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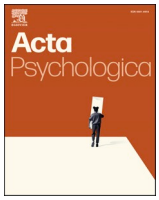

Metamemory mediates the protective effect of cognitive reserve on episodic memory during aging

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ABSTRACT

The present study investigated the impact of cognitive reserve on episodic memory and metamemory control during aging using a multidimensional index of cognitive reserve and a measure of metamemory control abilities. We tested the hypotheses that cognitive reserve may play a protective role against age-related differences in episodic memory and metamemory control and that metamemory control may mediate the effect of cognitive reserve on episodic memory during aging. Young and older adults carried out a readiness-recall task in which task difficulty was manipulated through a variation of the nature of the cue-target pair link (weak vs. strong semantic associates). Episodic memory was assessed through recall performance, and metamemory by a task difficulty index reflecting the ability to adjust study time to task difficulty. Results confirmed that older adults recall fewer words, indicating an age-related deficit in episodic memory, and that older adults adjust less to task difficulty, suggesting impaired metamemory control. Findings also showed that metamemory control moderates the age-related decline in episodic memory and that cognitive reserve plays a protective role against age-related deficits in episodic memory and metamemory control. In addition, metamemory abilities mediated the beneficial effect of cognitive reserve on episodic memory performance during aging. Hence, this study sheds new light on the mechanisms underlying the impact of cognitive reserve on cognitive aging, highlighting the role of metacognitive processes.

1. Introduction

Episodic memory is the form of long-term memory that is most impaired by the aging process (Craik and Jennings, 1992; Light, 1991). There is a wealth of evidence that older adults typically perform less well than young adults in episodic memory tests, particularly under the most effortful conditions that require the self-initiation of strategies. The cognitive reserve hypothesis (Barulli and Stern, 2013; Stern, 2002a, 2002b, 2009) offers an explanation of why the magnitude of these age-related memory changes varies across individuals, some older adults maintaining a very high level of memory abilities until they are very old (Christensen et al., 1999; Nilsson et al., 1997; Nyberg et al., 2012; Wilson et al., 2003). The concept of cognitive reserve refers to the ability of the cognitive system to optimize performance by adapting processes to offset brain damage. The cognitive reserve model is an active system, in which the brain actively attempts to cope with age-related impairments by using pre-existing cognitive processes or by deploying alternative compensatory processes. This cognitive reserve is built up over life as a result of experiences. Classical proxies for cognitive reserve typically include intellectual stimulation provided by education, lifetime leisure, professional and physical activities (Stern, 2002a, 2002b, 2009).

Each of these factors has been linked to more favorable cognitive aging trajectories. For instance, education level has been found to be one of the strongest predictors of age-related decline in cognitive functioning, particularly episodic memory (Angel et al., 2010; Bherer et al., 2001; Le Carret et al., 2003). Several studies with older adults have reported slower rates of cognitive decline among individuals who engage in intellectually stimulating leisure activities (Andel et al., 2015; Rouillard et al., 2017; Schooler and Mulatu, 2001; Wang et al., 2012; Wilson et al., 2003 but see Gow et al., 2014; Salthouse, 2006 for a divergent view). Job complexity may also be positively associated with cognitive functioning, including episodic memory, in older adults (Adam et al., 2013; Andel et al., 2015; Marquie et al., 2010; Rouillard

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et al., 2017). An increasing number of studies have shown that the practice of physical activity has a protective role against age-related cognitive decline (Barnes et al., 2003; Hindin and Zelinski, 2012; Kelly et al., 2014; Kramer and Colcombe, 2018; Laurin et al., 2001; Smith et al., 2010; Yaffe et al., 2001; but see Sabia et al., 2017 for a divergent result; for reviews, see Albinet et al., 2010; Audiffren et al., 2011). Although very few studies have focused specifically on memory abilities, a meta-analysis suggests that older adults' performance in episodic memory tasks can be improved by physical training (Hindin and Zelinski, 2012). A large majority of these studies have focused on the effect of one specific factor of cognitive reserve. Yet, Stern (2009) explained that each of these factors may contribute independently to cognitive reserve, but also that they may interact, to shape the cognitive reserve of an individual as some of them overlap to some degree. For instance, job complexity is closely associated with level of education (Baldivia et al., 2008). Thus, it seems important to examine the joint effect of different factors.

