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ORIGINAL ARTICLE

Cognitive mechanisms underlying free recall in episodic memory performance across the lifespan: testing the control/representation model

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Abstract

Episodic memory (EM) develops up to early adulthood, and declines in aging, following an inverted U-shaped profile. This study assessed the contribution of both Control (processes enabling adaptive and flexible behaviour in line with current goals) and Representation (crystallized schemas involved in memory and general knowledge) as factors likely to underlie this pattern of change. We hypothesized that these two cognitive resources are differentially involved in EM performance across development and aging. Participants from 8 to 80 years were administered a free-recall task and tests measuring control and representation. Results show that EM and control scores follow an inverted U-shaped profile (i.e., quadratic relationship), whereas representation increases across the lifespan. EM was associated with representation at all ages, while it was associated with control only in the youngest children and in the adults groups. Representation mainly contributed to age-related difference in EM performance across development. Across aging, control, and to a lesser extent, representation, accounted for EM performance decline. These results showed that EM development and decline do not depend on the same cognitive resources, increased representation being crucial for EM development, and a decline in control with advancing age being responsible for the age-related change in EM performance.

Many cognitive abilities follow an inverted U-shaped developmental/aging trajectory across the lifespan. Episodic memory (EM), which refers to the ability to retrieve information or events associated with their context of learning (Tulving, 2002), is no exception, with performance increasing up to the end of adolescence (e.g., Gathercole, 1998; Ghetti & Angelini, 2008; Newcombe et al., 2007), remaining relatively stable during adulthood, and declining after about 60 years of age (e.g., McDaniel et al., 2008, and see Fandakova et al., 2015, for a review on the lifespan memory change). An important question to be addressed concerns the mechanisms underlying these age-related changes. Following Craik and Bialystok's (2006, 2008) Control/representation model of cognitive development across the lifespan, the present paper examines the respective roles of cognitive control and representation in EM performance and how their respective influence changes as a function of age across the lifespan. Processes sustaining EM in childhood and in aging have often been studied separately, but, to our knowledge, there has been no exploration of the contributions of control and representation to memory performance taking a long lifespan perspective. The main aims of this study were thus first to depict the whole lifespan developmental trajectory of EM performance, secondly, to explore how the respective roles of control and representation change from one age group to another, and thirdly, to examine whether control and/or representation systems can account for age-related differences in memory performance in development and in aging. We, therefore, explored the idea that different mechanisms underlie the increase in memory during childhood

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(where the representation system would be especially important) and its decline during aging (where control would be decisive), reflecting not only quantitative but also qualitative changes (e.g., Baltes et al., 2006; Craik & Bialystok, 2006, 2008).

The control/representation framework

Craik and Bialystok (2006, 2008) developed a model accounting for cognitive changes across the lifespan based on the "the growth and stability of representational systems and the growth and decline of control processes acting on these systems" (Craik & Bialystok, 2006, p. 136), thereby suggesting that the inverted U-shaped developmental trajectories of many cognitive abilities, including EM, could be based on different mechanisms at each end of the lifespan. Representation refers to "the set of crystallized schemas that are the basis for memory and knowledge of the world", and control refers to "the set of fluid operations that enable intentional processing and adaptive cognitive performance" (Craik & Bialystok, 2006, p. 131).

This model is widely supported by studies on neural development. On one hand, the frontal lobes, which support cognitive control, are among the last cerebral regions to mature (Casey et al., 2000; Giedd et al., 1999; Shaw et al., 2006), but they are also those which decline first, in early aging (Park & Gutchess, 2005; Raz, 2000; Raz et al., 2005), reflecting the "first-in, last-out" model of the aging brain (Craik & Bialystok, 2008). As a consequence, cognitive control improves continuously throughout childhood and adolescence (Diamond, 2002; Huizinga et al., 2006; Kalkut et al., 2009; Reynolds et al., 2008; Shaw et al., 2006; see Diamond, 2013 and Doebel, 2020 for reviews) and is affected early in aging, by 55/65 years (e.g., Raz, 2000; Raz et al., 2005; West, 1996). On the other hand, representation is likely to be mediated by more posterior cerebral networks that tend to mature early (Casey et al., 2000; Ofen et al., 2007; and see Craik & Bialystok, 2006, for a review) and decline less and later with age than anterior cerebral structures (Dennis & Cabeza, 2008). Thus, representation develops from infancy to adulthood and remains relatively stable across aging, or can even be higher in old age (e.g. Park et al., 2002; Verhaegen et al., 2003). Note that according to the differentiation–dedifferentiation hypothesis (e.g., Baltes et al., 1980) which postulates that intellectual abilities are less differentiated at early ages, representation and control, although considered as independent in adulthood, could be more associated in childhood (see Doebel, 2020 and Li et al., 2004 for discussions of this point). One of the reasons for this relative interdependence is that each resource would rely on the other to develop, and in particular, the increase in knowledge with age could provide scaffolding for the development of control (Doebel, 2020).

The relationship between age-related neurocognitive modifications and performance in EM has been extensively studied, particularly in aging, in which executive function decline has been found to be closely associated with the decline in memory performance (e.g., Angel et al., 2010, 2016; Bouazzaoui et al., 2014; Taconnat et al., 2006, 2007, 2009; and see Buckner et al., 2006 for a review), and to a lesser extent, in child development (Ofen et al., 2007). However, how cognitive control and representation might account for differential memory changes has not been examined from a lifespan perspective.

Involvement of control and representation in episodic memory

Both the representation system (i.e., crystallized capacities, knowledge) and cognitive control (i.e. fluid capacities, such as working memory and executive functions) are determinants of EM. On one hand, the representation system, by providing a general understanding of the world, may give structure and meaning to the episodic memory system (Newcombe et al., 2011). Greater representation capacities would, therefore, enhance memory through richer and more elaborate encoding and retrieval cues, thanks to a better organizational structure (Salthouse, 2002) and to better distinctive processing (Rawson & Overschelde, 2008). Indeed, according to Tulving's model Tulving (2001), encoding in EM first requires the storage of knowledge in semantic memory. Using knowledge at encoding allows deep processing of the to-be-learned materials, which improves EM performance (Craik, 2002; Craik & Lockhart, 1972). On the other hand, intact control, in particular executive functioning (Moscovitch & Winocur, 2002), is vital to the performance of many tasks that rely on goal-directed strategic cognitive operations and coordination of multiple processes. Controlled processes, primarily underpinned by the frontal lobes, enable the use of controlled memory processes, particularly during encoding and retrieval (Ghetti & Fandakova, 2020 for a review). Notably, free recall, a resource-dependent memory task, relies heavily on cognitive control (Buckner, 2003; Moscovitch & Winocur, 2002; Parkin & Walter, 1992; Shallice & Burgess, 1991; Stuss, 1992; Velanova et al., 2007). Furthermore, according to Braver et al. (2001), control processes interact with the representation system by selecting existing knowledge that will act as an internal support for efficient information processing. The different changes in representation and cognitive control from early childhood to late adulthood raise the question of their respective contribution to EM over the lifespan.

Contributions of control and representation to episodic memory during childhood

Successful learning of new information involves its integration into existing knowledge (Coutanche & Thompson-Schill, 2014), and one of the most robust findings in the memory development literature is the effect of knowledge on children's memory performance (Bjorklund & Bernholtz, 1986; Roberstson & Köhler, 2007; Schneider et al., 1989, and see Bjorklund, 1987; Bjorklund & Schneider, 1996; Hernández Blasi et al., 2001; Ornstein et al., 2006; Schneider & Bjorklund, 1998; Schneider & Pressley, 1997 for reviews). According to Bjorklund (1987), the age-related increase in the knowledge base contributes to the development of children's EM, because knowledge improves the ease with which information stored in permanent memory can be activated, in turn improving the use of cognitive resources required for other cognitive operations, such as encoding and retrieval strategies. In line with this assumption, several studies have shown that children's prior knowledge substantially affects their choice of memory strategy and significantly influences memory performance (e.g., Robertson & Khöler, 2007; Schneider et al., 1989).

