true and false memory in a naturalistic situation, we implemented a variant of the DRM paradigm in a virtual environment. We asked young and older participants to walk in a busy virtual city, looking closely at a series of semantically related items (clothes, fruits, vegetables, animals...), arranged in naturalistic contexts (shops, stalls in the market, pens in a park). Then, we asked them to recall all the items seen in the virtual city, and we administered a visual recognition memory task. We investigated true and false recall and true and false recognition and the associated state of consciousness (remember or know judgments).

Moreover, we distinguished false recognition mediated by the strength of semantic association (critical lure), semantic similarity (items that belong to the same semantic category), and perceptual similarity (old items, thus the same semantic information but perceptually different in shape or color).

In a naturalistic context, we sought to examine what type of lure contributes most to the production of false memories, age-related increase and cognitive processes that sustain false productions. Our main hypotheses were threefold. First, we expected an age-related decrease in the number of correct recognitions, but an increase in the number of false recognitions and illusory recollections. Second, we assumed that both age groups would produce a rate of false recognition associated with a subjective sense of remembering depending on the type of lure. We anticipated a higher propensity to false recognition of critical lures relative to semantically and perceptually related items. Critical items are highly likely to be more difficult to distinguish from studied items, followed by perceptually related items, and then, semantically related items. Finally, we hypothesized an age-related increase in false recognition and illusory recollection that would be more pronounced for critical lures than for perceptually and semantically related items. To go a step further in investigating the cognitive mechanisms of false memories we conducted a brief neuropsychological evaluation assessing cognitive flexibility, verbal abstract reasoning, working memory, and episodic memory to examine the relationship between age, memory performance, and neuropsychological tests.

2. Materials and Methods

2.1 Participants

A total of 104 participants took part in this study; 52 were younger adults (23 ± 2.4 yrs) and 52 were older adults (70.6 ± 5.7 yrs). Younger adults were recruited from Paris Descartes University, whereas older adults were recruited from the University of the third age. All participants spoke French fluently, had a normal or corrected-to-normal vision and did not suffer from colorblindness. All participants were in general good health with no history of psychiatric or neurological conditions. They all have attained at least the bachelor's degree. The older adults were all living in their own homes and were autonomous in their daily life activities. The two age groups were matched on their schooling education (level 4: Bachelor's degree and postgraduate studies) as assessed by the Poitrenaud scale (Kalafat, Hugonot-Diener & Poitrenaud, 2003) and their verbal skills and crystallized intelligence according to the 44-item

Mill Hill Test, a multiple-choice synonym vocabulary test (Deltour, 1993). **These measures were chosen in preference to the number of years of education as the educational system in France is not comparable across these two cohorts.** Both age groups were examined with the Beck Depressive Inventory (BDI; Cottraux, 1985) to exclude participants exhibiting a depressive state (cut-off < 7/39). Additionally, older adults were screened for basic cognitive functions using the Mini-Mental State Exam (MMSE > 27/30; Folstein, Folstein, & McHugh, 1975). All participants gave their written informed consent for their participation in the study following the Declaration of Helsinki. Demographic data for the participants are shown in **table 1**. The sex ratio was equivalent across the two groups ($\chi^2=0.35, p>0.50$).

Both age groups were screened for their cognitive ability using a brief battery. Executive functions were evaluated using the Trail Making Test (Lezak et al., 2004), administered to assess cognitive flexibility capacities; it highlighted an age effect, with the older adults being slower than the younger ones (TMT B-A). The similarities subtest (Verbal Abstract Reasoning) evaluating the capacity of elaboration and abstraction and verbal reasoning dependent on executive functions also revealed an age effect, with the younger adults performing better than **the older adults**. For the older adults, an additional standard test of executive function, the Frontal Assessment Battery (FAB; Dubois et al., 2000) was also administered. The performance of all the older participants was normal for their age (**table 1**).

Furthermore, an age-related difference between the two age groups was revealed for working memory (WM) assessed by Digit forward/backward span (Wechsler, 1997). Additionally, we evaluated episodic memory (EM) using a visual task, the Family Pictures test (FP, Wechsler, 2001), in which participants must learn a series of pictures and then recall the characters present in the scene, what each character did and where each of them was. The result indicated an age effect, with younger adults outperforming **older adults (table 1)**.

2.2 Encoding task: Virtual environment and apparatus

The virtual environment (VE) named **FalseMem** was developed via UNITY 3D and in-house software (EditoMem & SimulaMem) and displayed on a PC laptop (15.6 inches; 34.5 cm x 19.5 cm). The environment (see <https://cloud.parisdescartes.fr/index.php/s/xGSn5cPqbCoQBbs>) was projected 30 cm in front of participants who were seated in a comfortable chair.

They had to navigate as a pedestrian in the virtual town using a joystick. The virtual environment (VE) was designed to induce the immersion of participants in a realistic

environment close to daily life, rich in perceptual details, sounds and general objects (buildings, cars, trees....) and avatars where we implemented 7 validated DRM categorized lists (Dubuisson, 2011) (clothes, tools, vegetables, fruits, furniture, musical instruments, and animals). Each list (except one) contained 11 elements; 10 of them were presented during the study phase grouped by categories, and **the strongest associated one**, the *critical item*, was not presented (for an example, **see figure 1**). Of note one list contained only 10 elements. The seven DRM lists were exhibited **one by one** in a naturalistic setting (e.g., for example, the fruits displayed **on** a stand, the furniture presented in a flea market, tools displayed on a table in a flea market) and in front of each category, a red carpet was placed to target the elements to be memorized during the navigation.

2.3 Recognition task: stimulus characteristics

The recognition test was programmed in Python 3.5 using the Neuropsychia module (Makowski & Dutriaux, 2017). The test consisted of the presentation of 157 stimuli representing **pictures** of elements seen during the navigation in the VE (*Old*, $n=69$) and others unseen (*New*, $n=88$). The new elements contained the **critical items** related to each **list** ($N=7$): **they correspond to the top exemplar of the list and its strongest associate. They also contained items semantically related** to each **list** ($N=28$); **these differ from the critical item in that they correspond to weak semantic associates of items on the lists. Third, the new elements contained items perceptually related** to each **list** ($N=28$) consisting of old items (*seen during the navigation*) but **in** which **some** perceptual details such as the shape or color **had been changed**. And finally, we also presented **new items** that were not semantically or perceptually related to old items, and that should be easily recognizable as novel items ($N=25$). **See figure 2.**

2.4 Procedure

Participants were tested individually in a quiet experimental room with the light switched off during encoding to increase the immersion and sense of presence but also to ensure that all participants experienced the same room condition. The overall procedure involved a **familiarization phase** during which the participants were free to navigate in an environment containing only general elements (e.g., buildings, trees, cars, avatars). This training session lasted until the participants felt comfortable with the joystick and the apparatus. Then, during **the encoding phase**, they were immersed in the FalseMem environment and were asked to follow yellow arrows to reach the train station. Most importantly, they were asked to spot the

red carpets and to memorize the maximum of elements of all the lists with their contextual (e.g., where, when) and perceptual (e.g., color, shape) information.

The DRM lists were presented one by one (figure 1). The navigation lasted, on average, 10 min. After the encoding phase, participants first completed a scale about the immersion in the virtual environment during 3 min and then underwent a *free recall phase*, in which they were requested to recall the maximum of all items encountered during the navigation. No cue was provided regarding the name and the number of lists. Both age groups then completed a brief battery of neuropsychological tests during 15 min, and finally, they underwent the *recognition phase* (figure 3).