The cognitive mechanisms underlying this protective role of cognitive reserve on cognitive aging are still unclear. Studies that have explored the effect of cognitive reserve have implicitly assumed that these factors may help to compensate the effects of aging on cognition by promoting efficient strategies, notably in memory. Efficient strategy implementation relies on metamemory functioning. Metamemory can be defined as knowledge about one's own memory functioning as well as about memory in general, and the ability to regulate this memory activity (Flavell and Wellman, 1975). Two distinct metacognitive processes associated with memory have been identified: monitoring and control (Nelson and Narens, 1994). Metacognitive monitoring refers to the ability of the learner to assess their current state of knowledge in memory. It can be assessed experimentally through specific paradigms such as *Feeling of Knowing* (FOK), *Judgments of learning* (JOL), or judgments of confidence. Metacognitive control encompasses processes that regulate memory to maximize performance by selecting the optimal strategy according to task specificity and difficulty. For instance, it may allow individuals to adjust study time to the perceived difficulty of the task (Souchay and Isingrini, 2004a). Findings about the effects of aging on metamemory abilities are mixed; some studies have found that monitoring processes are impaired in aging (Guerrero-Sastoque et al., 2021; Sacher et al., 2013; Thomas et al., 2012), while others found that older adults could assess their memory as accurately as young adults (e.g. Froger et al., 2012; Souchay and Isingrini, 2004b; see Castel et al., 2012; Hertzog and Hultsch, 2000; Perrotin and Isingrini, 2010 for reviews). Concerning metacognitive control, the literature reports that there are changes across the lifespan in the ability to select efficient strategies and to adjust them to the task. For instance, Bouazzaoui et al. (2010), using the *Metamemory in Adulthood Questionnaire* (MIA; Dixon et al., 1988), observed that older adults reported less internal strategy use than young adults, while their use of external strategies tended to increase. Age-related changes in strategy use have also been identified when exploring strategy implementation directly during the memory task (see Froger et al., 2014 for a review). Several studies have reported that older adults have difficulty regulating learning effectively according to the nature of the task (Dunlosky and Hertzog, 1998; Froger et al., 2012; Murphy et al., 1981; Murphy et al., 1987; Souchay and Isingrini, 2004a). For instance, Froger et al. (2012) and Souchay and Isingrini (2004a) manipulated the difficulty of a readiness-recall task, in which participants can adjust their study time for each item, by varying the length of the list (7, 9, and 11 items; Souchay and Isingrini, 2004a) or the nature of the cue-target pairs (weak vs. strong semantic associates; Froger et al., 2012). The authors found that older adults increased their study time less than young adults when task difficulty increased, suggesting that they have difficulty adapting study time to task demands. In the literature, it has been suggested that the age-related differences in episodic memory may in part be due to deficient strategy use (Shing et al., 2010). More specifically, several authors showed that these memory deficits may be mediated by deficits in metamemory control during aging (Berry et al., 1989; Dunlosky and Hertzog, 1998; Souchay and Isingrini, 2004a). Older adults' difficulty selecting and adjusting memory strategies to task demands may at least partly explain the decline of episodic memory performance with advancing age.

Despite the age-related differences in strategy use and metamemory abilities and their involvement in episodic memory deficits, few studies have examined how they may be influenced by cognitive reserve factors. Frankenmolen et al. (2018), in a sample covering the entire adult lifespan, found that cognitive reserve, indexed by educational level and IQ estimation, was a strong predictor of strategy use in daily life and in an experimental memory task, being related to the use of more complex and more efficient strategies (e.g. mental imagery or sentence generation). In line with these results, cognitive reserve has also been observed to moderate the benefits of strategy instructions on associative memory across the adult lifespan, older adults with a higher IQ benefiting more than those with a lower IQ (Frankenmolen et al., 2017). Several studies have also reported a relationship between cognitive reserve and metamemory abilities during aging, using the MIA questionnaire (Dixon et al., 1988). They showed that high cognitive reserve, assessed by specific indexes such as physical activity (André et al., 2018) or educational level (Guerrero-Sastoque et al., 2021; Min and Suh, 1999; Ponds and Jolles, 1996) is associated with better strategy use. However, most of these studies included only older adults (with the exception of Ponds and Jolles, 1996, but they did not explore this question directly), so they were unable to test whether the interaction between age and cognitive reserve could have a protective effect on metamemory. Moreover, while there is considerable evidence of the beneficial effect of cognitive reserve on episodic memory and metamemory during aging, to our knowledge, only one study (Guerrero-Sastoque et al., 2021) has explored the role of metamemory abilities on the relationship between older adults' episodic memory and cognitive reserve. The results of that study suggest that the use of internal strategies in daily life (measured by the MIA questionnaire) mediates the beneficial effect of educational level on episodic memory in older adults; older individuals with a high educational level would have a greater strategy implementation capacity, which would explain their better memory performance. To extend these results, it would be interesting to explore whether the mediating role of metamemory in the effect of cognitive reserve on episodic memory during aging would also be observed when metamemory abilities are assessed objectively, rather than using a subjective measure such as the MIA questionnaire. Another limitation of these previous studies is that they used only one specific factor (i.e., educational level or physical activity) to index cognitive reserve. Given the multidimensional nature of cognitive reserve, it would be interesting to examine its impact on episodic memory and metamemory by using a more global index based on different factors linked to the stimulant cognitive experiences during the lifespan.

Our study aimed to improve the understanding of the impact of cognitive reserve on memory performance in older adults by examining the influence of metamemory in this relationship and addressing some methodological limitations of the previous studies. Thus, instead of using subjective measures of metamemory, we assessed metamemory control objectively by examining how participants adjusted their study time to task difficulty, yielding a task difficulty adjustment index. Moreover, instead of focusing on a specific factor (e.g. educational level; Guerrero-Sastoque et al., 2021) the present study assessed cognitive reserve through a composite index including educational level, engagement in physical and leisure activities across the lifespan, and professional demands, in order to grasp the multidimensional nature of this variable. Although premorbid intelligence quotient (IQ) has also been used in some previous studies to estimate cognitive reserve, the approach taken in this study was based on the construct of cognitive reserve as the cognitive and neural resources that are developed during lifetime thanks to engagement in a variety of brain-stimulating activities. We postulated that these measures of cognitive reserve and intelligence, even though they are undoubtedly related, do not refer to the