The relationships between EM and control, notably frontal/executive functions, which increase with age (e.g., Chevalier, 2015) have been also explored from a developmental perspective (see Ghetti & Fandakova, 2020, for a review). Control processes contribute to memory especially when the tasks require strategic behavior at encoding and/or retrieval (e.g., Ofen & Shing, 2013; Shing et al., 2010; Yu et al., 2018). This is the case for the free recall task (used in the present study), which has been found to depend on executive functioning (see Bouazzaoui et al., 2014 for an experiment in adults). An fMRI study by Ofen et al., (2007, and see Ofen et al., 2012 for a review) found that the improvement with age (from 8 to 24 years) in a picture recognition task was correlated with greater activation in the prefrontal cortex, confirming the role of this cerebral region, known to support executive functions, in EM in early childhood. Executive functions have also been found to be related to other aspects of EM in children, such as memory for the color of various objects (Cycowicz et al., 2001), the recall of the temporal and spatial contexts of information acquisition (Picard et al., 2012), or the recall of personal events (Picard et al., 2009).

Overall, these studies highlight the importance of both representation (knowledge) and cognitive control (executive functioning) in the development of EM across childhood. However, they do not tell us anything about the respective involvement of each resource, because none has examined the roles of the two resources in the same experiment. Because control and representation are less dissociated in childhood (e.g., Doebel, 2020 and Li et al., 2004), both could have an important contribution to memory performance in children.

Contributions of control and representation to episodic memory in aging

There is general agreement that EM performance declines with age (see Balota et al., 2000; McDaniel et al., 2008 for reviews). Many results suggest that the magnitude of age-related decline increases with the level of the task's strategic demands. For instance, age-related differences are greater in free-recall than in recognition tests (Craik & McDowd, 1987) and in explicit than implicit memory tasks (La Voie & Light, 1994; Isingrini et al., 1995; see Prull et al., 2000 for a review). These specific deficits match the environmental support hypothesis formulated by Craik (1983, 1986), which postulates that older adults have difficulty when they have to implement self-initiated cognitive processes (i.e. not driven by external cues, or without environmental support) to complete a memory task. This "aging memory" profile has been well-accounted for by the executive hypothesis (Raz, 2000; West, 1996), which postulates that because of their specific decline in executive functions, older adults have difficulty implementing the controlled, self-initiated processes that are required for memory performance. This assumption has been extensively corroborated by various studies showing that age-related differences in the performance of memory tasks relying on strategic processes are accounted for by a decline in executive functions (Angel et al., 2010; Bouazzaoui et al., 2013, 2014; Bryan et al., 1999; Crawford et al., 2000; Ferrer-Caja et al., 2002; Parkin, 1997; Taconnat et al., 2006, 2007, 2009).

While the decline of executive functions can be considered as a crucial cause of the age-related decline of EM, this may not be true for the representation component, because, unlike executive functions, it remains stable or even increases with age (e.g. Park et al., 2002; Verhaeghen et al., 2003). In contrast to the ample examination of the role of cognitive control in age-related EM decline (see above), few studies have examined the role of representations in EM performance in aging. Overall, they show a positive link between representations and EM measures in adulthood (Hedden et al., 2005; Meinz & Salthouse, 1998; and see Salthouse, 2002 for a review). Others studies found that representation was the sole contributor to EM performance in younger adults, whereas both control (assessed with executive function measures), as the main factor, and, to a lesser extent, representation, accounted for EM performance in older adults (Bouazzaoui et al., 2013; Guerrero-Sastoque et al., 2020). Other studies examining the role of expertise on memory performance have found that older adults with extensive knowledge in a particular domain exhibit less decline in memory for information related to this domain (e.g., Castel, 2007; Noice & Noice, 2006; Shimamura et al., 1995). Nevertheless, the amount of knowledge and its accessibility do not necessarily allow full compensation for the impairment in executive functions.

The current study

The main aims of this study were to show that different resources underlie EM development and decline across the lifespan, and that the respective contributions of control and representation vary at different ages. To that end, memory, control and representation were examined in seven groups of different ages, ranging from 8 to 80 years. In line with previous research, we expected to observe the classic developmental and aging patterns for memory, control and representation, namely, performance improving from childhood to adulthood, with EM and control declining from early adulthood and late adulthood, respectively (i.e., inverted U-shaped performance), and representation increasing up to adulthood and then stabilizing or increasing in old age. On the basis of the Control/Representation model proposed by Craik and Bialystok (2006), we predicted that the extent to which Representation (assessed here with knowledge measures) and Control (assessed here with executive function measures) account for memory performance would depend on age. More precisely, we expected that the association between Representation and EM would decrease gradually from childhood to the oldest age, while the role of Control would increase gradually from the youngest to the oldest individuals. Representation would play a greater role in explaining memory performance during development than during aging, while the reverse pattern would appear for Control (i.e., quadratic relationships). Thus, Analyses of variance (ANOVAs) were conducted to confirm the usual effects of age on EM, Control and Representation with planned comparisons to examine the differences between consecutive age groups. Then, correlational analyses were carried out to examine the associations between EM and Control, and between EM and Representation and then, the factors underpinning age-related changes in memory performance were examined with regression analyses. Finally, regression analyses were performed in each age group separately to test the idea that the contributions of Control and Representation to EM change gradually from early childhood group to the oldest age group, with Control contributing least in the youngest children and increasing across age, and Representation playing the greatest role in the youngest children and decreasing over the lifespan.

Methods

Participants

A total of 217 participants, divided into 7 age groups, were included in this experiment. There were two groups of children (younger, 4th grade level-primary school, aged 8–9.5 years, $N = 30$; older, 6th grade level-middle school, aged 10–11.3 years, $N = 31$), and two groups of adolescents (younger, 8th grade level-middle school, aged 12.3–14 years, $N = 31$; older, 11th grade level-high school, aged 15.5–16.8 years, $N = 31$). There were three groups of adults (31 young adults aged 20–39 years, 31 middle-aged adults aged 40–59 years, and 32 older adults aged 60–79 years). All the participants were volunteers and gave their signed consent, plus that of the parents and school authorities for the minors. Ethical approval for the research was obtained from the Psychology Department of Tours University. All aspects of this study were performed in accordance with the ethical standards set out in the 1964 Declaration of Helsinki.

Children and adolescents were tested at school. All the adults participants lived at home and were recruited from leisure clubs and the Senior Citizens' University. The older participants were screened on the Mini-Mental State Examination (MMSE; Folstein et al., 1975), with the cutoff threshold set at 27 points to minimize the risk of including people with preclinical dementia. Adult participants were interviewed individually to exclude any with a history of alcoholism, undergoing treatment for psychiatric illness, or taking psychoactive medication. Number of years of formal education, self-reported health—measured on a 5-point scale ranging from 0 (''poor health'') to 5 (''very good health'')—as well as anxiety and depression scores on the HADS (Hospital Anxiety and Depression Scale; Zigmond & Snaith, 1983) were controlled in the adult participants, because level of formal education may affect learning strategies, and because depression, generally found to be linked to self-evaluated health, is known to affect motivation to learn. The characteristics of each group are presented in Table 1. After the experiment, participants were informed about the general goal of the research. We determined the size of our sample on the basis of previous studies that investigated the development of episodic memory across lifespan. For instance, the mean number of participants for the nine age groups included in the study of Dikmen et al. (2014), who recently investigated episodic memory across the age range from 20 to 85, is 29.44. The sample size in recent studies investigating episodic memory across lifespan varied generally between 20 and 42 participants (e.g., Fandakova et al., 2013; Guerrero-Sastoque et al., 2020; Shing et al., 2008). The size of our sample ($N = 31, \pm 1$) is, therefore, in line with these studies.

