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Research Article

Metamemory and executive function mediate the age-related decline in memory

Michael K. Yeung
Department of Psychology, The Education University of Hong Kong, Hong Kong, China and University Research Facility in Behavioral and Systems Neuroscience, The Hong Kong Polytechnic University, Hong Kong, China

Abstract

Objective: Although the effect of aging on episodic memory is relatively well studied, little is known about how aging influences metamemory. In addition, while executive function (EF) is known to mediate the age-related decline in episodic memory, the role of metamemory in aging-related memory differences beyond EF remains unknown. This study aimed to elucidate the effect of aging on metamemory and to clarify the role of metamemory in the age-related decline in memory. **Method:** One hundred and four adults aged 18–79 years (50 M, 54 F) performed several EF tasks, as well as a face-scene paired-associate learning task that required them to make judgments of learning, feeling-of-knowing judgments, and retrospective confidence judgments. **Results:** Aging was significantly associated with poor metamemory accuracy and increased confidence across metamemory judgment types, even after controlling for EF and memory performance. A parallel mediation analysis indicated that both confidence of learning and EF performance had significant partial mediation effects on the relationship between aging and memory, albeit in different ways. Specifically, poor EF explained the age-related decline in memory, whereas increased confidence of learning served to compensate for this memory decline. **Conclusions:** Aging is associated with general changes (i.e., poor inferences from cues) rather than specific changes (i.e., declined activation or utilization of certain cues) in metamemory monitoring. Also, changes in confidence of learning and in EF ability contribute to the preservation and decline of memory during aging, respectively. Therefore, boosting confidence during encoding and enhancing EF skills might be complementary memory intervention strategies for older adults.

Keywords: aging; metamemory; metacognition; memory; learning

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Public significance statement

This study found that memory confidence during learning and executive function skills mediated the age-related decline in memory, albeit in opposite directions. These findings suggest that boosting confidence during learning, as well as enhancing executive function skills, might be memory intervention strategies for older adults.

Metamemory and executive function mediate the age-related decline in memory

Aging is associated with decline across cognitive functions, particularly higher-order cognitive processes subserved by the prefrontal cortex (Cabeza & Dennis, 2013; West, 1996). Beginning in early adulthood, episodic memory begins to decline with age (Salthouse, 2003), and this decline is of particular concern to researchers and practitioners due to the importance of memory in independent living and memory decline's prognosis for the future development of dementia (Gainotti et al., 2014; Tromp et al., 2015). This deterioration is detectable across tests, including recall and recognition tasks formatted as list learning or paired-associate learning (Rhodes et al., 2019). Some studies have shown that the age-related decline in episodic memory is partly the result of the age-related deterioration in executive function (EF) skills (Crawford et al., 2000; Lee et al., 2012), including mental flexibility, inhibitory control, working memory, and efficient access to long-term memory (Fisk & Sharp, 2004; Miyake et al., 2000).

Although the effect of aging on episodic memory is relatively well studied, little is known about how aging affects the metacognitive aspect of episodic memory. Metamemory refers to the knowledge and monitoring of one's own memory (Dunlosky & Tauber, 2013; Nelson & Narens, 1990). It includes metamemory monitoring, the ability to gather accurate information about the current state of the memory system, which enables the deployment of strategies to enhance subsequent learning and memory (i.e., metamemory control). Different metamemory monitoring processes function over the time course of learning. During acquisition, one can make judgments of learning (JOLs) to predict the likelihood of remembering information in the future. During retrieval, one can also make feeling-of-knowing judgments (FOKs)

Corresponding author: Michael K. Yeung; Email: michaelyeung@eduhk.hk
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to anticipate the probability that one will be able to remember, in the future, information that they currently cannot recall. In addition, after performing a memory task, one can make retrospective confidence judgments (RCJs), which reflect one's confidence in successfully remembering the information.

According to the isomechanism framework of metacognition, different metacognitive judgments used to predict future cognitive (memory) performance are essentially based on the same system of inferences about the available internal and external cues (Dunlosky & Tauber, 2013). These cues, however, differ partly across judgment types. In the context of paired-associate learning, for example, JOLs made while studying item pairs are based on material features (e.g., pair relatedness and perceptual features), aspects of study processes (e.g., strategy production and ease of processing), and context of study (e.g., number of study trials and expected test format). In addition, FOKs made upon presentation of a cue are based on previous recall/recognition outcome, recall/recognition latency, cue familiarity, and accessibility to partial information. Furthermore, RCJs made after the recognition test are based on cue familiarity, speed of recognition decision, and the recollection of episode in which the items were studied (see Figure 25.3 in Dunlosky and Tauber, 2013, for a list of potential cues available for inference-based processing in single trial learning).