In the *recognition phase*, items belonging to different lists were randomly presented and were accompanied by two statements: *Yes* or *No* (*I saw* or *I did not see the item in the VE*). For each of the 157 items, participants had to choose the corresponding statement. When participants chose the *Yes* statement, we assessed the related level of recollection (Gardiner, 2001) by asking the participant to specify whether it was: a **Guess** judgment (“I assume the item was encountered during the navigation in the VE, I am not sure”), a **Know** judgment (“I know the item was encountered during the navigation in the VE, I am sure but I have no other details in mind”) or a **Remember** judgment (“I remember that the item was encountered during the navigation in the VE and I can re-experience the encoding context”). A Guess judgment was proposed to check the level of certainty of responses on Know and Remember judgments. Before starting, we ensured that the participants fully understood what was meant by Remember/ Know/ Guess judgments. It is to note that the participants' different responses (Yes/No responses; Remember/Know/Guess judgments) were directly recorded on the computer (Neuropsychydia module).

3. Results

3.1 Navigation duration and virtual reality questionnaire

First, navigation duration presented no effect of age. As revealed by the debriefing, older adults indicated that they enjoyed navigating in the virtual environment and had a stronger subjective sense of presence than the younger adults. Finally, there was no effect of age on the self-evaluation of task difficulty (table 2).

3.2 Statistical analyses of memory performance

All the analyses were performed using Statistica 13 software. A series of one-way ANOVAs with Age group (Older adults vs. Younger adults) was carried out on the percentage of true (correct free recall and recognition) and false memories (intrusions and false recognition) followed by a series of repeated-measure ANOVAs with false recognition type (Critical, Semantically related, Perceptually related, Neutral) as a within-subject factor and Age (Younger adults vs. Older adults) as a between-subject factor. To investigate the phenomenology associated with recognition performance in both age groups, we conducted the same ANOVAs on Remember and Know judgments. Detailed statistical results are presented in table 3 and table 4.

We computed an index of memory sensitivity, an *a prime* score (A'), to evaluate discrimination performance between hits and lures according to age group and type of false recognition (performance near 1 indicating a good discriminability while a value near 0.5 suggests poor discrimination). We also computed an index of the decision criterion estimation, a *beta* score (B'), which captures the response bias towards the responses (a beta value of 0 indicates no bias, a positive number indicates a conservative bias reflecting a tendency to provide a No response, while a negative number represents a liberal bias reflecting a tendency to answer Yes). Both A' and B' scores were calculated using the formulas previously proposed by Pallier (Pallier, 2002).

Each size effect (η^2) is reported, and when interaction was significant, each pairwise comparison using PLSD Fisher *post hoc* tests was calculated. Finally, to reach our secondary goal regarding the age-related mechanisms of true and false memories, we performed Pearson correlations and mediation analyses through a series of statistical regressions. The aim was to test whether the relationships between age and memory performances (i.e., percentages of correct free recall and recognition and intrusions and false recognition of critical items) were mediated by the effects of age on other cognitive functions (i.e., cognitive flexibility, working memory, verbal abstract reasoning, episodic memory). Unless otherwise specified, the level of significance was $p < .05$.

Finally, the internal consistency of the FalseMem test was determined using the split-half method by dividing the total set of lists of items into halves (e.g., odd-numbered and even-numbered lists) and comparing the results obtained from the two subsets of lists thus created. Using the Spearman-Brown Prophecy formula, the reliability coefficient of the whole test was 0.847 and 0.807 for free recall and intrusions, respectively.

3.3 True and False memories performance between age groups

Free recall performances. During the free recall task (see table 3), younger adults recalled more correct elements than older adults did while older adults intruded more critical items than the younger adults.

Recognition performances. On the recognition task (see table 3), correct recognition (Hit) performance showed an age effect, with younger adults outperforming older adults. However, no age effect was revealed for false recognition performance.

Further, the repeated measures ANOVA indicated no age effect but an effect of false recognition type and no age and false recognition type interaction (see table 3). Both age groups produced more false recognition related to the critical item, followed by perceptually related false recognition, then semantically related false recognition, and finally false recognition related to neutral items (all $p < 0.001$).

Phenomenology associated with recognition performance between age groups

First, a one-way ANOVA performed on the percent of Remember or Know judgments associated to correct recognition showed that compared to older adults, younger adults associated more Remember judgments to their correct recognition but an equivalent proportion of Know judgments (table 4).

To investigate the phenomenology associated with different types of false recognition, we performed different repeated measures ANOVAs, separately on Remember and Know judgments. The ANOVA performed on Remember judgments revealed no age effect. However, it revealed a main effect of false recognition type as well as an age and recognition type interaction (table 3). *Post hoc* PLSD tests indicated that for younger adults, a larger percentage of Remember judgments was associated with perceptually related false recognition compared to false recognition of critical items ($p < 0.001$), semantically related items ($p < 0.001$), and neutral items ($p < 0.001$). There was no difference in the percentage of Remember judgments associated with false recognition of critical and semantically related items ($p = 0.24$). For older adults, a larger percentage of Remember judgments was associated with both false recognition of critical and perceptually related items compared to false recognition of semantically related items ($p < 0.001$) or neutral items ($p < 0.001$). There was no difference in the percentage of Remember judgments associated with false recognition of critical and perceptually related items ($p = 0.83$). Besides, an age effect was revealed only for Remember judgments associated

with false recognition of critical items: compared to younger adults, older adults associated more Remember judgments to their false recognition of critical items ($p < 0.01$) (See **figure 4**).

The repeated measure performed on Know judgments indicated no effect of age. There was no effect of false recognition type and no age - recognition type interaction (**table 4**).

3.4 Signal-Detection: index of discrimination and response bias

A repeated measure ANOVA performed on the A' and B' scores with false recognition type (Critical, Semantically related, Perceptually related, Neutral) as a within-subject factor and Age (Younger adults vs. Older adults) as a between-subject factor (see **figure 5**).

Regarding the A' score, it revealed a main effect of age [$F(3, 306) = 8.34, p < 0.01, \eta^2 = 0.07$], an effect of false recognition type [$F(3, 306) = 129.67, p < 0.001, \eta^2 = 0.56$], but no age and false recognition type interaction [$F(3, 306) = 0.22, p = 0.88, \eta^2 = 0.00$]. For all types of false recognition, the A' score of the younger adults was significantly higher than that of older adults. For both age groups, the A' for neutral items was the highest, followed in descending order by semantically related items, perceptually related items, and finally, critical items. Thus, critical items were the most difficult to discriminate for both age groups (all $p < 0.0001$).

The same repeated measure ANOVA on the B' score revealed no effect of age [$F(3, 306) = 0.63, p = 0.43, \eta^2 = 0.00$], an effect of false recognition type [$F(3, 306) = 156.05, p < 0.001, \eta^2 = 0.60$] and no age and false recognition type interaction [$F(3, 306) = 0.54, p = 0.65, \eta^2 = 0.00$]. For both age groups, the score associated with different types of false recognition was positive, suggesting a conservative bias. In descending order, the bias was the highest for neutral items, followed by semantically related, then perceptually related, and finally critical items (all $p < 0.001$).

3.5 Relationships between age, true and false memories performance, and neuropsychological tests

First, to assess the links between age, neuropsychological tests and the FalseMem task, simple correlation analyses were conducted. Results are detailed in **table 5** and show that the correlations between age and neuropsychological test performances were generally higher than those between age and FalseMem scores, except for free recall. As regards true memories, free recall and correct recognitions (Hit and RHit) were negatively related to age and some neuropsychological measures ($p < .05$ to $p < .001$). Of note, they were positively correlated with

the standard episodic memory test (Family Picture test), denoting the FalseMem test's convergent validity. By contrast, for false memories (intrusions, false recognition), a few significant positive correlations were found between age and intrusions or false recognitions (R critical and R neutral) performance and between those scores and some neuropsychological measures. Moreover, for the older adults, scores of the Frontal Assessment Battery were correlated with false recognition (R critical and R perceptual). Overall, the lower the neuropsychological abilities, the lower the true memories, and the higher the false memories.