Table 1 Means (and SD) of characteristics of the sample

	Groups						
	YC ($n=30$)	OC ($n=31$)	YAdo ($n=31$)	OAdo ($n=31$)	YA($n=31$)	M-A A ($n=31$)	OA ($n=32$)
Age (in years)	8.72 (0.32)	10.71(0.46)	12.36 (.48)	16.15 (.23)	28.13 (4.28)	48.71 (5.65)	70.18 (5.41)
Education level[a]	3 (0.00)	5 (0.00)	7 (0.00)	10 (0.00)	13.58 (1.28)	12.13 (2.39)	12.21 (1.62)
Self-reported health	4.70 (.46)	4.71 (.46)	4.64 (.49)	4.75 (.44)	4.25 (.77)	3.71 (0.97)	4.31 (.73)
HADS A[b]	–	–	–	–	5.70 (2.33)	4.32 (2.94)	6.94 (4.13)
HADS D[c]	–	–	–	–	5.84 (2.33)	3.52 (2.46)	6.78 (3.05)
MMSE[d]	–	–	–	–	–	–	28.03 (1.03)

YC Younger children, *OC* Older children, *YAdo* Younger adolescents, *OAdo* Older adolescents, *YA* Younger adults, *M-A A* Middle-aged adults, *OA* Older adults

[a]Mean number of years of education

[b]Hospital Anxiety/Depression Scale: Anxiety

[c]Hospital Anxiety/Depression Scale: Depression

[d]Mini Mental State Examination

Materials and procedure

Episodic memory (recall task)

Participants were shown once a list of 20 non-organizable common and frequent concrete nouns. The words were 5–8 letters long, with 2–3 syllables. Their age of acquisition was checked to ensure that the youngest children should know all the words (Lachaud, 2007). The stimuli were presented on a computer screen, for 3 s each with a 2 s interval between each item. All participants were told that they would be presented with twenty words one by one, that they should pay attention, because they should then try to recall them. After learning the word list, participants performed a letter-comparison task (X-O, Salthouse, 1990) for 45 s to avoid any recency effect at recall. In this processing speed task, participants were instructed to decide whether the two members of the letter pair were identical or not, and to tick the 'identical' or 'different' column accordingly. After that, they were asked to say out loud as many words as they could recall, and the recalled words were recorded by the experimenter. This avoided any writing difficulty, particularly in the children and older adults. At the end of learning and recall, participants relaxed for a few minutes before taking the remaining tests, which lasted about 40 min. At the end of the experiment, all the children were asked about their knowledge of the words. None of them said that there were words that they did not know or did not understand. The measure of episodic memory was the proportion of words correctly recalled. Note that false recall was not taken into account, because there was less than 1 false recall on average per group.

Control tasks

Three of the most commonly used executive tasks were used to assess cognitive control. They were chosen, because they can all be used from childhood to late adulthood. These tasks have already been used in the context of child development (e.g., Chelune & Baer, 1986 for the Wisconsin Card Sorting Test, Okuniewska & Maryniak, 2012 for the Stroop Test, and Lee et al., 2014, for the Trail Making Test) and aging (e.g., Taconnat et al., 2006), and all are sensitive to development and aging.

The Wisconsin Card Sorting Test was administered following the standard procedure (Heaton et al., 1993; Lezak, 1995). Participants had to match each of 128 cards containing multidimensional drawings with target cards according to one of three possible criteria (color, shape, and number of geometric patterns). The right criterion had to be inferred from the experimenter's feedback. Once the participant had sorted the cards correctly on 10 consecutive trials, the sorting principle changed. This test is a goal-oriented task with several possible scores believed to reflect executive functioning (Greve et al., 2005); the score we chose was the number of perseverative errors, which is the most sensitive to age effects and the most representative of the executive function factor (Bryan et al., 1999; Salthouse et al., 2002; Taconnat et al., 2006, 2007). Higher scores indicate poorer executive functions.

Stroop color-word Test (SCWT). Two subtests of the standard SCWT (Stroop, 1935) were used: color naming (Condition A, congruent trials), in which participants had to name the color of crosses (XXX), and color-word interference (Condition B, incongruent trials), in which they had to name the color of color-words while ignoring the printed word (e.g., the word "blue" written in red). Participants were instructed to name the colors aloud as quickly as possible, and the number of correct responses in 45 s was recorded for each condition. The score was the measure of interference, computed as follows: (Score A–Score B)/Score A (Li & Bosman, 1996). Higher scores indicate lower inhibition capacity.

The Trail-Making Test (TMT; Reitan, 1958) was used to measure flexibility. It is a paper and pencil task involving two parts: A and B. In part A, participants have to link letters in alphabetical order. In part B, they have to alternately link letters in alphabetical order and digits in ascending order (e.g., 1a2b3c, etc.). The stimuli are random arrays of 25 letters (part A) and of 25 letters and numbers (part B). In part A, the participant uses a pencil to connect the letters in alphabetical order. In part B the participant connects letter and number in alphabetical and numerical order, alternating between the letters and numbers. Performance was measured as the time spent to complete each part. A flexibility score was calculated with the following formula: (completion time part B—completion time part A/completion part A). According to Salthouse (2011), the simple difference (B–A) primarily reflects speed, and although the ratio measure does not completely eliminate the influence of speed, it does so to a much greater extent than the simple difference. Higher scores indicate lower flexibility ability.

To ensure that the highest scores corresponded to the best performance, all executive test scores were multiplied by (− 1).

Representation measures

To avoid any ceiling effect, and in contrast to the tests used to assess Control, the tests used to assess Representation were adapted to the participants' age. Thus, the Vocabulary and Information subtests of two tests were used to capture Representation abilities, the WISC-IV (children, adolescents) and the WAIS-R (adults).

The vocabulary subtest of the WISC-IV (Wechsler et al., 2012) consists of 31 words that the children and adolescents were asked to define (e.g., "what is an umbrella?"). The WAIS-R Vocabulary subtest (Wechsler, 2008) consists of 35 words that the adults had to define (e.g., "What does the word 'fiction' mean?"). For both tests, the score is the sum of correct answers (two points for a complete definition and one point when the definition is incomplete).

The information test used for the children and adolescents consists of 33 questions about general knowledge (e.g., "What are the four seasons?"). The test for the adults comprised 29 questions (e.g., "How many months are there in a year?"). For both tests, the score is the sum of correct answers (one point for each correct response).

Because the vocabulary and information subtests of the two scales do not have the same number of items, performance was measured by dividing the number of items completed by the total number of items (ratio). For both tests, higher scores indicate better performance.

To reduce the data, a principal component analysis (PCA) on the scores obtained in the five tasks was performed on the whole sample to test the dissociation between cognitive control (executive functions) and representation (Vocabulary and Information). Two components with an eigenvalue greater than one were extracted. The number of perseverative errors on the Wisconsin Card Sorting Test, the inhibition score of the SCWT, and the flexibility score of the TMT loaded mainly on the first factor, whereas Vocabulary and Information loaded on the second factor. These analyses were also conducted in each group separately to ensure that the same factor structure appears in all groups. The results of these analyses are presented in Table 2. The five tests are distributed on two factors that can be identified as a "control" factor (Factor 1), on which executive tests (WCST, SCWT and TMT) have a higher load, and a representation factor on which Vocabulary and Information tests have a higher load. Regarding the TMT, the loading of this test was distributed on the two factors (with non-significant loading) in the two adolescent groups. However, as the PCA solution fitted the others similarly, we have chosen to keep this test in the analyses to calculate a similar control index for all groups. The important cognitive transitions that take place during adolescence may explain this pattern of results.

Based on the dissociation produced by the PCA, we computed two composite scores (Control and Representation) for each participant, corresponding to the means of the standardized (z) scores on each task.