same dimension of cognitive reserve, given that IQ is a measure of performance whereas other measures of reserve are not and that IQ is mostly used to provide an estimation of premorbid functioning. Consequently, we chose not to include IQ in our cognitive reserve index. Young and older adults carried out a readiness-recall task, in which task difficulty was manipulated by varying the nature of the cue-target pair link (weak vs. strong semantic associates; Froger et al., 2012). First, we examined age effects on memory and metamemory. We expected to observe poorer memory performance by older adults, particularly in the most difficult condition (weak associates), given the age-related deficit in associative memory (Naveh-Benjamin, 2000). We also expected to observe a negative effect of aging on metamemory control. Study time was expected to be longer for weak than strong associates, with older adults showing greater difficulty adjusting study time to task difficulty. Secondly, we examined the relationships between episodic memory, metamemory and cognitive reserve for each age group. We conducted General Linear Model (GLM) and correlation analyses to examine: 1) the effects of metamemory control on age-related differences in episodic memory, and 2) the effects of cognitive reserve on age-related differences in episodic memory and metamemory control. We expected to observe an effect of the interaction between age and metamemory control on episodic memory, suggesting that the age-related deficit in memory would be reduced in individuals with higher metamemory abilities. We also expected that the interaction between age and cognitive reserve would have an effect on recall performance and on the task difficulty adjustment index, indicating the protective role of cognitive reserve on episodic memory and metamemory during aging. Finally, given that metamemory can be considered to be a cognitive mechanism of memory, and based on the findings of previous analyses, we conducted regression analyses to test the hypothesis that metamemory control mediates the effect of cognitive reserve on episodic memory in older adults.

2. Methods

2.1. Participants

In order to estimate the sample size necessary to conduct our analyses, an a-priori power analysis has been conducted using G*Power, based on the effect size from the study of Guerrero et al. (2021; $f^2 = 0.66$), which is the study that pursues an objective closest to our study since that explored the role of metamemory abilities (assessed by the MIA questionnaire) on the relationship between older adults' episodic memory (cued recall task) and cognitive reserve. This power analysis revealed a minimum sample size of 27 participants by group. Because of the risk of excluding some participants, we chose to increase a little bit the number of participants included in the study. Participants were 36 young adults (age range 22–40) and 31 older adults (age range 60–79), recruited from the local community (see Table 1). All were native French speakers and had normal or corrected-to-normal vision. They all reported to be in good physical and mental health, and to be free from medication known to affect the central nervous system. Older adults who obtained a score below 27 (maximum score: 30) on the Mini Mental State Examination (MMSE; Folstein et al., 1975) were excluded, in order to eliminate any risk of possible neurodegenerative disease. 2 additional participants filled the cognitive reserve questionnaires in an uncomplete way and consequently they had to be excluded. Younger adults had a significantly higher educational level than the older adults ($t(65) = 3.02$, $p < .01$). However, older adults had higher scores on the Mill Hill vocabulary test (Deltour, 1993), ($t(65) = -2.58$, $p < .05$), in which participants choose the best synonym for a word, providing an assessment of cultural level. Anxiety and depression level, assessed by the HADS (Zigmond and Snaith, 1983), did not differ between groups. The study was approved by the local ethics committee of the University of Tours, and all participants signed a consent form. Participation in this study did not involve financial compensation.

Table 1
Characteristics of each experimental group.

	Young ($N = 36$)	Old ($N = 31$)	t(65)
Age (years)	28.03 (4.77)	69.97 (6.35)	/
Education (years)	13.89 (2.92)	11.58 (3.34)	3.02
Mill Hill	23.03 (4.34)	25.77 (4.36)	−2.58
Physical activity score	9.04 (7.47)	13.82 (12.79)	−1.89
Leisure activity score	9.08 (1.99)	8.47 (2.98)	0.98
Professional demands score	14.49 (6.77)	12.79 (6.59)	1.04
HADS	13.39 54.01)	13.16 (5.77)	0.19

Note: SDs are shown in parentheses, Physical activity score: mean energy expenditure associated with physical activities throughout life, Leisure activity score: mean cognitive stimulation associated with leisure activities, Professional demands score: overall decision latitude, HADS: Hospital Anxiety and Depression Scale.

2.2. Material and procedure

2.2.1. Episodic memory and metamemory task

To assess episodic memory and metamemory abilities, participants performed a cued-recall task, inspired by Froger et al. (2012), in which the difficulty was manipulated by varying the strength of semantic association between the cue and the target.

2.2.1.1. Material. The stimuli consisted of two lists of 30 pairs of words, extracted from Izaute et al. (1996), with 15 weak associates (e.g. milk-TURTLE) and 15 strong associates (e.g. slug-LETTUCE). The degree of cue-target association was counterbalanced between the two lists. Each target item was strongly associated with a cue in one list (e.g. slug-LETTUCE), and weakly associated with a different cue in the other list (e.g. sword-LETTUCE). The use of the two lists for the two conditions was counterbalanced across participants. Six additional pairs (three weak and three strong associates) were used for the practice phase.