To go one step further, we then tested the possibility that the direct correlations between age and true and false memory might reflect indirect influence of age on neuropsychological measures. We therefore conducted mediation analyses through a series of statistical regressions, following the procedure proposed by Judd and Kenny (Judd & Kenny, 1981; see also Baron & Kenny, 1986; Abram et al., 2014). Accordingly, we checked for (1) a significant relationship between age and each FalseMem score selected, (2) a significant relationship between age and each neuropsychological mediator, (3) a significant relationship between each neuropsychological mediator and FalseMem Scores, and finally (4) a reduction in the strength of the relationship between age and FalseMem scores when the neuropsychological mediators were added to the model (Multiple regression).

The results are presented in figure 6. Multiple regressions showed that neuropsychological measures fully mediated the effect of age on true and false memories resulting in a non-significant age effect. Consequently, age exerted an indirect effect on true and false memories. Regarding correct free recall, all neuropsychological tests (Family Picture test, Digit span, Similarities subtest and Trail Making Test assessing respectively, episodic memory, working memory, verbal abstract reasoning, cognitive flexibility) fully mediated the effect of age on correct recall ($\beta = -0.15$; $p = 0.26$), whereas cognitive flexibility fully mediated the effect of age on intrusions ($\beta = 0.14$; $p = 0.28$). These models accounted for 45% and 7.5% ($p < .001$ and $p < .05$) of the variance on free recall, respectively. Regarding recognition, episodic memory, working memory and verbal abstract reasoning fully mediated the effect of age on Hits performance ($\beta = -0.06$; $p = 0.71$), whereas working memory and verbal abstract reasoning fully predicted the effect of age on false recognition (R critical), ($\beta = 0.03$; $p = 0.81$). These models accounted respectively for 15% and 9% ($p < .01$ and $p < .05$) of the variance on recognition. Some neuropsychological measures which mediated the FalseMem scores after controlling for age remained partially related to these scores, indicating that these mediators were not entirely due

to the aging effect, especially verbal abstract reasoning skills on free recall and recognition, and also working memory on free recall.

4. Discussion

This study investigated for the first time the production of daily life true and false memories and their related phenomenology (remember or know judgments) in younger and older adults after encoding a naturalistic version of the DRM paradigm, displayed in a setting close to what participants may encounter in everyday life thanks to virtual reality. We reported, for both age groups, the production of intrusions and false recognitions of critical items, which highlights that semantically-based false memories can occur in a naturalistic context and thus validates our variant of the DRM paradigm. Age effects were found, confirming the sensitivity of VR for memory assessment in aging. Compared to younger adults, older adults produced fewer recalls, fewer correct recognitions and associated fewer remember judgements to their correct recognitions, but they produced more intrusions, and associated significantly more remember judgments to false recognition of the critical items. First, we will discuss the different findings on the production of false memories in our experimental design and confront them with the existing literature. Then, we will consider the cognitive mechanisms mediating this production with respect to prominent theories of false memories.

4.1 False memories production in a naturalistic context

4.1.1 Validity of VR- DRM variant to study true and false memories production in young and older adults

First, interestingly, this study that used a new virtual city enriched with a series of semantically related items replicated previous VR EM studies on correct free recall and recognition in aging (Abichou et al., 2019; Arvind Pala et al., 2014; Jebara, Orriols, Zaoui, Berthoz, & Piolino, 2014; Plancher, Gyselinck, Nicolas, & Piolino, 2010). This extends to more ecological settings the finding of laboratory studies highlighting an age-related decline in remember judgments (Angel et al., 2013; Bastin & Van der Linden, 2005; Clarys, Bugaiska, Tapia, & Baudouin, 2009; Clarys, Isingrini, & Gana, 2002; McCabe et al., 2009; Piolino et al., 2006; Plancher, Guyard, Nicolas, & Piolino, 2009; Souchay, Moulin, Clarys, Tacconnat, & Isingrini, 2007; Yonelinas, 2002). Second, and foremost, this study extends to a naturalistic context some of the main results of the literature using the classical DRM paradigm examining true memories and associative false memories in younger adults and aging (Dehon & Brédart, 2004; Devitt &

Schacter, 2016; Gallo, 2010; Mather, Henkel, & Johnson, 1997; Norman & Schacter, 1997; Tun et al., 1998; Watson, Balota, & Sergent-Marshall, 2001).

For instance, the present finding is in line with previous studies using DRM word lists that highlight an age-related decline for true recognition (Budson, Sullivan, Daffner, & Schacter, 2003; Gallo & Roediger, 2003; Koutstaal & Schacter, 1997) and associated remember judgments (Plancher, Guyard, Nicolas, & Piolino, 2009). Most interestingly, when considering all false memories, we reported the opposite pattern. Older adults produced more intrusions than the younger adults, as previously found in DRM studies (Balota et al., 1999; Chan & McDermott, 2007; Dehon & Brédart, 2004; Norman et al., 1997; Smith et al., 2005; Tun et al., 1998). However, unexpectedly, there was no difference between the age groups concerning false recognition, which is nevertheless in line with some other studies highlighting a null effect of age-related increase in false recognition (Gallo, 2006; Gallo & Roediger, 2003; Intons-Peterson, Rocchi, West, McLellan, & Hackney, 1999; Kensinger & Schacter, 1999; Skinner, Erin, Fernandes, 2009).

4.1.2 Proposals on the reasons for the lack of an age effect on false recognition

This age-related difference according to the task is in keeping with the fact that recognition and free recall entail different cognitive operations (respectively, automatic versus strategic processes) partly sustained by distinct neural regions (respectively, limbic versus prefrontal areas) that are differently affected by aging (Cabeza, 2001; Tulving, Voi, Routh, & Loftus, 1983; Wang, Daselaar, & Cabeza, 2017). Brain regions involved during recognition such as the medial temporal lobe cortex (including entorhinal, perirhinal, and para-hippocampal regions) are reported to be better preserved than the prefrontal cortex during normal aging (Danckert & Craik, 2013; Raz et al., 2005). By contrast, the reduction in free recall together with the increase in intrusions (Butler et al., 2004; Chan & McDermott, 2007; Dehon & Brédart, 2004; Smith et al., 2005) have been extensively related to the declining efficiency of prefrontal lobe and executive processing during aging (Craik, Mcdowd, & Craik, 1987; Hasher & Zacks, 1979; Jennings & Jacoby, 1993; Kliegl & Lindenberger, 1993). Accordingly, we found that the group of older adults was less efficient than the younger age group as regards executive functions (cognitive flexibility, verbal abstract reasoning) and working memory and interestingly, the mediation analyses showed that executive functions and working memory fully mediated the effect of age on intrusions and false recognitions.