Data analysis

Analyses were conducted to address four sets of questions. First, to test our prediction that performance in EM (recall) and control would follow an inverted U-shaped trajectory across the lifespan, while representation would show continuous growth from childhood to late adulthood, separate analyses of variance (ANOVAs) (with the 7 Age Groups as between-participants factor) were conducted on the recall scores, and on the Control and Representation indexes. Moreover, planned comparisons on recall, Control and Representation indexes were performed to examine the differences between consecutive age groups, were also performed on these measures. Second, after having examined the relationships between Representation and Control in the whole sample and in each group, correlational analyses were computed to examine the links between EM and Control and between EM and Representation, for the whole group, and for each

Table 2 Loading extracted from the principal component analysis (PCA)

Factors	Young children		Older children		Young adolescents		Older adolescents	
	1	2	1	2	1	2	1	2
WCST	**0.84**	0.11	**0.77**	0.33	**0.78**	0.32	**0.88**	0.04
SCWT	**0.84**	0.07	**0.80**	0.32	**0.92**	0.02	**0.68**	0.31
TMT	**0.89**	− 0.01	**0.70**	0.24	0.30	0.16	0.34	0.48
Vocabulary	0.32	**0.90**	0.05	**0.89**	0.13	**0.92**	0.13	**0.70**
Information	− 0.13	**0.95**	0.39	**0.69**	0.11	**0.87**	0.10	**0.70**
% of variance accounted	46.61	34.75	35.70	31.27	36.14	30.56	28.86	24.36
Factors	**Young adults**		**Middle-aged**		**Older adults**		**Whole sample**	
	1	2	1	2	1	2	1	2
WCST	**0.87**	0.16	**0.85**	0.03	**0.71**	0.45	**0.85**	0.05
SCWT	**0.84**	0.35	**0.59**	0.22	**0.87**	0.09	**0.82**	0.04
TMT	**0.60**	0.32	**0.71**	0.36	**0.88**	0.11	**0.68**	0.20
Vocabulary	0.10	**0.87**	0.21	**0.87**	0.11	**0.87**	0.17	**0.91**
Information	0.15	**0.73**	0.22	**0.86**	0.16	**0.80**	− 0.02	**0.94**
% of variance accounted	32.32	36.13	31.71	35.69	29.31	27.27	38.69	35.62

Significant loadings in bold

WCST Wisconsin Card Sorting Test, *SCWT* Stroop Color-Word Test, *TMT* Trail Mating Test

group separately. Third, we tested for moderated regression, focusing particularly on the interaction of Age (quadratic) × Control and Age (linear) × Representation on EM free recall scores to examine the factors underpinning age-related changes in memory performance. Finally, to analyze the role of Control and Representation in EM performance in each age group, regression analyses were conducted on recall performance with age used as a continuous variable.

Results

Episodic memory

Table 3 summarizes the mean scores for memory, control and representation measures at each age.

A one-factor (Age Group) ANOVA performed on the proportion of recalled words showed a statistically significant main effect of Age group, $F(6,210) = 14.79$, $\eta_p^2 = 0.29$, $p < 0.001$, corresponding to an inverted U-shaped curve (see Fig. 1), as confirmed by a quadratic effect, $F(1, 210) = 55.14$, $\eta_p^2 = 0.21$; $p < 0.0001$.

Table 3 Mean performance, SD (in parentheses) and 95% confidence intervals for recall performance, Control index and Representation index by age group

Groups	YC ($n=30$)	OC ($n=31$)	YAdo ($n=31$)	OAdo ($n=31$)	YA ($n=31$)	M-A A ($n=31$)	OA ($n=32$)
Recall (Proportion)	0.32 (0.07)	0.35 (0.08)	0.52 (0.12)	0.57 (0.09)	0.57 (0.14)	0.54 (0.12)	0.42 (0.16)
95% CI	[0.29; 0.34]	[0.32; 0.38]	[0.47; 0.57]	[0.50; 0.64]	[0.52; 0.63]	[0.47; 0.60]	[0.35; 0.49]
Control	− 0.12 (0.72)	0.21 (0.78)	0.45 (0.60)	0.56 (0.45)	0.42 (0.48)	− 0.53 (0.47)	− 0.89 (0.92)
95% CI	[− 0.39; 0.14]	[− 0.01; 0.43]	[0.32; 0.61]	[0.47; 0.73]	[0.24; 0.60]	[− 0.70; − 0.36]	[− 1.40; − 0.73]
Representation	− 1.59 (0.31)	− 0.59 (0.39)	− 0.09 (0.36)	− 0.02 (0.35)	0.61 (0.45)	0.78 (.61)	0.88 (.63)
95% CI	[− 1.71; − 1.41]	[− 0.73; − 0.45]	[− 0.24; 0.02]	[− 0.15; 0.10]	[0.41; 0.77]	[0.59; 1.03]	[0.65; 1.11]

YC Younger children, *OC* Older children, *YAdo* Younger adolescents, *OAdo* Older adolescents, *YA* Younger adults, *M-A A* Middle-aged adults, *OA* Older adults

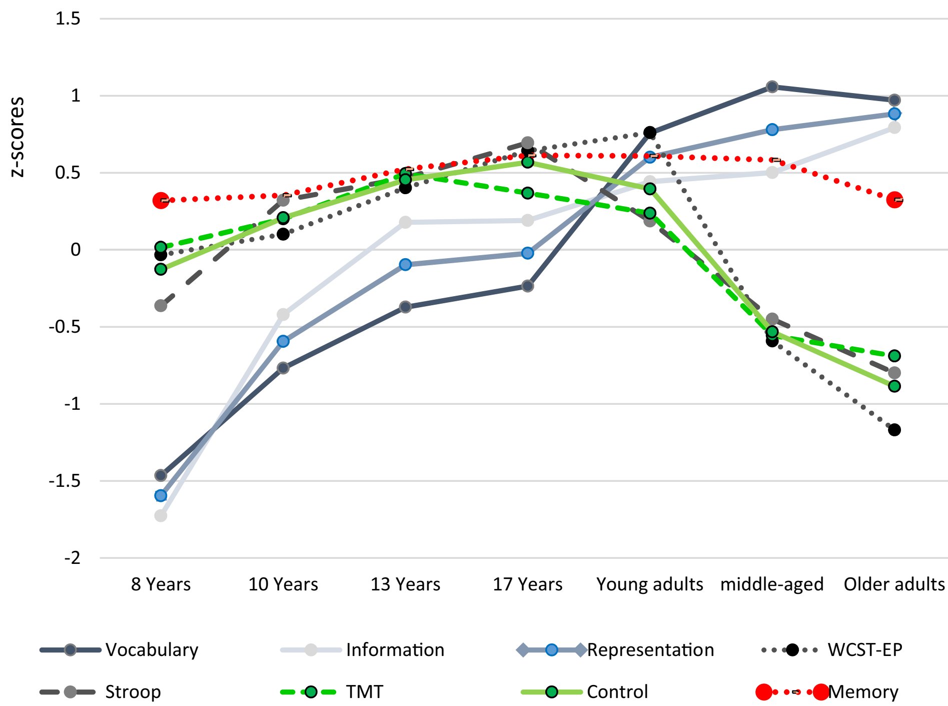


Fig. 1 Cognitive performance and scores to the composite indexes across age groups (*z* scores)

Table 4 Planned comparisons between two consecutive age groups for Recall, Control index, and Representation index

	YC vs. OC $F(1,210)$	OC vs. YAdo $F(1,210)$	YAdo vs. O Ado $F(1,210)$	O Ado vs. YA vs $F(1,210)$	YA vs. M-A A $F(1,210)$	M-A A vs. OA $F(1,210)$
Recall	< 1, ns –	12.84, $p<0.001$ $\eta_p^2=0.06$, $d=0.40$	1.58, ns –	< 1, ns –	< 1, ns –	9.65, $p<0.001$ $\eta_p^2=0.05$; $d=0.64$
Control	4.63, $p=0.05$ $\eta_p^2=0.03$; $d=0.49$	2.89; $p=0.09$ $\eta_p^2=0.02$; $d=0.51$	< 1, ns –	< 1, ns –	38.33, $p<0.001$ $\eta_p^2=0.15$; $d=1.98$	5.34, $p<0.05$ $\eta_p^2=0.03$; $d=0.38$
Representation	63.82, $p<0.001$ $\eta_p^2=0.23$; $d=2.28$	16.61, $p<0.001$ $\eta_p^2=0.07$; d = 1.30	< 1, ns –	25.88, $p<0.001$ $\eta_p^2=0.11$; $d=1.58$	9.95, $p<0.001$ $\eta_p^2=0.05$; $d=0.37$	< 1, ns –

YC Younger Children, *OC* Older Children, *YAdo* Younger Adolescents, *OAdo* Older Adolescents, *YA* Younger Adults, *M-A A* Middle-aged Adults, *OA* Older Adults, *ns* not significant

Furthermore, planned comparisons showed that, although the effect sizes were rather small, memory performance increased from the older children to the older adolescents, remained stable until middle age, and finally decreased in old age (see Table 4 for the outcomes of these analyses).