2.2.1.2. Procedure. Participants were instructed to read the word pairs and memorize the second word for a subsequent cued-recall test. The pairs of items were randomly presented on a computer screen one at a time at the participants' own pace, by pressing a button when they were ready to move on to the next pair. This self-paced condition enabled us to examine how participants adjusted their study time to task difficulty. Participants then performed a 1-min interfering countdown task before carrying out the cued-recall test. Cues from the encoding phase were presented one at a time on the computer screen, and participants were instructed to recall the target word (e.g. slug-LETTUCE), giving their answer aloud, with no time limit. All the participants completed a practice phase with 6 cue-target pairs before the experimental task comprising the 30 cue-target pairs.

2.2.1.3. Measures. Memory performance was measured by the proportion of correctly recalled target items for the strong and the weak associates. For GLM, correlation and regression analyses, memory performance was assessed through an average of the proportion of correctly recalled targets for strong and weak associates. We also recorded mean study time per item for weak and strong associates. Metamemory control was assessed through a task difficulty adjustment index (TDAI), computed as follows: (Study time weak associates – Study time strong associates) / (Study time weak associates + Study time strong associates). A high TDAI indicates good ability to adjust study time to task difficulty.

2.2.2. Cognitive reserve measures

Cognitive reserve was assessed through four measures estimating the level of education, job demands, leisure activity and physical activity.

2.2.2.1. Level of education. Participants reported the highest educational qualification they had attained. Educational level was then computed as the number of years associated with this qualification (Stern et al., 1992).

2.2.2.2. Physical activity. Lifetime physical activity was assessed through a French version of the HLAQ questionnaire (Kriska et al., 1988) adapted by Rouillard et al. (2017). First, participants were given a list of 95 physical activities and asked to select the eight that they had performed most during their life. They then reported the time spent on each of these activities (number of years, number of months per year, and number of hours per week) at different time periods (6–18, 19–34, 35–54, over 55 years old). This enabled us to estimate for each activity the mean number of hours per week and in each period. Each activity was characterized by its energy expenditure, estimated through the METS (Metabolic Equivalent of Task, Ainsworth et al., 2011)). The total energy expenditure for a period was computed as follows: $\sum$ for the 8 activities (mean number of hours per week $\times$ METS). The final score, reflecting the mean energy expenditure associated with physical activities throughout life, was obtained by averaging the total energy expenditure for the four time periods.

2.2.2.3. Leisure activity. The leisure questionnaire was also an adaptation of the HLAQ by Rouillard et al. (2017). Participants were instructed to select from a list of 66 predefined activities the 8 that contributed the most to their personal development for each period of their life (6–18, 19–34, 35–54, over 55 years old). They indicated the average frequency of each activity on a 5-point scale (from never to everyday) during each period, and the mental load associated with it on a 5-point scale (from very little to very heavy load). The mean frequency of an activity throughout life was computed by averaging the scores for the four periods. The degree of cognitive stimulation associated with an activity was computed as frequency multiplied by the mental load estimated by the individual. The final score, reflecting mean cognitive stimulation associated with leisure activities, was the sum of the cognitive stimulation scores for all activities.

2.2.2.4. Professional demands. After reporting their work experience, participants completed a French version of the Job Content Questionnaire (JCQ, Karasek et al., 1998). For each of their three main jobs, they were asked to answer items from the decision latitude subscale of this questionnaire (9 items), assessing the amount of control workers have over performance of their job, such as flexibility in dealing with professional demands. Participants responded to each item on a 4-point scale ranging from 1 (strongly disagree) to 4 (strongly agree). We computed overall decision latitude using the formula proposed by Rouillard et al. (2017), namely the mean of decision latitude for each of the three jobs weighted by the number of years in each job.

2.2.2.5. Cognitive reserve index. We carried out a principal component analysis on education, physical activity score, leisure activity score and professional demands score to verify whether these cognitive reserve measures, even though measuring different dimensions, converge to load on a single factor. This analysis indicated that the 3 measures loaded on a single factor (eigenvalue greater than one), which reflected the shared factor of these measures. The cognitive reserve index (CRI) was thus computed as the average of the z-scores of the four cognitive reserve measures: years of education, mean energy expenditure associated with lifetime physical activity, mean cognitive stimulation associated with leisure activities, and total decision latitude associated with professional demands.

3. Results

The data were analyzed in two stages. First, to explore the effect of age and task difficulty on memory and metamemory performance, we performed analyses of variance with factors of age group (young vs. old) and strength of association (weak vs. strong) on the proportion of correctly recalled target items and on study time. When necessary, planned comparisons were executed to elucidate significant interactions. We also examined the effect of age group on a global measure of episodic memory that was used for subsequent analyses (proportion of correctly recalled target items averaged for both weak and strong associates) and on the TDAI through Student *t*-tests. Secondly, in order to determine the relationships between age group, episodic memory, metamemory abilities and cognitive reserve, we conducted a series of General Linear Model (GLM) analyses. We examined whether metamemory control modulates age-related differences in episodic memory through a GLM analysis on episodic memory, including factors of TDAI and age group. Additionally, in order to explore whether cognitive reserve modulates the age effect on memory and metamemory, we also included factors of age group and cognitive reserve index in analyses of the episodic memory measure (proportion of correctly recalled target items averaged for both weak and strong associates) and metamemory measure (TDAI). When necessary, correlation analyses were performed separately in each age group in order to better describe significant interactions. Finally, based on the pattern of results of older adults, we conducted regression analyses specifically in this group to identify whether the best predictors of episodic memory performance during aging were cognitive reserve or metamemory control (TDAI). We specifically tested the hypothesis that metamemory control mediates the effect of cognitive reserve on episodic memory during aging.