Besides, the absence of a quantitative age-related difference in the production of false

recognition as well as the relatively low rate of false recognition overall (i.e., younger adults~15%; older adults~17%) may be related to our experimental design since we used pictorial material animated in a naturalistic display thanks to virtual reality. Studies have suggested that false recognition rates for pictures differ from false recognition rates for words. For example, Israel and Schacter (1997) used a DRM word list presented in a picture encoding condition (lists of items were presented auditory with their corresponding pictures) or in a word encoding condition (lists of items were presented auditory with their corresponding visual words). For younger adults, they found that the proportion of false recognitions and their related remember judgments were much lower in the picture encoding condition (35%) (24% of Remember judgments and 11% Know judgments) than in the word encoding condition (66%) (47% Remember judgments and 19% Know judgments). In a later study, they conducted the same procedure in younger and older adults (Schacter et al., 1999) and reported the same pattern of a dramatic reduction in false recognition during pictorial encoding, compared to verbal encoding. However, the age-related difference in false recognition was barely significant ($p=.089$) in the two conditions (Picture encoding: younger adults (35%); older adults (46%), Verbal encoding: younger adults (66%); older adults (72%)). Furthermore, other studies have also reported that when false recognition is derived from visual scenes, recognition rates for critical lures were relatively low (~30%; Otgaar, Howe, Peters, Smeets, & Moritz, 2014). To account for these material-related differences in false recognition, Israel and Schacter (1997) suggested that during the test phase, an item is endorsed as “old” only when its recognition elicits the recollection of distinctive details (i.e., the picture), a test strategy termed a *distinctiveness heuristic* (Dodson & Schacter, 2001; Schacter, Cendan, Dodson, & Clifford, 2001; Schacter et al., 1999). Consequently, recollecting distinctive details provides diagnostic evidence that an item was studied whereas the absence of such details leads participants to report that it was not studied (Gallo, 2004; Gallo, Weiss, & Schacter, 2004).

Not only did our virtual DRM paradigm involve the encoding of pictorial elements, but unlike DRM studies using simple visual material, it involved 3D features implemented in scenes and characterized by unique and rich perceptual details. This may have substantially favored a distinctive heuristic strategy during retrieval and may explain the low rate of false memories produced in our study. Interestingly, the index of decision criterion for the (yes/no) recognition supports this interpretation. The participants seemed exigent about the expected details as we found for both age groups a conservative criterion. When participants failed to gain access to the item’s expected details, they more often responded no.

Finally, another explanation concerns the **encoding processes**. We encouraged participants to pay attention **to** (and to memorize) all **the** elements and their related perceptual details and **spatiotemporal** context. The instruction may have favored an item-specific encoding, which has been reported to decrease false recognition rates (McCabe, Presmanes, Robertson, & Smith, 2004). In the same vein, some authors (Arndt & Reder, 2003) stressed the implication of memory processes operating during encoding to produce false memories. They showed that DRM illusions were selectively reduced after encoding distinctive (vs. not distinctive) fonts in both between and within designs. However, such an encoding process does not seem to explain our finding since, even if the rate of false recognition related to critical items was high in both groups, it was also high in perceptually related compared to semantically related false recognition (see below for more details). If participants had encoded enough details and thus privileged an item-specific encoding we would expect to have less perceptually than semantically related false recognition, especially in younger adults, highlighting a better pattern separation **during encoding**. Thus, a distinctive heuristic operating during retrieval seems to better explain our quantitative finding concerning the overall rate production of false recognition.

4.1.3 Modulation of False recognition production and associated phenomenology by lure types

Remarkably, **as expected**, our findings showed that the pattern of false recognition production depended on the type of lure (**critical items and items semantically related, perceptually related, or unrelated**). Both age groups produced more false recognition related to the critical items, followed by perceptually related items, then, semantically related items, and finally, unrelated items. The type of lure also modulated the index of discrimination, with the critical lure being the most difficult to discriminate. In line with previous studies, younger adults had a better index than older adults (Aizpurua, Garcia-Bajos, & Migueles, 2011; Schacter et al., 1999). The type of lure also modulated the index of decision which mirrored the result of the index of discrimination. Indeed, the most conservative bias concerned the lure that was the easiest to identify (i.e., unrelated item). Additionally, the presence of free recall (correct recall and intrusions) may have played a role in the production of different types of false recognitions and their related illusory phenomenology. In our study, the production of false recognitions (Critical items, semantically related and perceptually related items), and recollection of critical items (R Critical), specifically, was negatively correlated to free recall. In contrast, the number of

intrusions (free recall of critical items) was positively correlated to the number of false recognitions of critical and semantically related items (see table 5). These correlations were maintained when age effect was controlled, except for the R Critical. It is conceivable that the activation of the information during free recall may have facilitated monitoring during the recognition phase (e.g., A' index). This view is of particular interest in the field of eyewitness testimony and deserves further investigation. It suggests that administering a free recall before recognition could prevent the production of false memories.

When considering the Remember/Know judgments, our results showed that the phenomenology associated with false recognition also depended on the type of lure (critical items, items semantically related, perceptually related, or unrelated), and remarkably it was also mediated by age. Regardless of the age group, overall participants provided false recognitions based on a level of certainty, either recollection or familiarity. Among the younger adults, the false remember judgment was the highest for perceptually related items, followed by critical items and finally semantically related items. For older adults, it was higher to an equal extent for critical and perceptually related items, followed by semantically related items, which is in line with previous DRM studies reporting a high propensity of older adults to illusory recollection mediated by associative strength and perceptually related items (Burnside et al., 2017; Butler et al., 2004; Gallo, 2010; Gallo & Roediger, 2003; Norman & Schacter, 1997). More precisely, while the percentage of remember judgments associated with perceptually related items was similar in the two age groups (table 4), i.e. above 50 %, older adults associated 50% of their false recognition of the critical items with remember judgments against only 33 % in the younger adults. This age-related increase was mediated by an age-related decline in working memory and verbal abstract reasoning.

4.2 The cognitive processes underpinning the production of different types of false recognition in young and older adults

The production of false memories in the DRM implies **semantic processing**: on the one hand, through the spread of implicit activation among semantic networks converging on the activation of the most strongly associated items, the critical lures (e.g., for the vegetable category, the critical item was carrot), and on the other hand, through high semantic similarity, mediated by related elements belonging to the same category (e.g., for the vegetable category, a semantic item was eggplant) (Devitt & Schacter, 2016; Koutstaal et al., 2003; Koutstaal & Schacter, 1997; Tun et al., 1998). We confirmed this finding using a VR DRM task by inducing false

recognition of both critical items and semantically related items in young and older adults. Interestingly, we also showed that false memories increase in both age groups due to a failure to discriminate perceptual differences from a similar concept, i.e., perceptually related items (e.g., red versus green pepper). Indeed, in our study, even if the rate of production of perceptually related false recognition was lower than false recognition for the critical lure, it was significantly higher than semantically related false recognition. Such false recognition of perceptually related items can be accounted for by **a failure of perceptual discrimination** mediated by a pattern separation difficulty during encoding (McClelland, McNaughton, & O'Reilly, 1995).