Control

As expected, performance on the Control measures and the Control index both showed inverted U-shaped profiles (see Fig. 1). Because the three measures used to assess Control loaded on the same factor, analyses were only conducted on the composite index of Control. The ANOVA showed a significant main effect of Age Group, $F(6,210)=26.29$, $p<0.0001$, $\eta_p^2=0.43$. A polynomial analysis on the entire set of data revealed that performance followed a significant quadratic trend, $F(1,210)=100.45$, $p<0.0001$; $\eta_p^2=0.33$. Planned pairwise comparisons showed that the Control index score increased from the youngest children to the younger adolescents, remained stable up to young adulthood, and then progressively decreased up to the oldest age (see Table 3 for the outcomes of these analyses).

Representation

As expected, performance on the Representation measures and the Representation index increased across age (see Fig. 1). Because the two measures used to assess Representation loaded on the same factor, analyses were only conducted on the computed index of Representation. The ANOVA showed a significant effect of Age Group, $F(6,210)=104.76$, $p<0.0001$, $\eta_p^2=0.75$. Planned pairwise comparisons showed that the Representation index increased from early childhood to middle age, and then remained stable (see Table 3 for the outcomes of these analyses).

Factors underlying episodic memory performance across age

Correlational analyses (Bravais–Pearson correlations)

First, the relationships between the two composite indexes of Control and Representation, were examined in the whole sample and in each group separately. The two indexes were positively correlated in the whole group ($r=0.23$, $p=0.001$). In the two groups of children, the two measures were positively (but marginally) correlated ($r=0.35$, $p=0.05$ in the young children and $r=0.31$, $p=0.078$ in the older children). In the other groups, the correlations between Representation and Control did not reach significance (all ps > 0.20).

Then, to examine the relationships between Memory and Control, and between Memory and Representation, Bravais–Pearson correlation analyses were performed to test (i) the association between the recall scores and the Control index and (ii) between recall scores the Representation index. These analyses were performed in the whole group and in each age group separately. Correlations between Representation and recall and between Control and recall are depicted in Fig. 3a, b, respectively, and the outcomes of these analyses are presented in Table 5. The analyses indicate that both Control and Representation are associated with memory ($r=0.48$ and $r=0.34$, respectively). The results from the analyses conducted in each age group separately showed different patterns in the different age groups. In the younger children (8–9 years) both the Control and Representation indexes were significantly related to recall performance, with Representation being more strongly associated with recall than Control ($r=0.81$ vs. $r=0.39$, respectively). In the older children (10–11 years) and both groups of adolescents (12–14 years and 15–17 years), only the Representation index was significantly correlated with recall performance ($r=0.67$ in the older Children, $r=0.57$ in the younger adolescents and $r=0.46$ in the older adolescents), suggesting a limited association between Control and EM at these ages. In the young adults (20–39 years), both Representation and Control indexes were correlated with recall, and at the same degree ($r=0.41$ vs. $r=0.39$, ns). For the middle-aged adults (40–59 years), both Representation and Control indexes were correlated with recall, also at a similar level ($r=0.32$ vs. $r=0.51$, ns). For the older adults (60–79 years), both Representation and Control indexes were correlated with recall, the correlation being lower for Representation than for Control ($r=0.36$ vs. $r=0.80$), suggesting a higher implication of Control in EM in the oldest participants.

Comparisons of correlation coefficients corresponding to the link between Representation and recall on one hand and between Control and recall on the other hand, provided interesting results (right column of Table 5). They indicate that (1) in the whole group, representation and control are both associated with memory in an equivalent way, (2) representation is stronger associated with memory than control in the youngest ages, up to the end of adolescence, (3) from the early stage of adulthood up to middle age, representation and control are of equivalent importance, and (4) that in the older adults, control is more associated with memory than representation.

Representation was correlated with recall in the whole group and in each group analyzed separately. Correlations seemed greater in the younger groups than in the older groups but no significant difference appeared when two consecutive age groups were compared (all ps > 0.1). However, when contrasting more distant age groups, the following differences emerged: Young children vs. Older adolescents $p=0.022$; Young children vs. Young adults: $p=0.013$;

Table 5 Correlations (and comparisons of correlation coefficients) between the recall scores and cognitive resources in the whole group, and each age group

Groups (*N*)	Representation	Control	Representation vs. Control (Hotelling–Williams test)
Whole group (217)	0.48***	0.34***	1.39, $p=0.16^{ns}$
Young children (30)	0.81***	0.39*	7.09, $p<0.001$***
Older children (31)	0.67**	0.17^{ns}	2.94, $p=0.02$*
Young adolescents (31)	0.57***	0.27^{ns}	2.84, $p=0.02$*
Older adolescents (31)	0.46**	0.22^{ns}	1.36, $p=0.18^{ns}$
Young adults (31)	0.41*	0.39*	0.56, $p=0.58^{ns}$
Middle-aged adults (31)	0.32*	0.51**	1.7, $p=0.29^{ns}$
Older adults (32)	0.36*	0.80***	2.88, $p<0.002$**

ns not significant

*$p<.05$

**$p<.01$

***$p<.001$. Correlations corrected with Bonferroni test

Young children vs. Middle-aged: $p = 0.043$; Young children vs. Older adults $p = 0.007$. This suggests that the association between Representation and recall is particularly higher in the young children group than in the other groups.

Control was associated with recall only in the whole sample, in the young children and in the adults groups. No association between these two measures was significant in the older children and in the adolescent groups. However, as found for Representation, no significant difference appeared when two consecutive groups were compared (all $p < 0.1$). Comparisons between more extreme groups revealed significant differences: Young children vs. Older adolescents $p = 0.026$; Young children vs. Older adults $p = 0.004$; Older children vs. Older adults $p = 0.008$; Young adolescents vs. Older adults $p = 0.002$; Older adolescents vs. Older adults: $p = 0.001$; Young adults vs. Middle-aged: $p = 0.039$: Young adults vs. Older adults p = 0.013, globally indicating that the association between Control and memory decreases progressively from childhood to adulthood, and then increases from the young adult group to the older adults group.

Regression analyses

To determine the best predictor of memory performance, hierarchical regression analyses using the Representation and Control indexes and Age as a continuous variable were performed on recall. Results revealed that Representation predicted 25% ($p < 0.001$) of the variance of recall score alone and that Control predicted 22% ($p < 0.001$) of the variance after controlling for Representation. After controlling for both cognitive resources, Age^2 (quadratic) added 1% to the variance ($p = 0.011$).

In addition, two multiple regression analyses were conducted to determine whether or not the relationship between (1) Control and Recall depends on Age, and whether or not the relationship between (2) Representation and Recall depends on Age. In the first model (1), Control, Age^2 (quadratic) and Control × Age^2 (quadratic) interaction were entered in the equation as predictive factors and recall score as dependent variable. Results revealed that Age^2 (quadratic) and Control had significant direct effects on recall score ($\beta = 0.40$, $t = 5.01$, $p < 0.001$, 95% CI [0.24;0.56] and $\beta = 0.32$, $t = 3.50$, p < 0.001; 95% CI [0.14;0.50], respectively), and that the interaction term, Age^2 × Control, was also significant ($\beta = 0.37$, $t = 3.67$, $p < 0.001$; 95% CI [0.17;0.57]). In the second model (2), Representation and Age (linear) and Representation × Age (linear) interaction were entered in the equation as predictive factors and recall as dependent variable. The results showed that Age and Representation had direct effects on recall score ($\beta = -0.37$, $t = -4.61$, $p < 0.001$; 95% CI [− 0.53;− 0.21]; $\beta = 0.97$, $t = 10.17$; $p < 0.001$; 95% CI [0.78;1.15]); the interaction between Age and Representation was also significant ($\beta = -0.27$; $t = -2.53$, $p < 0.05$; 95% CI [− 0.48;− 0.06]).