3.1. Age-related differences in episodic memory and metamemory control

Means and standard deviations for cued-recall performance and study time are shown in Figs. 1 and 2 respectively.

ANOVA of memory performance (i.e. proportion of correctly recalled target items) revealed a significant main effect of age group ($F(1,65) = 20.69$, $p < .001$, $\eta_p^2 = 0.24$), with higher scores for young than older adults. A significant main effect of strength of association ($F(1,65) = 182.66$, $p < .001$, $\eta_p^2 = 0.73$) showed that memory performance was significantly better for strong than weak associates. Results also revealed a significant interaction between age group and strength of association ($F(1,65) = 7.11$, $p = .009$, $\eta_p^2 = 0.09$), suggesting better recall for strong than weak associates in both age groups, but to a greater extent for older adults (young: ($F(1,65) = 63.58$, $p < .001$); older: ($F(1,65) = 121.85$, $p < .001$). In addition, age differences were significant in both conditions, but more pronounced for weak ($F(1,65) = 21.96$, $p < .001$) than strong associates ($F(1,65) = 13.50$, $p < .001$).

Analyses of study time showed a significant effect of age group, young adults spending longer studying pairs of items than older adults (*F*

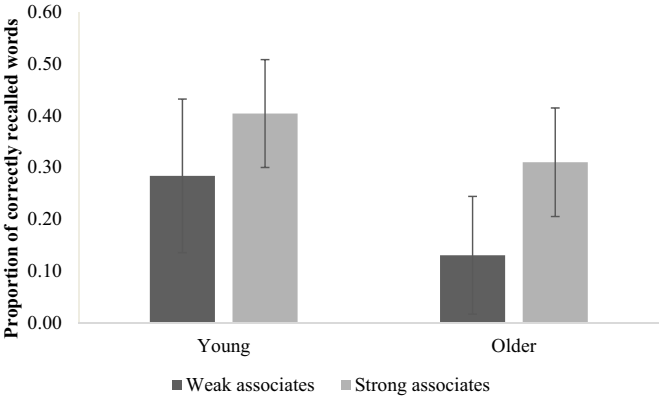

Fig. 1. Mean proportions and standard deviations of correctly recalled words according to group and strength of association.

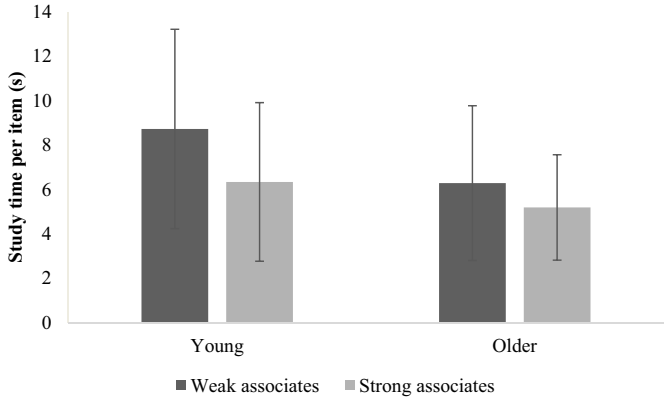

Fig. 2. Mean proportions and standard deviations of study time by item according to group and strength of association.

(1,65) = 4.53, $p = .04$, $\eta_p^2 = 0.07$). A significant main effect of strength of association showed that weak associates elicited longer study time than strong associates ($F(1,65) = 43.51$, $p < .001$, $\eta_p^2 = 0.04$). The interaction between age group and strength of association was also significant ($F(1,65) = 5.97$, $p = .02$, $\eta_p^2 = 0.08$). Planned comparisons indicated that both age groups spent longer studying weak than strong associates, but the adjustment of study time to task difficulty was less pronounced for older adults (young: $F(1,65) = 44.17$, $p < .001$; older: $F(1,65) = 8.02$, $p = .006$). The effect of age group was significant for weak associates ($F(1,65) = 6.01$, $p = .02$), with shorter study time by older than young adults, but not for strong associates ($F(1,65) = 2.32$, ns).

3.2. Relationships between episodic memory, metamemory control and cognitive reserve

3.2.1. Does metamemory control moderate the effect of age on episodic memory?

Results of the GLM analysis on the global episodic memory measure, with age group and TDAI as factors, confirmed the effect of age group ($F(1,63) = 22.83$, $p < .001$, $\eta_p^2 = 0.03$). The main effect of TDAI was significant ($F(1,63) = 7.32$, $p = .009$, $\eta_p^2 = 0.10$), suggesting that better metamemory abilities are associated with better episodic memory performance. Analysis also revealed a significant interaction between age group and TDAI ($F(1,63) = 4.28$, $p = .04$, $\eta_p^2 = 0.06$), suggesting a moderating role of TDAI on the effect of age on episodic memory. Correlation analyses conducted in each age group revealed that TDAI was positively associated with the episodic memory measure in the older group ($r = 0.59$, $p < .001$) but not in the young group ($r = 0.08$).