Considering these findings in light of the prominent false memory theories, the pattern of results related to different types of false recognition seems consistent with the **Fuzzy Trace Theory (FTT)**. As highlighted in the introduction, according to FTT, gist-based false recognitions depend on remembering gist or relational information but not item-specific information. Even perceptually related items were to a certain extent highly familiar (items similar to those presented during encoding, but not identical in that their shape or color had been changed). This may have favored reliance on gist during retrieval; participants may have privileged an automatic response sustained by gist and familiarity. Therefore, it is conceivable that in our study, for both age groups, the production of different types of false recognition (critical, perceptually and semantically related) was due to reliance on the shared meaning among study items (gist): items that are consistent with the gist of the lists are considered as familiar and can in turn be associated with false remember judgments, also referred to as “phantom recollections”. The rate of false recognitions in both age groups and the increase in false remember judgments associated with critical items in the older adults are in line with gist-based processing and its preservation in aging (Koutstaal & Schacter, 1997; Paige, Cassidy, Schacter, & Gutchess, 2016; Tun et al., 1998). FTT also assumes a process called “recollection rejection” that reduces the incidence of false alarms at retrieval when the recollection of a studied item is used correctly to reject an associated distractor despite its enhanced familiarity (Brainerd, Reyna, Wright, & Mojardin, 2003; Carneiro et al., 2012). Such a process may explain younger adults’ low propensity to remember judgements associated with critical lures compared to those related to perceptually related ones. Indeed, such a diagnostic process may have made the distinction of critical lures (which are characterized by a distinct verbatim from old items) easier than perceptually related items (which share more verbatim with old items than critical items). As a result, the FTT seems to fit many aspects of our data, especially those of younger

adults. Nevertheless, FTT makes it more challenging to report on some of our findings. For instance, the gist-based process cannot fully account for the higher propensity for false recognition of critical lures relative to semantically and perceptually related items. Above all, it does not explain why the age-related increase in illusory recollection concerned only the critical items. This might suggest that some other processing was involved in the production of false recognitions, primarily among older adults. In this respect, the Activation Monitoring Theory (AMT) seems to provide a better explanation of all the results.

The AMT stresses the implication of associative activation rather than gist extraction in the production of false memories: false memories arise because of an implicit activation of the related non-presented lures at encoding, with an advantage in favor of the most highly associated items in terms of the strength of association followed by a failure of the source monitoring process (Johnson, Hashtroudi, & Lindsay, 1993). It follows that AMT predicts a high rate of false recognition of the critical items as well as higher recollective experience related to critical lures (mediated by associative strength). Our general pattern of the production of false recognition in younger and older adults (i.e., with the highest rate of false recognition occurring for critical items) fits with this assumption. Furthermore, AMT provides a relevant explanation for the age-related phenomenology difference concerning false recognition of the critical lure by stipulating the existence of monitoring failure. Monitoring failure leads to confusion at test in determining whether the lure's salience in memory is due to its external presentation or rather due to an internal generation. The confusion is particularly pronounced for generated critical items. Indeed, in our study, compared to the younger adults, the rate of false recollection related to critical lures was the highest among older adults. Nevertheless, source monitoring impairment seemed widespread in older adults, affecting both discriminations of external vs. external stimuli (i.e., old items vs. perceptually related items) as well as external vs. internal stimuli (old items vs. critical items). For younger adults, monitoring external vs. internal stimuli seems to be more efficient than for older adults, whereas monitoring external vs. external stimuli appears to be more challenging.

Additional evidence for source monitoring implication in false recognition comes from mediation analysis. It reveals that the age effect was mediated by working memory (i.e., digit span) and executive functions (i.e., similitudes subtest). Besides, the high rate of remembering associated to both false recognition of critical and perceptually related items was negatively correlated to older adults' performance on the Frontal Assessment Battery: high performances on executive functions decreased the susceptibility to illusory false recognition in older adults.

It is noteworthy that, to a lesser degree, the susceptibility to illusory false recognition in younger adults was also related to their level of executive functions (verbal abstract reasoning) and working memory, reflecting the basic role of source monitoring in false memory. Working memory is closely connected to executive functions and the prefrontal cortex (D'Esposito & Postle, 2002), and source monitoring (Moscovitch, 2000; Reinitz & Hannigan, 2004). Interestingly, working memory capacity has been proposed to mediate source monitoring failures, which predict false memories susceptibility (Watson, Bunting, Poole, & Conway, 2005; Peters, Jelicic, Verbeek & Merckelbach, 2007; Unsworth & Brewer, 2010). Accordingly, individual differences in working memory capacity influence the encoding of distinctive information. In the case of the DRM paradigm, reduced working memory processing may influence the encoding of items lists' characteristics. Lacking the detailed perceptual information needed to differentiate the semantically related critical item from studied items leads to source monitoring errors and as a result, false memories.

4.3 Strength, perspectives, and conclusion

Overall, our findings stressed the importance of the activation of associative networks in producing false recognition in the DRM paradigm, extended here for the first time to an ecological setting. Hence, we have provided additional evidence in younger and older adults of the involvement of semantic processing and perceptual similarity in producing false recognition in situations close to those of daily life. Furthermore, we emphasized the role of source monitoring in mediating the production of false memories and their related illusory recollection. In the future, it will be critical to combine our VR DRM device with additional control of memory encoding such as recording of the time spent in front of each stand and attention to each item using a Head Mounted Display with eye-tracking. Also, developing an incidental encoding condition will be challenging to enhance the naturalistic approach of false memories in daily situations. Finally, advanced research on the FalseMem test should establish diverse reliability measurements such as test-retest reliability to strengthen its use in different fields of applied psychology. Nevertheless, we have reported elements that indicate a satisfactory internal reliability (Spearman-Brown coefficient), and convergent validity (i.e., correlations between free recall or recognition and a standard test of episodic memory). A direct comparison of the same items using either a classic DRM presentation or a VR immersion will substantiate the specific contribution of VR DRM studies of false memories.

To conclude, this research suggests that the production of false memories in situations close to those of daily life may be less pronounced than what is recorded in the classic DRM paradigm. Moreover, it expands our knowledge of mechanisms by which various types of associative false recognition, relevant to daily life, may become compelling, in both younger and older adults and stresses the role of source monitoring complexity in triggering false memories. In the continuation of this kind of naturalistic false memory assessment, further research should investigate various types of false memories beyond those targeted in the DRM paradigm and the potential of the VR method, like the FalseMem task, in the early detection of false memory disorders and, more generally, in providing an indicator of the reliability of eyewitness testimony.

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Figure1.

Example of DRM lists encountered in the virtual FalseMem environment. A tool stand (*the critical item is hammer*), a vegetable stand (*the critical item is carrot*).



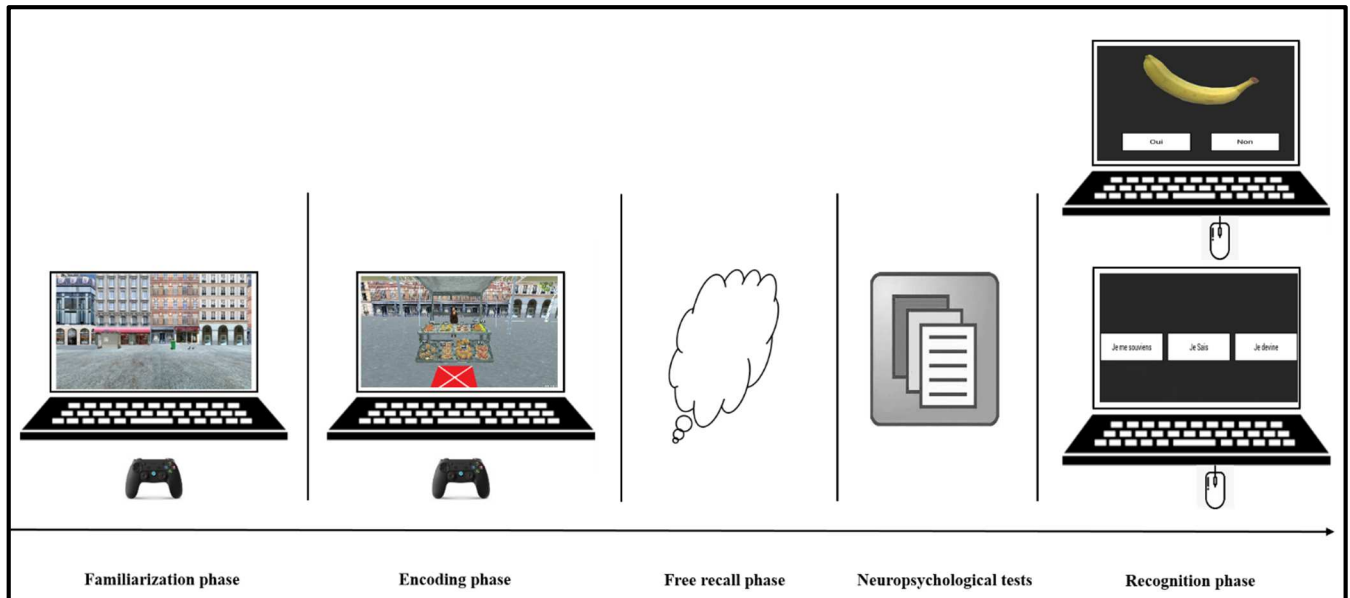
Figure 2.