Currently, the effects of aging on metamemory monitoring are poorly understood. Some studies have reported spared JOL accuracy for familiarity-based memory in aging (Connor et al., 1997; Kuhlmann & Undorf, 2018). However, Connor et al. (1997) found that during learning, older adults overestimated subsequent memory performance. Some studies have found that FOK accuracy is impaired with aging (Souchay et al., 2000, 2007), whereas others have found it to be preserved (Eakin & Hertzog, 2012; Eakin et al., 2014; Hertzog et al., 2010; MacLaverty & Hertzog, 2009). Furthermore, some studies have found that aging is associated with reduced RCJ accuracy even after matching the young and old groups on recollection test accuracy (Wong et al., 2012). In contrast, other studies have reported no significant difference between younger and older adults in RCJ accuracy (Eakin et al., 2014). Most aging studies have examined only one type of metamemory judgment at a time. Therefore, any differential effects of aging, whether aging affects all or only specific kinds of metamemory judgment, are still unclear. According to the isomechanism framework, aging may similarly affect different types of metamemory judgment as these judgments are based on common mechanisms.

Although metamemory monitoring is theorized to play a key role in learning and memory, the contribution of metamemory to the age-related decline in memory remains elusive. Wong et al. (2012) found that RCJ accuracy differed between younger and older adults even after controlling for memory performance. However, the question of whether this age-related decline in memory is mediated by changes in metamemory monitoring remains open. In addition, some evidence suggests a relationship between metamemory and EF. Both metamemory and EF are mediated by the prefrontal cortex (Chua et al., 2014). Also, some studies have found that the age-related decline in metacognitive control (e.g., study time) is partly due to EF decline (Souchay & Isingrini, 2004), and that performance on certain EF tasks (e.g., set-shifting) is associated with self-beliefs of metamemory efficacy in younger adults (Mäntylä et al., 2010) and with FOK accuracy in older adults (Souchay et al., 2000) (see Isingrini et al., 2008, for a discussion on the relationships among aging, metamemory, and EF). However, only FOK accuracy, but not JOL accuracy, significantly correlates with EF measures in older adults (Souchay et al., 2004), and impairment in JOL accuracy, but not in FOK accuracy, has been found in dysexecutive patients (Pinon et al., 2005), suggesting specific (but equivocal) relationships between metamemory and EF. However, this varied research does not elucidate the role of age-related changes in metamemory monitoring to explain age-related decline in memory beyond EF deterioration.

The aim of the present study was to clarify the effect of aging on metamemory monitoring and the roles of metamemory and EF in the relationship between aging and episodic memory. Recently, we developed a face-scene paired-associate learning task that enables the comparison of JOL, FOK, and RCJ (Yeung, 2022). This task places little demand on language and therefore is usable for a wide range of age and education levels. Because the present study focused on almost the entire adulthood, and the level of education varied greatly in the Hong Kong (Chinese) adult population (Census and Statistics Department of the Government of the Hong Kong Special Administrative Region, 2021), this study used this visual paired-associate learning task to probe metamemory processes.

Aging is associated with a functional decline in the prefrontal cortex (Cabeza & Dennis, 2013; West, 1996), a region implicated in metamemory (Chua et al., 2014). Metamemory judgments are also believed to be based on the same system of inferences about available cues, although the cues partly differ across judgments (Dunlosky & Tauber, 2013). Therefore, if aging is associated with deficits in general inferences from cues, age differences in metamemory would be similar across judgment types. In contrast, if aging is associated with deficits in activating and utilizing certain cues, the age differences in metamemory would be moderated by judgment types. In addition, metamemory judgments are partially distinct from episodic memory and EF (Pinon et al., 2005; Wong et al., 2012). Therefore, the age difference in metamemory was expected to remain significant after controlling for memory and EF performances, and both metamemory and EF predicted the age-related decline in memory.