3.2.2. Does cognitive reserve moderate the effect of age on episodic memory?

Next, we performed a GLM analysis of the global episodic memory measure, with factors of cognitive reserve index and age group. Episodic memory performance was again significantly lower in older than young adults ($F(1,63) = 15.28$, $p < .001$, $\eta_p^2 = 0.19$), but the main effect of cognitive reserve was not significant ($F(1,63) = 0.19$, ns. The interaction between age group and cognitive reserve index also appeared significant ($F(1,63) = 4.38$, $p = .04$, $\eta_p^2 = 0.07$). Episodic memory performance was significantly positively correlated to the cognitive reserve index in the older group ($r = 0.48$, $p = .006$) but not in the young group ($r = -0.15$, ns). This suggests a moderating role of cognitive reserve on the effect of age on episodic memory.

3.2.3. Does cognitive reserve moderate the effect of age on metamemory control?

The final GLM analysis examined the effect of the cognitive reserve index and age group on TDAI. An age-related deficit in metamemory control was confirmed by the significant effect of age group ($F(1,63) = 18.97$, $p < .001$, $\eta_p^2 = 0.23$). The main effect of the cognitive reserve index on TDAI was not significant ($F(1,63) = 2.01$, ns), but the interaction between the cognitive reserve index and age group suggested that cognitive reserve moderates the effect of age on metamemory control ($F(1,63) = 14.46$, $p < .001$, $\eta_p^2 = 0.19$). Interestingly, correlation analyses indicated that TDAI was associated with the cognitive reserve index, negatively in the young group ($r = -0.44$, $p = .007$) but positively in the older group ($r = 0.42$, $p = .02$).

3.2.4. Does metamemory control mediate the effects of cognitive reserve on episodic memory during aging?

Based on the pattern of results identified in the previous GLM and correlation analyses, we examined in greater depth the predictors of episodic memory during aging. In older adults, episodic memory performance was found to be positively associated with both cognitive reserve and metamemory control abilities, and the relationship between cognitive reserve and metamemory was also significant. Thus, we conducted a series of regression analyses in order to identify the best model explaining variance in episodic memory in older adults. Given that episodic memory was not related to cognitive reserve in young adults, we did not perform these analyses in this group. Results of the different models tested are presented in Table 2.

Regression analyses of the global episodic memory measure indicated that TDAI alone explained a significant 34.69% of the variance of this variable (Model 1; $\beta = 0.59$, $t(29) = 3.92$, $p < .001$). The cognitive reserve index was also a reliable predictor of episodic memory performance, explaining 22.9% of the variance (Model 2; $\beta = 0.48$, $t(29) = 2.93$, $p < .001$). Model 3 tested the combined effects of TDAI and cognitive reserve index, and more specifically whether cognitive reserve continued to account for variance in episodic memory after controlling for TDAI. When TDAI and cognitive reserve index were entered together, only TDAI proved to be a reliable predictor; cognitive reserve did not contribute significantly to the variance. The change in R^2 when adding the cognitive reserve index was reduced to a non-significant level when TDAI was controlled for ($\beta = 0.28$, $t(29) = 1.76$). The cognitive reserve index-related variance in episodic memory was reduced by 71.75%, suggesting that the effect of cognitive reserve on episodic memory in older adults is strongly mediated by metamemory control abilities.

4. Discussion

4.1. Age-related differences in episodic memory and metamemory control

Our results extend previous research on cognitive aging by confirming a significant age-related deficit in both episodic memory (Craik and Jennings, 1992; Light, 1991; McDaniel et al., 2008) and metamemory control (Dunlosky and Hertzog, 1998; Froger et al., 2012; Murphy et al., 1981; Murphy et al., 1987; Souchay and Isingrini, 2004a). The reduced performance of older adults in the cued-recall task compared to young adults, especially in the condition involving weak associates is in agreement with previous findings (Froger et al., 2012; Taconnat et al., 2008) and adds support to the associative deficit hypothesis (Naveh-Benjamin, 2000), which postulates that the age-related decline in episodic memory can be explained by older adults' difficulty

Table 2
Regression analyses predicting episodic memory performance by TDAI and CRI in older adults.

Regression models	Variables	Beta	R^2	R^2change	*p*
1	TDAI	0,59	34,69	34,69	
2	CRI	0,48	22,9	22,9	
3	TDAI	0,59	34,69	34,69	
	CRI	0,28	41,16	6,47	ns

Note: TDAI: Task Difficulty Adjustment Index, CRI: Cognitive Reserve Index.

associating different components of an episode into a cohesive unit. In our experiment, integration of strongly associated cues and targets was facilitated by the preexisting relationship between pair items, whereas for weak associates, participants had to generate relationships at encoding, which would particularly penalize older adults. This finding is also consistent with the environmental support hypothesis (Craik, 2016), which posits that age-related differences in memory are influenced by the amount of support provided by the environment. Because of their deficit in processing resources, it is difficult for older adults to self-initiate effortful associative strategies, especially for the weak associates that provide less support. On the contrary, the preexisting semantic relationship between pair items for the strong associates can be considered as an environmental support helping participants, especially older ones, to initiate a semantic processing of items at encoding. Then, at retrieval, the presence of a cue strongly associated to the target can also facilitate its retrieval.