Example of different old and new stimuli presented during the recognition FalseMem task.

<i>Old</i>	<i>New</i>			
Studied item	Critical item	Item Semantically related to studied item	Item Perceptually related to studied item	Item unrelated to studied item
				
				
				

Figure 3.

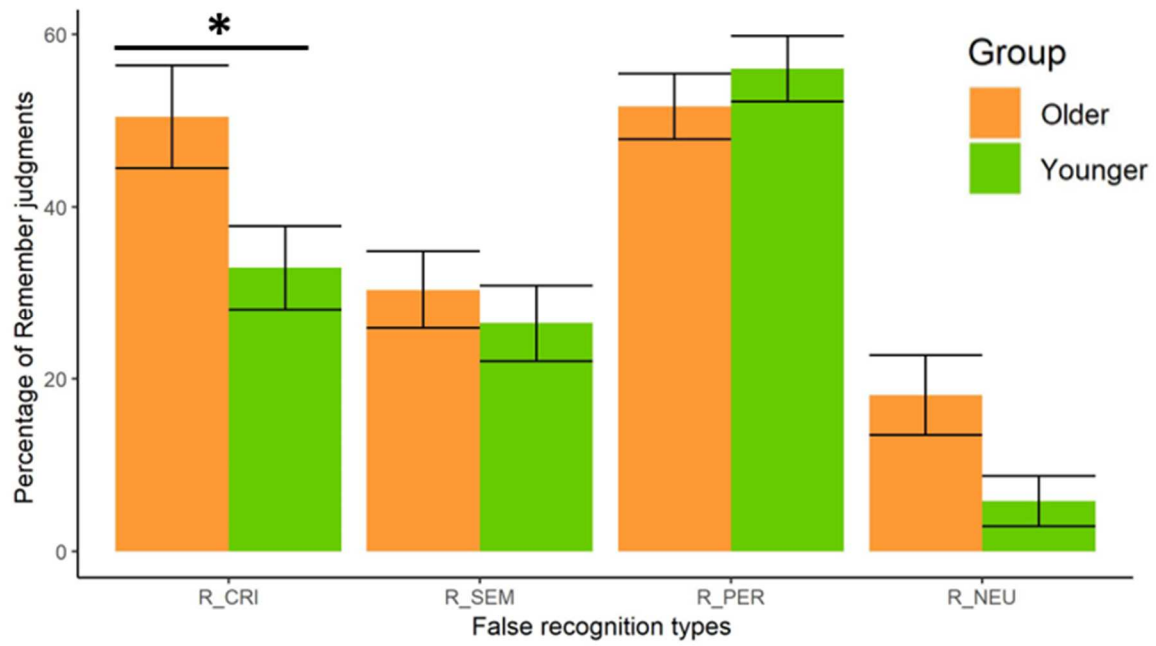
Design of the experimental FalseMem task, schematic representation of the procedure



Note. Recognition phase (Oui : yes; Non : No; Je me souviens : I remember ; Je sais : I know ; Je devine : I guess)

Figure 4.

Remember judgements (R) associated to different types of false recognition (Critical (CRI), semantically related (SEM), perceptually related (PER), Neutral (NEU) items) for young and older adults (mean and standard deviation)



Note. * $p < 0.05$

Figure 5.

Index of discrimination (a prime, A') and response bias (beta prime, B') associated with different types of false recognition (Critical (CRI), semantically related (SEM), perceptually related (PER), Neutral (NEU) items) for young and older adults