Methods

Participants

One hundred 39 Chinese adults aged 18–79 years were recruited via advertisement on the university campus. Exclusion criteria included: (1) a history of any neuropsychiatric disorder; (2) a traumatic brain injury that required hospitalization; (3) currently used psychotropic medication; (4) left handedness; (5) nonfluency in Cantonese speaking; (6) self-reported visual impairment even after correction. To achieve stratified sampling, implemented to ensure an even age distribution and prevent the overrepresentation of young adults, 44–51 individuals with an approximate 1:1 male-to-female ratio were recruited from each of the three age groups: 18–39 years (young adults), 40–59 years (middle-aged adults), and 60–79 years (old adults). The Hong Kong Montreal Cognitive Assessment (HK-MoCA) was administered to all individuals (Wong et al., 2009). No participant scored below the cutoff (18/19) for dementia. Participants gave written informed consent before the study began. The present study was approved by the Human Subjects Ethics Sub-committee of The Hong Kong Polytechnic University (HSEARS20201110006) and conducted in compliance with the Declaration of Helsinki.

To ensure the inclusion of valid data in analyses, 35 participants were excluded for the following reasons: (1) missing gamma score

Table 1. Means and standard deviations of the demographic variables

	Descriptive statistics	
	Mean	*SD*
Demographic variables		
Age (years)	46.1	17.9
Sex (males/females)	50/54	/
Education (years)	16.2	3.9

across all three judgment types on at least one test trial ($n = 31$); (2) missing gamma score on more than one test trial for at least one judgment type ($n = 2$); (3) lack of completion of EF tasks ($n = 2$). Thus, the final sample consisted of 104 adults with a mean age of 46.1 years (see Table 1). This sample size was determined based on a previous study that reported altered RCJ accuracy and confidence levels in older adults compared to younger adults (Wong et al., 2012). Given a mean Cohen's f of 0.31 ($r = .30$), a power of 0.80, an alpha level of 0.05, and the use of two-tailed Pearson's correlation tests, the estimated required sample size was 85. Because middle-aged adults were recruited in the present study to give a full picture of age differences in metamemory across adulthood, the sample size recruited was slightly larger than the one required to ensure enough power. There was no significant difference in the proportion of participants excluded among the three age groups (young: 12/51; middle-aged: 10/44; old: 12/44), $\chi^2(2) = 0.28$, $p = .87$.

Regarding the socioeconomic background, the young adults were mostly university students, and the middle-aged and old adults came from diverse backgrounds (i.e., university staff and visitors who were retired or holding a wide variety of occupations). Due to the university setting of the study, the educational levels of the present sample were generally higher than those of the general population across age groups (Census and Statistics Department of the Government of the Hong Kong Special Administrative Region, 2021).

Procedure

Eligible participants were invited to the university campus to take part in an aging study. After providing consent, each participant completed a background questionnaire and performed several tasks to assess metamemory (paired-associate learning) and EF (Attention Network Test, animal fluency, Shape Trail Test). The administration order of the tasks was fixed for each participant: (1) Attention Network Test; (2) paired-associate learning; (3) animal fluency; and (4) Shape Trail Test. For computerized tasks, stimuli were presented using the E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA).

Test materials

Metamemory monitoring

A face-scene paired-associate learning task was used to assess metamemory monitoring (Fig. 1). This task was described elsewhere (see Yeung, 2022, for details and justification of task design). Test stimuli included 54 photographs of neutral, front-facing Chinese adult faces taken from the CUHK student database (Wang & Tang, 2008) and 54 scenic pictures that were in the "people" category from the Nencki Affective Picture System (Marchewka et al., 2014). The 54 faces and 54 scenes were randomly paired and then equally divided into three sets for each participant.

There were three test trials, each of which began with a study phase, followed by a distractor task and then a test phase. During the study phase, pairs of faces and scenes were presented on the left and right sides of a computer screen, respectively, one pair at a time. After 3 s, the JOL question ("Will you remember after 5 min?") and a Likert scale ranging from 1 ("no") to 9 ("yes") appeared onscreen. Participants made a JOL by touching a scale point within 5 s, during which the face–scene pair remained onscreen. Thus, the study time was 8 s per pair. The stimulus pair was then followed by 1 s interstimulus interval.

After studying all 18 face–scene pairs, participants performed a visual go/no-go distractor task for 60 s, followed by the beginning of the test phase. For each item, participants were first shown a previously studied face and prompted to indicate whether they could recall the picture paired with the face (i.e., answering "yes" or "no"). Because it is impossible to retrieve every detail of a real-world scenic picture studied for 8 s, the responses reflected the retrievability of partial information only. After that, participants made a FOK ("Will you recognize, given 3 alternatives?") by rating on a Likert scale from 1 ("no") to 9 ("yes"). In keeping with some studies, FOKs were solicited regardless of the outcome of the retrieval attempt (Chua & Solinger, 2015; Koriat, 1993).