We also examined age differences in metamemory control abilities. Both age groups increased study time with task difficulty, spending longer studying weak than strong associates, but older adults adjusted their time less efficiently. This finding provides further evidence of the deficit of metamemory control during aging (Dunlosky and Hertzog, 1998; Froger et al., 2012; Murphy et al., 1981; Murphy et al., 1987; Souchay and Isingrini, 2004a), older adults adjusting their study time to task difficulty less efficiently than young adults. This age-related deficit in metamemory control may be due to a deficit in metacognitive knowledge, such as knowledge of their abilities and of the task and/or strategies. Indeed, there is evidence in the metamemory and aging literature that evaluation of one's own memory efficacy is impaired in older adults, who typically underestimate their performance, which may result in their difficulty self-regulating their memory strategies (metamemory control; Dixon et al., 1988; Hultsch et al., 1987; Loewen et al., 1990; McDonald-Miszczak et al., 1995). Older adults may have greater difficulty estimating the differential difficulty of weak vs. strong associates, and even if they identify this difference, they may not use this knowledge efficiently to regulate their learning. Decline in metacognitive control with advancing age could also be explained by a deficit in executive control, in line with the executive hypothesis of cognitive aging (Guerrero-Sastoque et al., 2021; Souchay and Isingrini, 2004a). Future studies could examine further the involvement of these control processes in the deficit of metamemory control. Another factor that may impact older adults' metacognitive judgments is the age-related stereotype threat. Indeed, evidence suggests that activation of this stereotype impairs metacognition, assessed by the ability to predict subsequent recall, in aging (Fourquet et al., 2020). In our experiment, older adults' perceptions of memory during aging (e.g. “Older adults are slower”) may have influenced the time allocated to tasks varying in difficulty. It is possible that when older adults are faced with a task they perceive as difficult, they may feel they are unlikely to succeed and thus move on to the next pair rapidly, or they may not want to appear slow and thus not allow themselves to spend more time on difficult items. Future work should examine this possibility. In addition, study time allocation does not reflect only control abilities and may also be influenced by other factors including metacognitive monitoring (*monitoring-affects-control hypothesis,* Nelson and Leonesio, 1988). For instance, participants can allocate more study time to items that are perceived as having been learned well through monitoring judgments. Interestingly, some evidence suggest that older adults are less likely to base their study time allocation on their monitoring judgments (Dunlosky and Hertzog, 1998; Souchay and Isingrini, 2004a). Including measures of monitoring (e.g. JOL) would allow to determine the involvement of this dimension of metacognition on the way older and young adults adjust study time to task difficulty. In addition, it may also be possible that the time allocated to study items may also be influenced by non-cognitive other factors such as motivation.

4.2. Relationships between age, episodic memory, metamemory control and cognitive reserve

The main aim of our current experiment was to investigate the relationships between cognitive reserve, episodic memory and metamemory control in young and older adults. First, our results show that metamemory control moderates the age-related decline in episodic memory. The measure of metamemory control was associated with episodic memory in older but not young adults. During aging, the ability to adjust memory strategies to task difficulty influences episodic memory. This finding of a protective effect of strategic abilities on age-related memory deficit, together with considerable other evidence, supports the strategy-deficit hypothesis (Dunlosky and Hertzog, 1998) suggesting that age-related differences in strategy use contribute to explain age-related deficits in episodic memory. As stated previously, given the involvement of control processes in strategy use and strategy regulation, it would be interesting to investigate how they may act in the relationship between metamemory control and episodic memory during aging. For instance, Souchay and Isingrini (2004a) showed that cognitive shifting is related to the ability to adjust study time to task difficulty. Planning abilities may also be involved in metamemory control, enabling strategies to be implemented in order to achieve the desired goal.

Secondly, we focused on the impact of cognitive reserve on both episodic memory and metamemory control. One of the shortcomings of previous studies exploring the effects of cognitive reserve factors on episodic memory (education: Angel et al., 2010; Bherer et al., 2001; Le Carret et al., 2003; leisure activity: Andel et al., 2015; Rouillard et al., 2017; Schooler and Mulatu, 2001; Wang et al., 2012; Wilson et al., 2003; Salthouse, 2006, professional activity: Adam et al., 2013; Andel et al., 2015; Marquie et al., 2010; Rouillard et al., 2017; physical activity: for a meta-analysis, see Hindin and Zelinski, 2012) or metamemory (education: Guerrero-Sastoque et al., 2021; Min and Suh, 1999; Ponds and Jolles, 1996; Szajer and Murphy, 2013; physical activity: André et al., 2018; IQ: Frankenmolen et al., 2017, 2018) is that most of them only included older adults, and, to our knowledge, no study has yet explored directly the protective role of cognitive reserve on age-related differences in metamemory abilities. Furthermore, most of these studies assessed metamemory subjectively using self-report questionnaires (for two exceptions, see Frankenmolen et al. 2018; Szajer and Murphy, 2013), which could bias the results as participants with high cognitive reserve may have greater awareness of the strategies they use, without real difference in the strategies implementation according to cognitive reserve. The effect of cognitive reserve on an objective measure of metamemory control remained to be investigated. Finally, one major limitation of these studies is that cognitive reserve was assessed through a single measure, with the exception of Frankenmolen et al. (2018) who used both estimated IQ and educational level. Given the multi-determined nature of cognitive reserve, a more accurate assessment should include a combination of factors. In our experiment, we aimed to address these methodological limitations by including both young and older adults, using an objective measure of metamemory control, and computing a composite index of cognitive reserve.