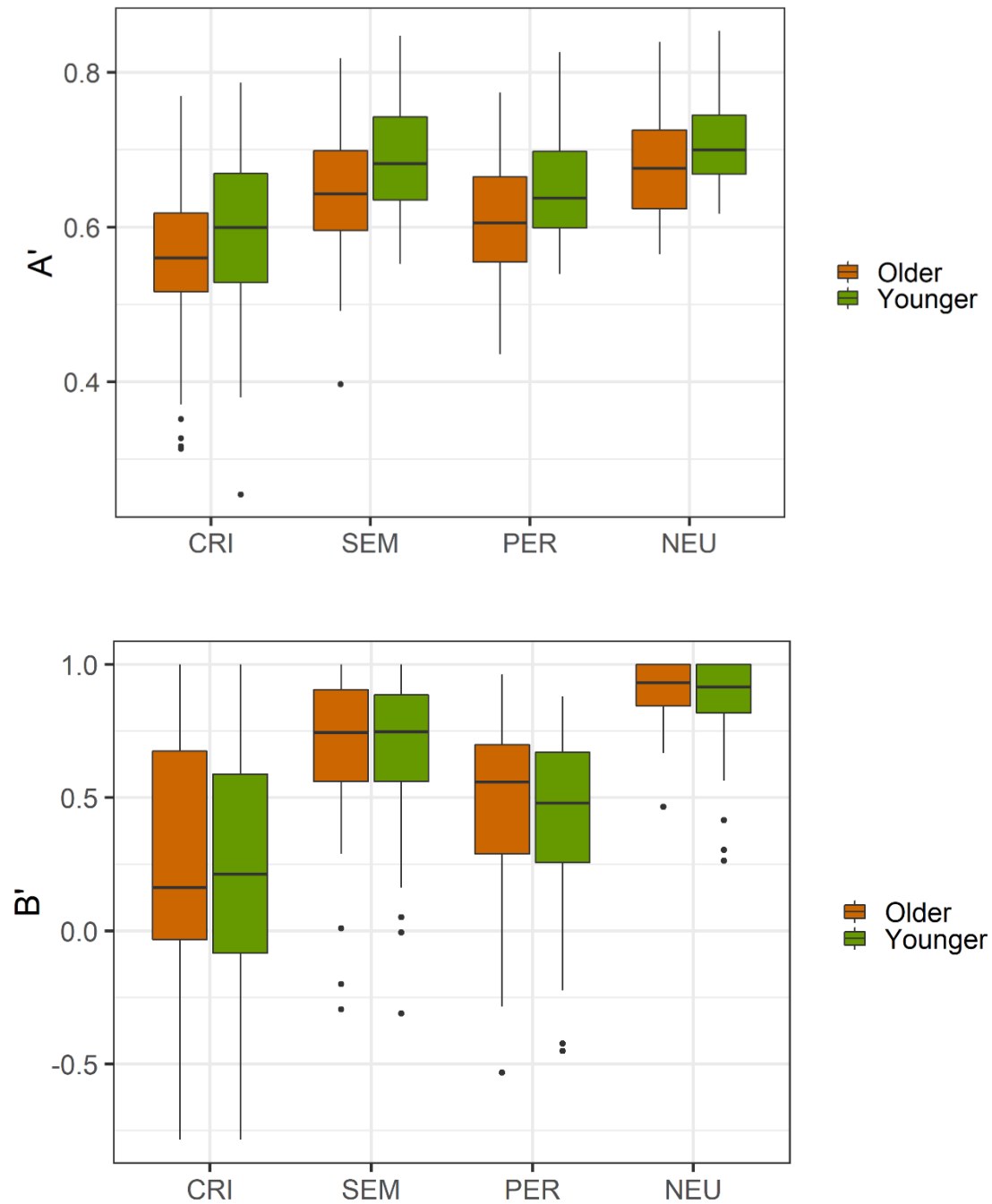
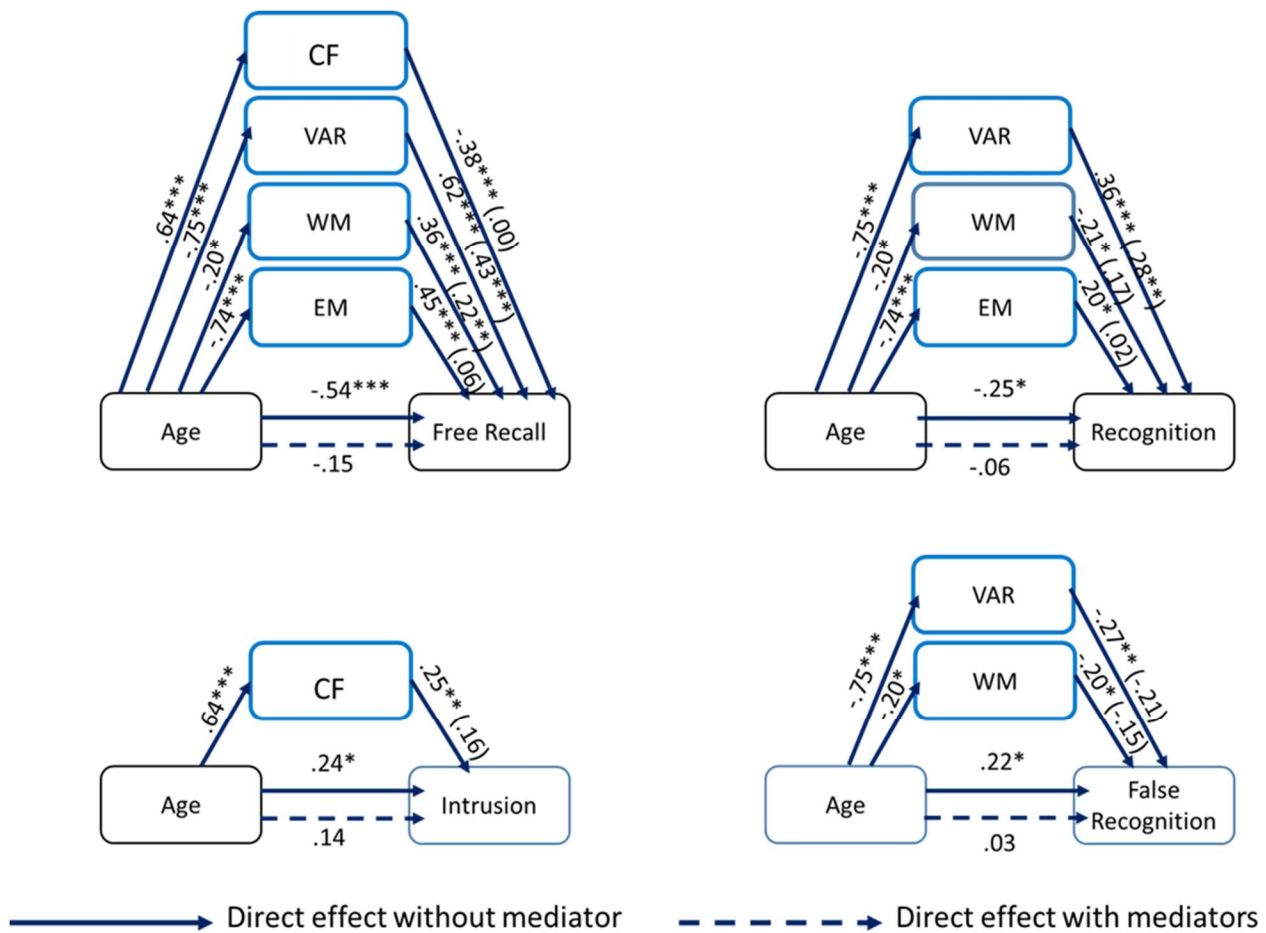


Figure 6. The mediating role of the neuropsychological variables on the relationship between age and FalseMem measures.



Note. The path model indicates the direct effect without mediator (black arrow) and with mediators (striped arrow) in each measure (correct free recall, intrusions, correct recognition – Hits, false recognition – R critical). Coefficients correspond to the beta weights, specifically those into brackets correspond to the beta weights of the multiple regression.

CF: Cognitive Flexibility (Trail Making Test B-A); VAR: Verbal Abstract Reasoning (Similarities subtest); WM: Working Memory (Digit forward/backward span); EM: Episodic Memory (Picture Family test).

* $p < .05$; ** $p < .01$; *** $p < .001$.

Table 1.

Participant characteristics: shown here are the means and standard deviation of demographics and inclusion and neuropsychological measures for younger and older adults and presentation of ANOVAs' results

	Younger Adults	Older Adults	F – value
<u>Demographic measures</u>			
Participants (M/F)	25/27	22/30	-
Age (yrs.)	22.98 (2.47) [22.29, 23.67]	70.58 (6.15) [69.00, 72.19]	3037.50 *** $\eta^2=0.97$
Education (yrs)[#]	3.58 (1.22) [3.20, 3.96]	1.66 (2.26) [0.99, 2.32]	24.57*** $\eta^2=0.22$
Mill Hill (/44)	35.90 (3.2) [34.99, 36.81]	35.73 (4.7) [34.42, 37.04]	0.05 p=.83 $\eta^2=0.00$
BDI (/39)	2.80 (3.20) [1.91, 3.70]	3.71 (2.99) [2.88, 4.54]	2.21 p=.14 $\eta^2=0.02$
MMSE (/30)	-	29.06 (0.91) [28.80, 29.33]	-
<u>Neuropsychological measures</u>			
TMT B-A (s)	25.88 (14.08) [21.49, 30.27]	69.25 (36.50) [58.65, 79.85]	52.41 *** $\eta^2=0.37$
Digit Span (/30)	15.58 (4.30) [14.36, 16.78]	14.08 (2.86) [13.25, 14.91]	4.04* $\eta^2=0.04$
Similarities subtest (/36)	33.65 (3.46) [32.66, 34.65]	21.46 (4.99) [20.01, 22.91]	196.08 *** $\eta^2=0.67$
FAB (/18)	-	17 (1.57) [16.54, 17.46]	-
Family Picture test (/64)	48.80 (11.68) [45.11, 52.49]	28.39 (6.25) [26.27, 30.51]	87.75 *** $\eta^2=0.54$

Note. Education (yrs) : the number of years after the baccalaureate; all the participants had the highest level of schooling education according to Poitrenaud scale (level 4: Bachelor's degree and postgraduate studies)

Note. () : Standard deviation; []:95% CI;

p-values in bold represent significance: *p<0.05; **p<0.01; ***p<0.001

Table 2.

Virtual reality measures: Mean and standard deviation of Virtual Reality navigation duration and debriefing scores for younger and older adults and presentation of ANOVAs' results.