Together, these analyses revealed that direct effects of cognitive resources, control and representation, are not enough to account for the variance of recall score. Significant interactions between cognitive resources and Age suggest that Age affects the relationships between cognitive resources and recall performance. Regression model for representation, control and recall scores, presented in Fig. 2, suggest that age affects the direction and strength of the relation between cognitive resources and recall in the way that relationship between Representation and recall is high during childhood, adolescence and in young adults then becomes lower in middle-aged and older adults for which relationship between control and recall becomes higher than for the younger groups. Association between recall and Representation, and between recall and Control in each age group are depicted in Fig. 3a, b, respectively.

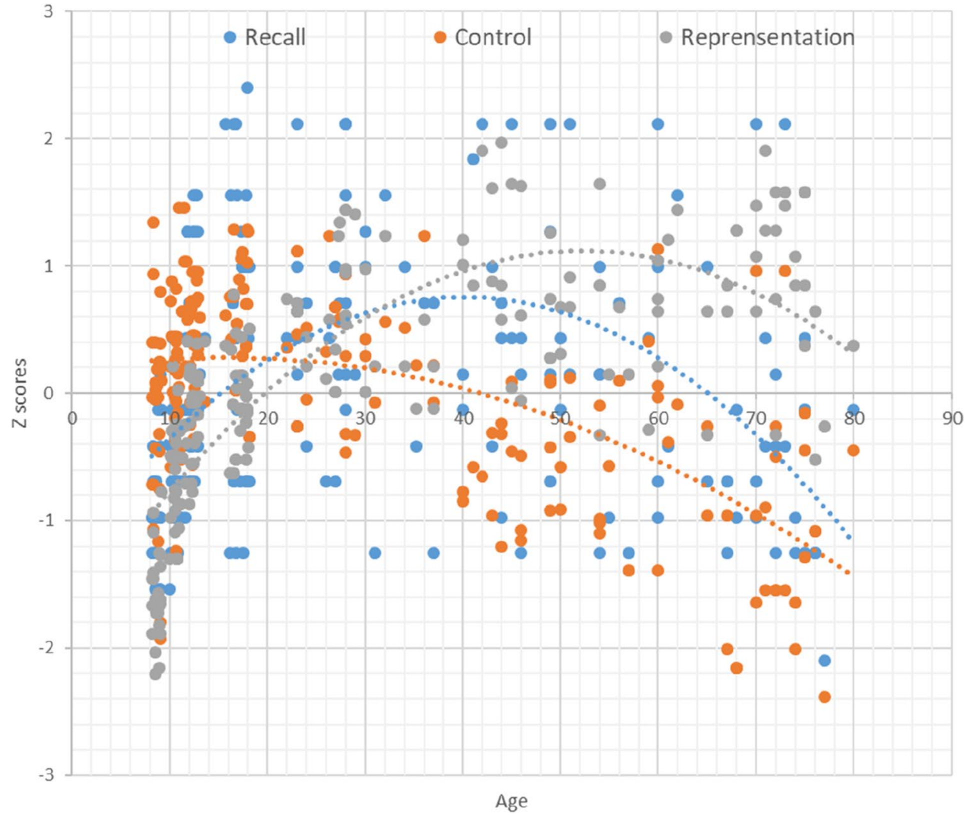
Finally, to specify the involvement of Control and Representation in episodic memory in each age group, we conducted regression analyses on the recall scores with Control and Representation entered in the analyses. A clear picture emerged across the different age groups. As shown in Fig. 4, the percentage of variance in recall performance explained by Representation decreased with age, from 53% in the youngest group to 9% in the oldest group. Conversely, the percentage of variance explained by Control became progressively greater with age, from 14% for the youngest group to 42% for the oldest group. An exception to this finding was that Control accounted more for the recall performance of the younger children than that of the older children and adolescents.

Overall, these results confirm that Representation is more important for the memory of the youngest participants, whereas Control is a crucial predictor of the memory performance of the oldest adults.

Discussion

The originality of this study was to deal primarily with the cognitive mechanisms underlying age-related differences in memory performance over the lifespan and in different age groups separately. The current research was specifically designed to test the Control/Representation framework of cognitive development across the lifespan proposed by Craik and Bialystok (2006, 2008). The study yielded several interesting and novel findings, and globally corroborated our predictions. In addition to confirming the classic effects of age on memory (free recall), control (executive functions) and representation (vocabulary and information), our results show that the improvement in recalling a word

Fig. 2 Scatter plots and non-linear (quadratic) regression lines for Recall, Control and Representation scores (centered reduced)



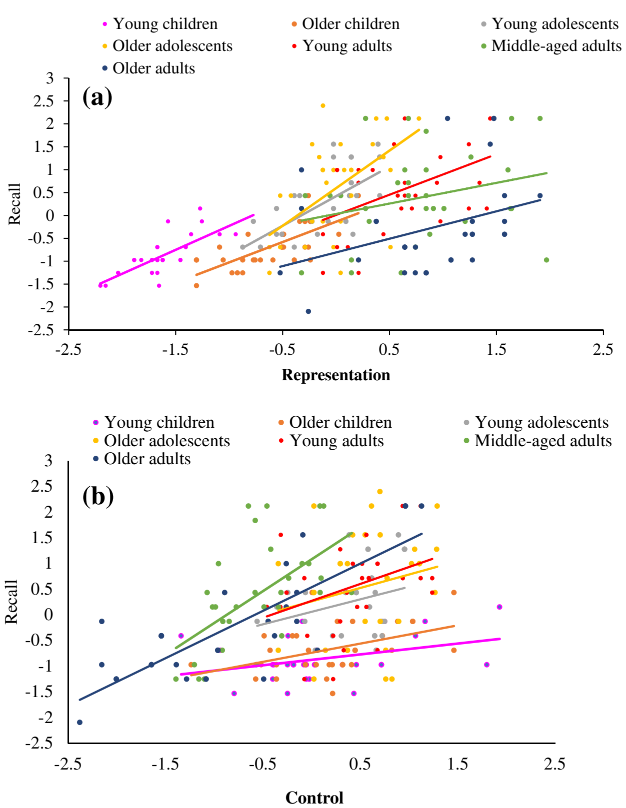


Fig. 3 a Association between Representation and Recall in each age group. b Association between Control and Recall in each age group

list from childhood to adulthood and its decline during aging are not sustained by the same cognitive mechanisms. More precisely, while the role of representation decreases across age groups, that of Control increases (see Fig. 4); overall, knowledge is thus crucial during childhood and control is crucial in adulthood.