After rating the FOK, participants were given a three-alternative forced-choice recognition test. One face was shown at the top of the screen, and three scenic pictures were shown at the bottom (Modirrousta & Fellows, 2008). One scene was the target, while the other two had been paired with another same-valence face or a different-valence face. Participants chose the scene paired with the target face by touching the picture. They then made an RCJ ("Confident that you were correct?") by rating from 1 ("no") to 9 ("yes"). The next test trial with a different set of stimuli began after all the face–scene pairs had been rated and tested. Participants practiced the task with two stimulus pairs before the actual start of the task. They were explicitly instructed to use the full range of the rating scales.

In young adults (Yeung, 2022), the internal consistencies of recognition performance and mean confidence judgments on this task were good to excellent. In addition, the internal consistencies of metamemory accuracy in terms of gamma coefficients varied from poor to excellent. The traditional Goodman–Kruskal (G–K) gamma, estimated based on concordant and discordant pairs of observations, had limited internal consistency across judgment types (Goodman & Kruskal, 1954; Nelson & Narens, 1990). In contrast, a new gamma (H–H gamma), estimated via the receiver-operating characteristic (ROC) curve and the trapezoidal rule, was found to be more accurate than the G–K gamma (Higham & Higham, 2019) and had higher internal consistencies overall. Therefore, the present study used this ROC-based gamma as a proxy for metamemory accuracy, but the G–K gamma was also analyzed to facilitate comparison with other studies.

EF skills

Three tasks were used to assess EF skills. First, the Shape Trail Test was used to assess mental flexibility (Yeung et al., 2016). This test is a variant of the Trail Making Test culturally adapted for the Chinese population. This test had two parts. During Part A, participants were asked to join, in ascending order, the circles on a paper with the numerals 1–25 in the circles. During Part B, participants were also asked to join the circles in ascending numerical order. However, the page contained two sets of numbers, one embedded in circles and the other one embedded in squares, and participants needed to alternate between circles and

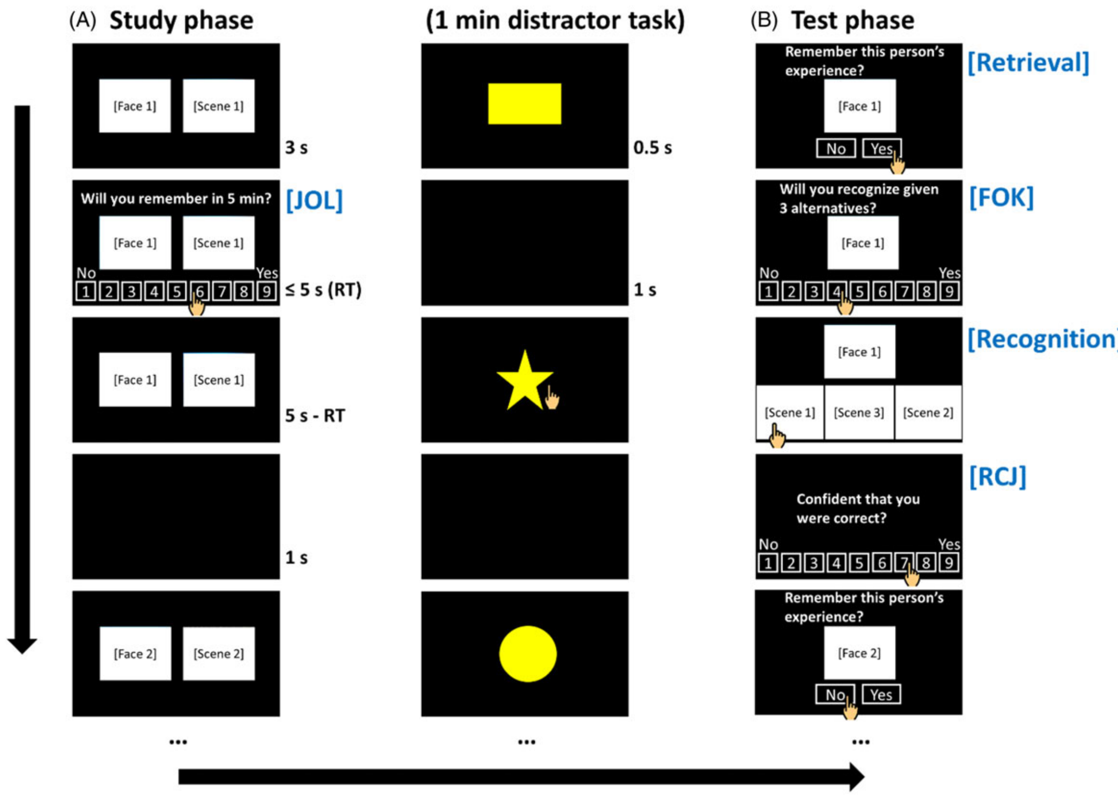

Figure 1. The face-scene paired-associate learning task. This figure was taken from Yeung (2023) and reused under the Creative Commons CC-BY 4.0 license.

squares. The dependent variable (DV) was the difference in time to completion between the two parts.