	Younger Adults	Older Adults	F – value
Navigation duration (s)	730.81(187.64) [678.57, 783.05]	756.27 (186.63) [704.31, 808.23]	0.48 p=.48 $\eta^2=0.00$
Debriefing			
Navigation assessment (Q1)	5.75 (2.34) [5.08, 6.43]	7.41 (2.22) [6.77, 8.06]	12.80*** $\eta^2=0.12$
Presence (Q2, Q3, Q4)	4.41 (2.11) [3.81, 5.01]	5.51 (2.06) [4.91, 6.11]	6.80* $\eta^2=0.07$
Task difficulty (Q5, Q6)	4.78 (1.95) [4.28, 5.28]	5.40 (2.29) [4.87, 5.94]	2.93 p=.09 $\eta^2=0.03$

Note. () : Standard deviation; []:95% CI;

p-values in bold represent significance: *p<0.05; **p<0.01; ***p<0.001

Ratings were made on a 1 (*Strongly Disagree*) to 10 (*Strongly Agree*) point Likert scale

Q1: Overall, did you enjoy your exploration of the proposed virtual environment? Q2: During the navigation in the virtual environment, did you have the feeling of walking in the city? Q3: Did you get the impression that the avatars were like real people? Q4: Did you feel as if you were really in the city? Q5: Did you find navigation in the virtual environment difficult? Q 6: Did you find the recall task difficult?

Table 3.

Percentage of correct and false free recall and recognition performances (mean, standard deviation) with presentation of ANOVAs' results

		Younger adults (N= 52)	Older adults (N= 52)	ANOVAs		
				Age	False recognition type	Interaction
Free recall performance (%)	Correct recall	44.09 (12.77) [40.53, 47.64]	27.00 (12.40) [23.55, 30.46]	F(1,102) = 47.88*** $\eta^2 = 0.32$	-	-
	Intrusions	8.51 (13.35) [4.8, 12.23]	14.56 (15.36) [10.28, 18.84]	F(1,102)= 4.58* $\eta^2 = 0.04$	-	-
Recognition performance (%)	Correct recognition (Hit)	57.50 (11.3) [54.36, 60.68]	50.40 (13.1) [46.76, 54.06]	F(1,102) = 8.73** $\eta^2 = 0.08$	-	-
	False recognition (total)	14.75 (6.60) [12.9, 16.59]	16.6 (8.70) [14.12, 18.95]	F(1,102) = 1.41 <i>p</i> = 0.25 $\eta^2 = 0.01$	-	-
	False recognition type					
	<i>Critical item</i>	34.6 (18.6) [29.43, 39.80]	35.4 (19.7) [29.95, 40.92]	F(3,306) = 0.82 <i>p</i> =0.36 $\eta^2 = 0.00$	F(3,306) = 172.28*** $\eta^2 = 0.63$	F(3,306) = 0.29 <i>p</i> = 0.83 $\eta^2 = 0.00$
	<i>Semantically related item</i>	12 (9) [9.3, 14.6]	14.6 (12.6) [11.06, 18.05]			
	<i>Perceptually related item</i>	22 (9) [19.41, 24.81]	24.5 (11.6) [21.28, 27.75]			
	<i>Neutral, unrelated item</i>	4 (4) [2.7, 5.3]	4.5 (5) [3.1, 5.9]			

Note. () : Standard deviation; []:95% CI;

p-values in bold represent significance: **p*<0.05; ***p*<0.01; ****p*<0.001

Table 4.

Percentage of Remember and Know judgments associated with correct and false recognition (Mean, Standard deviation) with presentation of ANOVAs' results

		Younger adults (N= 52)	Older adults (N= 52)	ANOVAs		
				Age	False recognition type	Interaction
Correct recognition (%)	Remember	74 (17) [69.28, 78.91]	65.5 (22) [59.36, 71.66]	F(1,102) = 4.86* $\eta^2 = 0.04$	-	-
	Know	15 (14) [10.97, 18.98]	15.6 (14) [11.51, 19.72]	F(1,102)= 0.05, <i>p</i> =0.82 $\eta^2 = 0.00$	-	-
False recognition (%)	Remember					
	<i>critical item</i>	33(35) [23.22, 42.66]	50 (43) [38.50, 62.32]	F (3,306) = 3.40 <i>p</i> = 0.07 $\eta^2 = 0.03$	F (3,306) = 41.32*** $\eta^2 = 0.29$	F (3,306) = 2.94* $\eta^2 = 0.03$
	<i>Semantically related item</i>	26.4 (32) [17.55, 35.31]	30 (32) [21.13, 39.38][]			
	<i>Perceptually related item</i>	56 (27) [48.37, 63.65]	51.6 (27) [44.01, 59,25]			
	<i>Neutral, unrelated item</i>	6 (21) [0, 11.6]	18 (33) [8.8, 20]			
	Know					
	<i>critical item</i>	28 (34) [18.39, 37.37]	17 (30) [8.9, 25.7]	F (3,306) = 3.55 <i>p</i> =0.06 $\eta^2 = 0.03$	F (3,306) = 1.03 <i>p</i> = 0.38 $\eta^2 = 0.01$	F (3,306) = 0.71 <i>p</i> =0.55 $\eta^2 = 0.00$
	<i>Semantically related item</i>	25 (32) [16.17, 34.21]	15 (22) [9, 21]			
<i>Perceptually related item</i>	20 (21) [13.9, 25.55]	18 (20) [12.8, 23.84]				
<i>Neutral unrelated item</i>	19 (36) [8, 27]	14 (29) [5.7, 22.10]				

Note. () : Standard deviation; []:95% CI; p-values in bold represent significance: ***p<0.05**; ****p<0.01**; *****p<0.001**

Table 5.

Correlations Matrix between age, memory performance and neuropsychological measures

	AGE	Free Recall	Intrusions	HIT	CRI	SEM	PER	NEU	RHIT	RCRI	RSEM	RPER	RNEU	A'CRI	A'SEM	A'PER	A'NEU
AGE		-.54***	.24*	-.25**	.02	.09	.08	.02	-.20*	.22*	.07	-.07	.21*	-.16	-.24*	-.24*	-.22*
TMT B-A (s)	.64***	-.38***	.25**	-.17	.12	.00	-.01	-.08	-.10	.07	-.01	.02	.26**	-.19*	-.11	-.11	-.11
Digit Span	-.20*	.36***	.05	.21*	-.19*	.06	.00	.09	.02	-.20*	.05	-.19*	-.11	.31**	.17	.21*	.21*
Similarities subtest	-.75***	.62***	-.17	.36***	-.04	-.12	-.15	.10	.20*	-.27**	-.08	-.07	-.19*	.28**	.36***	.38***	.31**
Family Picture test	-.74***	.45***	.05	.20*	.00	-.13	-.19*	-.09	.19*	-.12	.09	.16	-.17	.05	.17	.19*	.12
FAB #	-.21	.08	-.17	-.10	-.13	.02	-.11	.12	-.20	-.37**	-.14	-.30*	.07	-.03	-.12	-.06	-.14
Free Recall	-.54***		-.02	.63***	-.20*	-.26**	-.26**	-.04	.43***	-.24*	.08	.12	-.13	.59***	.66***	.66***	.58***
Intrusions	.24*	-.02		.14	.28**	.21*	.09	.01	-.07	.13	.17	-.17	-.10	-.14	.01	.09	.15

Note. **CRI** (critical item); **SEM** (semantically related items); **PER** (perceptually related items); **NEU** (neutral unrelated items)

A' (a prime score); **R** (remember judgement)

Correlations significant at $p < .05$ (*), $p < .01$ (**), $p < .001$ (***) in the whole population ($n=104$), except for the FAB (Frontal Assessment Battery) which was only carried out in the older group ($n=52$)

Partial correlations with age that remain significant are noted in grey case * ** ***