Our data revealed that cognitive reserve, assessed through a combination of factors including educational level, job demands, and leisure and physical activity, moderates the effect of age on both episodic memory and metamemory control. Cognitive reserve was positively associated with episodic memory, but only in older adults. This result confirms that a high level of cognitive reserve may serve to protect against memory decline during aging (Stern, 2002a, 2002b, 2009; Stern and Habeck, 2018). We also observed that cognitive reserve helps moderate age-related differences in metamemory control abilities. Cognitive reserve was associated negatively to metamemory control in young adults but positively in older adults. The negative association in young adults may appear surprising at first sight. One potential explanation is that young adults with a low level of cognitive reserve are those

who adjust their memory strategies most to task difficulty, while those with a high level make less adjustment, possibly because they do not need extra time to encode weak associates because this condition may not appear difficult for them. This hypothesis seems consistent with the lack of relationship between the metamemory measure and episodic memory in this group, suggesting that the degree of adjustment of study time is not associated with episodic memory performance. Alternatively, it could be that young people with a high level of cognitive reserve adjust their memory strategies according to task difficulty but without affecting study time, because the strategies do not differ in terms of processing time. By contrast, a high level of cognitive reserve would help older individuals counteract the negative effects of aging on metamemory control, and enable them to adjust their memory strategies better to task difficulty. The stimulating experiences throughout their life would have provided opportunities to improve their strategy use and adjust their memory strategies to different situations and demands. For instance, education develops a large range of skills, including memory strategies and the ability to adapt them to different learning contexts. Professional activity may also place strong demands on memory strategies, notably in jobs that involve cognitively complex tasks and require an adjustment of strategies. Some cognitively stimulating leisure activities (e.g. chess, artistic activities, cooking) may also strengthen these strategic abilities. In our study, the benefit of cognitive reserve was greater in older than young adults, possibly because they need to adjust their study time more to cope with increased task difficulty due to their limited resources. Nevertheless, as task difficulty increases, for instance in a free-recall task, it is possible that young adults, even those with a high level of cognitive reserve, would also need to rely more on their strategic abilities, resulting in a positive relationship between metamemory and cognitive reserve. While the beneficial effect of cognitive reserve factors has already been reported in older adults, our study is the first to reveal the protective effect of cognitive reserve on an objective measure of metamemory control in a sample of both young and older adults. Given that metamemory is a multifaceted concept, it would be interesting to explore the impact of cognitive reserve on other dimensions, such as monitoring, by using FOK or JOL measures for instance, or qualitative reports of strategies used in the memory task. It must be raised that even though these questionnaires have a good reliability (Falkner et al., 1999; Slattery and Jacobs, 1995) and reproducibility (Chasan-Taber et al., 2002), the accuracy of the lifetime activity self-reports can be influenced by several factors such as memory abilities of participants, characteristics of activities (e.g. low vs. high intensity) and characteristics of participants (e.g. age, social desirability tendency). Future studies are needed to better understand the impact of these factors and potentially adjust our tools allowing to assess lifetime leisure and physical activities.

The present study clearly shows that cognitive reserve plays a protective role against age-related deficits in episodic memory and metamemory control. Our main aim was to determine the role of metamemory control on the beneficial effect of cognitive reserve during aging. According to the cognitive reserve hypothesis, cognitive reserve fosters the use of alternative strategies, supported by recourse to additional neural resources. However, very few studies have directly explored the link between cognitive reserve, metamemory and memory performance. Our study clearly demonstrates that metamemory abilities mediate the beneficial effect of cognitive reserve on memory performance during aging. Future studies should also examine the neural patterns associated with the protective role of cognitive reserve and of metamemory control during aging. Neuroimaging studies have reported neural reorganization patterns (e.g. additional activations) in older individuals with a high level of cognitive reserve, but the relationship with metamemory control remains to be investigated. Our study supports the idea that metamemory abilities play a crucial role in episodic memory during aging, suggesting that they may constitute an interesting focus for training interventions. Given the relationship between metamemory control and cognitive reserve during aging, this kind of intervention could even be more efficient to optimize the memory performance of older individuals with a low level of cognitive reserve. Power analysis allowing to estimate sample size have been conducted on the basis of the effect size from the study of Guerrero-Sastoque et al. (2021) but no data on effect size were available in the previous studies using a similar readiness recall task. Despite the moderate sample size of our groups in the present study, we have been able to demonstrate moderating effects of cognitive reserve on age-related differences in episodic memory and metamemory. Nevertheless, results must be interpreted cautiously and further studies using a larger sample size are necessary to consolidate our conclusions.

To conclude, this study extends previous findings of the protective effect of cognitive reserve on age-related deficits in episodic memory, and is the first to show this protective role in metamemory control deficits using a composite measure of cognitive reserve and an objective measure of metamemory. It also demonstrates that metamemory control mediates the beneficial effect of cognitive reserve on episodic memory during aging. Hence, this study sheds new light on the mechanisms underlying the impact of cognitive reserve on cognitive aging, and opens up promising avenues for memory training in older adults.

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Declaration of competing interest

The authors state that there is no financial/personal interest or belief that could affect their objectivity.

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