Age effects on recall, control and representation

As expected, and in line with previous studies (e.g., Gathercole, 1998; Ghetti & Angelini, 2008; Newcombe et al., 2007), our results show that word recall increases from childhood to adolescence. They also show no significant difference between the performance of the older adolescents and that of the younger adults, suggesting that EM performance, assessed here by recall of a word list, is optimal at the end of adolescence (mean age 17 years). Moreover, memory performance remained stable up to middle age (mean age 48 years). Few studies have explored memory in middle age, age-related memory change mostly being examined by comparing young adults, generally 20–40 years, and older adults, generally over 60 years. In a previous study, Singh-Manoux et al. (2012) found a significant decrease in memory performance in middle age, contrary to our findings. This discrepancy might come from methodological differences in our respective designs (i.e., longitudinal design vs. cross-sectional design). It could also come from

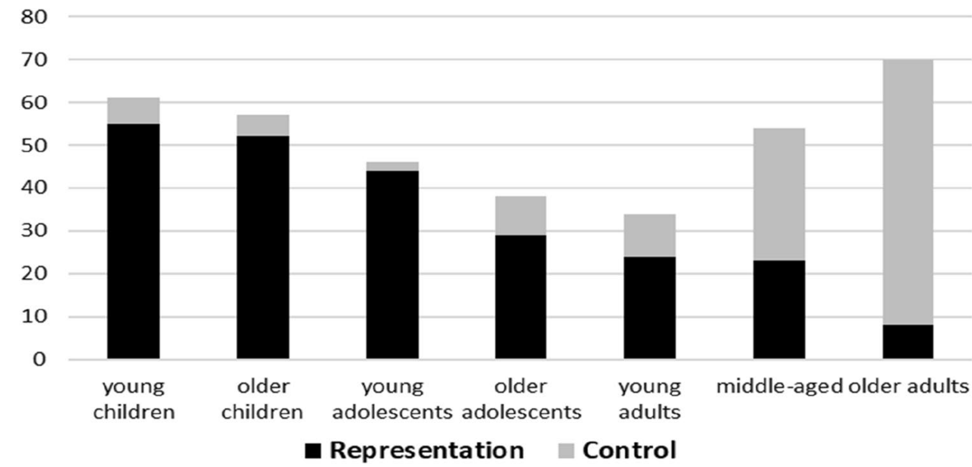


Fig. 4 Percentage of variance of memory performance accounted for by Control and Representation in each age group

the MMSE cutoff used in the present study (27/30), which may have resulted in middle-aged and older adults groups with (high) cognitive levels that are not representative of the aging population, by contrast to the sample examined in Singh-Manoux et al.'s (2012) study.

Last, memory scores were higher in the youngest than in the oldest adults, in line with the literature (Balota et al., 2000; McDaniel et al., 2008).

The measures of Control, as well as the composite Control index, showed the expected inverted U-shaped pattern as illustrated in the Fig. 1, corroborating results in the literature. Because this index was computed from scores of tests measuring executive functions, this pattern corresponds to the increase in executive functions across childhood (e.g., Chevalier, 2015; Diamond, 2013) and their decline in old age (e.g., Raz, 2000). During aging, Control index scores decreased between younger and middle-aged adults, and between middle-aged and older adults, suggesting a significant decline of control from early adulthood onward. Turning to the Representation measures, performance showed the expected continuous increase from childhood to middle age, followed by stability up to late adulthood. These results are in line with previous studies showing that knowledge increases from early childhood to old age (e.g., Robertson & Köhler, 2007; Ornstein et al., 2006 in childhood; Bouazzaoui et al., 2013; Craik & Bialystok, 2006; Park et al., 2002; Verhaegen et al., 2003 in adulthood).

Association between cognitive resources and recall according to age group

To assess the relationships between Control and Representation with memory, three tests supposed to tap Control (executive tests: WCST, SCWT and TMT) and two tests supposed to tap knowledge, or Representation (Information and Vocabulary) have been used. The scores to these tests have been submitted to a PCA for the whole group and for each group separately to confirm that they correspond to two factors, as suggested by the literature. The PCA solution fitted all groups similarly, the five tests being distributed on two factors identified as "Control" and "Representation". However, in adolescents, the TMT was distributed on the 2 factors, with no significant loading onto any of these factors. Thus, the Control factor is less clear for the adolescents. Moreover, correlational analyses revealed that Control and Representation were not correlated, except in the Children groups, where the correlations approached significance. Although the correlations between Representation and Control were only marginally significant in the children groups, perhaps due to relatively small samples, these results are in accord with the idea that intellectual abilities are not differentiated at early ages of life (Doebel, 2020; Li et al., 2004), and then become dissociated later (the correlation were not significant from adolescence to adulthood) (i.e., differentiation–dedifferentiation hypothesis, Baltes et al., 1980).

The Control Index was associated with memory in the whole sample, as well as in the young children groups (8 years) and in the three adults groups (20–80 years), but not in the older children or adolescents. Comparisons of the correlations between Control and Memory across groups showed that these correlations were significantly higher in the young children group than in the other children and adolescents groups; in the adults groups, the correlations were significantly higher in the older group than the other groups of adults. Thus, except for the youngest group, Control was more strongly correlated with memory performance in the adults groups. Globally, this is in line with a number of studies that have highlighted the importance of control, assessed here with executive functions tests, in memory performance. Notably, it corroborates the "working with memory" hypothesis of frontal lobe function developed by Moscovitch and Winocur (1992), which postulates that executive functions contribute to strategic processes mediating memory functioning. Control processes manage knowledge (e.g., Ghetti

& Fandakova, 2020) and allow initiating efficient strategies to attain a memory goal. The free-recall task used in this study is a memory task requiring heavily self-initiated retrieval strategies, particularly dependent on control capacities (Craik & McDowd, 1987). The involvement of control in a free-recall task is thus in line with work showing the relationship between these abilities and memory, especially in aging (e.g., Bouazzaoui et al., 2014; Taconnat et al., 2009, and see Guerrero-Sastoque et al., 2020, with a cued-recall task). In the adolescent groups, the lack of significant correlations between Control and EM is surprising. It could be suggested that at these ages, EM may function relatively automatically, i.e., without the necessity of relying on control process. However, it should be noted that the Control index is less clearly defined for both groups of adolescents than for all the other groups, because one of the executive functions test, the Trail Making test, did not load strongly on the Control factor (see Table 2). This specificity of the adolescents' control index may have prevented the detection of a correlation between control and memory in the adolescents. An alternative explanation would be that the relatively small samples do not allow significant correlations to appear. In the context of the present study, this finding is difficult to interpret and further research is needed to understand its origin.

With regard to Representation, the present results showed that memory was associated with the Representation index in all groups. Comparisons across groups of the correlations between Representation and Memory showed that these correlations were significantly higher in the children groups than in the other ones. This suggests that Representation is important for verbal EM throughout the lifespan, in particular in the youngest ages. Representation, assessed by vocabulary and information tests as in the present study, has been found to be associated with verbal memory performance in children (e.g., Ofen & Shing, 2013; Robertson & Khöler, 2007; Schneider et al., 1989 for a review), young adults (e.g., Bouazzaoui et al., 2013; Hedden et al., 2005) and older adults (e.g., Bouazzaoui et al., 2013; Guerrero-Sastoque et al., 2020; Hedden et al., 2005). Representation constitutes the basis of knowledge that is required for the implementation of encoding and retrieval strategies (e.g., Bouazzaoui et al., 2014). The integration of new incoming information is easier when it can be linked to prior knowledge, which promotes deeper encoding and thus better storage and retrieval in children (e.g., Ornstein et al., 2006; Schneider & Pressley, 1997 for reviews) and in adults (e.g., Bouazzaoui et al., 2013; Bransford & Johnson, 1972; Craik & Bialystok, 2006, 2008; Newcombe et al., 2011; Salthouse, 2002, and see Brod et al., 2013, for a review). Knowledge increases not only the possibility of organisational processing but also distinctive encoding (Rawson & Overschelde, 2008), which is important for free-recall tasks.

Thus, overall, the pattern of correlations differs in each age group. In the younger groups, correlations between memory and Representation were higher than between memory and Control, while the reverse profile was observed in the adult groups. Interestingly, the pattern of correlations in the adolescent groups was closer to that of the children than to that of the young adults. In other words, whereas their EM performance was equivalent to that of the young adults, it was associated with Representation and not Control. However, this pattern of results should be considered while keeping in mind that the control index in adolescents is not clearly defined. Finally, because Control and representation are less differentiated in the children groups, greater or lower association between these resources and memory score should be interpreted with caution.

Predictors of age-related difference in memory performance

The novelty of this study was that it assessed the contribution of both Control and Representation in EM. In this way, our results revealed that when both resources are taken into account, it is Representation that is crucial to EM performance in the early years, until the end of adolescence, while in adulthood, in particular in the older adults, Control is the first predictor of EM performance. Regression model for representation, control and recall scores, showed the direction and strength of the relation between cognitive resources and recall were different between age groups. The relationship between Representation and recall was important during childhood, adolescence and in young adults, but then became lower in middle-aged and older adults. By contrast, in the older groups, relationship between control and recall was higher than in the younger ages. As expected, and in accord with the results of the moderated regression, the regression analyses conducted on each age group separately showed that factors underlying development and aging of EM were different, in line with our predictions. In the children and adolescents groups, only Representation predicted the age-related differences in memory performance. Globally, these results support the existing literature showing that the representational system modulates EM in children (e.g., Bjorklund, 1987). However, no study has yet taken into account both resources (i.e. Control and Representation) in a single experiment to explore which provides the greatest support to EM in specific age groups. The present results showed that Representation was always either the main or the sole predictor of memory performance, but its contribution decreased with age, from 53% in the youngest children (8–9 years) to 31% in the oldest adolescents (15–17 years). Therefore, memory performance improves mainly because knowledge improves. Episodic memory and semantic memory could even represent similar functions in the young children (see Ofen & Shing, 2013, for a discussion about this point). Knowledge is the basis for verbal memory functioning, and control processes exploit this knowledge to optimize memory performance. Before knowledge has reached a substantial level, control does not seem critical in memory performance. The present results may reflect a shift in the kind of strategies used with age: from less to more cognitive control-demanding ones. Previous studies showed that children do not use memory strategy spontaneously to improve their performance before about 10 years (e.g., Lovett & Flavell, 1990). This suggests that metacognitive skills, which are still developing during adolescence (Bjorklund, 1989; Schneider & Pressley, 1997; Siegler, 1986), are not efficient enough to enable children to implement appropriate strategies when they learn a word-list. It is, therefore, quite clear that knowledge plays a greater role than cognitive control in memory performance during middle childhood and early adolescence, at least for tasks, where performance relies on both knowledge and self-regulated strategies, as the free recall task.

Furthermore, in our sample, the youngest children had the lowest levels in both Control and Representation, and Control accounted significantly for EM performance. An alternative possible explanation of this unexpected result, which does not fit with Craik and Bialystock's Control/Representation model, is that the youngest children used all their resources, including Control and Representation, to perform the memory task as well as possible, allowing them to attain the same level of performance as the older children. This suggestion seems particularly pertinent as we used a difficult, resource-demanding free-recall task to assess memory.

From early to late adulthood, Control significantly explained the effect of Age group on memory performance, while knowledge did not contribute to this effect. This result supports Craik and Bialystock's model. This is also in line with the executive hypothesis of cognitive aging (Raz, 2000; West, 1996) which predicts that age-related memory loss originates from the decline in executive functions associated with aging. It is also consistent with the prediction of the Control/Representation model, which postulates the increasing importance of Control on memory in aging. The regression analyses conducted in each age group separately yielded further interesting information. Overall, the contribution of Representation to memory performance decreased from young adulthood to old age, while the reverse was observed for Control. The contribution of Representation to memory performance was significant for each age group, in accord with previous studies (e.g., Hedden et al., 2005; Meinz & Salthouse, 1998; Salthouse, 2002), but decreased with age, from 27% in the younger adults, 21% in the middle-aged, to 10% in the older adults. By contrast, the involvement of control in EM increased with age, explaining, respectively, 14%, 26%, and 42% of the variance in memory scores in the young, middle-aged and older adults. These results corroborate those of previous studies showing that the level of executive functions (i.e., Control) used for recall is greater in older than in younger adults (Bouazzaoui et al., 2013, 2014). The results are also in line with the general hypothesis proposed by some authors that advancing age is associated with a general shift from automatic to controlled forms of processing (Bouazzaoui et al., 2013, 2014; Craik & Rose, 2012; Greenwood & Parasuraman, 2010; Park & Reuter-Lorenz, 2009), suggesting that memory processes could become less automatic and require more control with age. Executive functions might thus compensate for a decline in EM, the older adults with the highest executive level having the best EM performance.

A new finding of the present study is that EM performance remains stable up to middle age and is modulated by both Control and Representation in this group. Interestingly, EM performance in the middle-aged group was statistically equivalent to that of the younger adults, and slightly better than that of the older adults. Scores on the Representation index were higher in the middle-aged group than in the younger adult group, but equivalent to that of the older group, whereas for the Control index, the scores of the middle-aged group were lower than those of the younger group but higher than those of the older group. The pattern seen in our middle-aged group was intermediate between those of the younger and the older adults, with Representation being less involved than in the younger group but more than in the older group, while Control was involved more than in the younger group but less than in the older group. Moreover, Control and Representation were similarly involved (respectively, 26% and 21%, $p < 0.001$ each), although Control appeared to be the first predictor of memory performance, as in the older group. The distribution pattern of the predictors of EM performance in the middle-aged participants suggests that to attain a similar EM performance to that of the younger adults, they had to rely significantly on both Representation and Control resources, and more on their Control processes (which are lower) to manage their knowledge (which is higher).

This study was the first empirical test of the Craik and Bialystok's (2006, 2008) Control/Representation model of cognitive development in a life span sample. In sum, our results are in line with the predictions of this model, and show how the contributions of Control and Representation to EM performance change over age, suggesting that memory aging is not simply 'development in reverse' and that age-related differences over the lifespan are both quantitative and qualitative. Interestingly, our results show that Representation played a greater role in EM in childhood and up to early adulthood, but that it continued to contribute to EM performance throughout life, even though its contribution decreased with advancing age. By contrast, Control modulated EM performance mainly among the oldest participants, but also, to a lesser extent, among the youngest children. From 10 years, the importance of Control for EM increases, becoming the main contributor to memory performance in the older adults. For verbal EM processes, Representation is always involved, but Control is required to access representations and manage them to encode and retrieve the stored information efficiently. Thus, to perform a verbal EM task, children first and foremost use their available knowledge. The older adolescents had lower scores on Representation than the young adults, and similar Control and EM scores, but, unlike the young adults, the older adolescents did not rely on their Control processes for EM performance. It is possible that at this age, and given the fact that they have been continuously learning at school over a long time, their memory processes are more automatic and require few if any control processes. Good memory performance is observed when knowledge reaches a minimal threshold and when control processes are efficient, as is the case in early adulthood. In middle age, memory performance is similar to that of younger adults, although control is lower. However, in this age group, knowledge is at its peak, and it is possible that this resource acts as a mechanism to compensate for the slightly diminished control, leading to similar EM than the younger group through the use of verbal strategies. In the older adults, the representational system is highly developed, but control, required for accessing and managing this knowledge is low; thus, knowledge cannot be used efficiently to serve memory processes, leading to low memory performance.

Limitations and perspectives

A limitation of this study is that indirect inferences are made regarding strategic encoding behavior and metacognition, based on the relationships between the Control variable and EM performance. These inferences are consistent with numerous studies that have shown a very strong link between memory strategy use and control, represented by executive functions in our study, and between memory strategy use and metacognitive skills. In the present study, no measures of metacognition or strategic behavior in the free recall test were collected. Thus, one cannot exclude that other factors contributed to the age differences in EM performance reported in the present study (e.g. processing speed, inhibitory capacity; Bryan et al., 1999; Hasher & Zack, 1988). For instance, given the relatively fast pacing of word presentation in the learning phase of our memory task (one word every 5 s), a cognitive slowing associated with age could have interfered with encoding strategies. Therefore, future studies taking direct measures of strategies and metacognition are necessary to confirm our interpretations.

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Declarations

Conflict of interest Laurence Taconnat declares that she has no conflict of interest. Badiâa Bouazzaoui declares that she has no conflict of interest. Cédric Bouquet declares that he has no conflict of interest. Pascale Larigauderie declares that she has no conflict of interest. Arnaud Witt declares that he has no conflict of interest. Agnès Blaye declares that she has no conflict of interest.

Research involves human or animal participants All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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