The Attention Network Test, which is essentially a flanker task, was employed to assess inhibitory control (Yeung, 2023). In this task, horizontal arrays of five arrows were presented on either the top or bottom of the screen, one array at a time. The task was to judge the pointing direction (left and right) of the central arrow as fast as possible via a button press. On each trial, the pointing direction of the central arrow was either the same (congruent) or different (incongruent) from the pointing direction of the peripheral arrows. The time limit was 1.7 s, and the intertrial interval was 4 s. The DV was the difference in mean reaction time (RT) between congruent and incongruent trials.

The animal fluency test, administered as a subtest of the HK-MoCA (Wong et al., 2009), was used to assess verbal fluency, or access to long-term memory. Participants were asked to generate as many animal names as possible within 60 s. No repetition was allowed. The DV was the total number of correct and unique words generated.

The present EF tasks were chosen based on previous studies investigating the role of EF in the age-related decline in episodic memory (Crawford et al., 2000; Lee et al., 2012). Like metamemory, these tasks are sensitive to frontal lobe functioning (Hu et al., 2013; Robinson et al., 2012; Varjacic et al., 2018). In addition, these tasks required the control of attention toward task-relevant information and the monitoring of information retrieved from long-term memory, which were processes involved in metamemory judgments. For example, while making FOK judgments, one needed to retrieve and select memory traces relevant to the present trial while inhibiting access and attention toward the irrelevant information.

Data processing and analyses

The relationships among demographic variables and the relationship among age, EF, and episodic memory were first examined. A composite EF *Z*-score was derived by averaging the *Z*-scores of the three primary measures. The *Z*-transformation was based on the entire analytic sample. The scores were transformed, where appropriate, so that higher scores represented better task performance. Memory performance was represented by the mean recognition accuracy on the paired-associate learning task.

For metamemory accuracy, two gamma coefficients were analyzed, but interpretation was based on the H–H gamma recently found to be less biased than the traditional G–K gamma (Higham & Higham, 2019). The H–H gamma was computed via ROC curves and the trapezoidal rule. It was calculated for each judgment type by considering the predictability of the ratings on subsequent recognition performance. The gamma score was estimated for each test trial and then averaged across the three trials. Because of the imperfect relationship between the retrieval response and recognition performance, FOK accuracy was computed based on all items (Yeung, 2022).

To investigate the effects of aging on metamemory and the specificity of these effects, repeated measures ANCOVAs, with judgment type (JOL, FOK, and RCJ) as a within-subjects factor, and age, composite EF score, and mean recognition accuracy as continuous predictors, were conducted separately on mean judgment ratings and the gamma coefficients. All predictors were mean-centered before analyses. The Greenhouse–Geisser correction was applied when the sphericity assumption was violated. Bonferroni tests or multiple regression tests were used for *post hoc* analyses.

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Table 2. Means and standard deviations of the outcome measures

	Descriptive statistics	
	Mean	*SD*
Executive function tasks		
Flanker: Reaction time interference (ms; incongruent minus congruent)	104.4	36.9
Shape Trail Test: Time to completion (s; Part B minus Part A)	53.4	22.9
Animal fluency: Number of words produced	22.4	6.1
Composite executive function *Z*-score	0.00	2.00
Paired-associate learning task		
Mean recognition accuracy (%)	64.7	13.9
Mean JOC confidence ratings	5.4	1.5
Mean FOK confidence ratings	5.2	1.4
Mean RCJ confidence ratings	6.2	1.5
JOL H–H gamma	−.03	.28
FOK H–H gamma	.09	.23
RCJ H–H gamma	.18	.34
JOL G–K gamma	.11	.32
FOK G–K gamma	.21	.35
RCJ G–K gamma	.43	.28

FOK = feeling-of-knowing judgment, HKLLT = Hong Kong List Learning Test, JOL = judgment of learning, RCJ = retrospective confidence judgment. Gamma was estimated using the Higham–Higham (H–H) or Goodman–Kruskal (G–K) method.

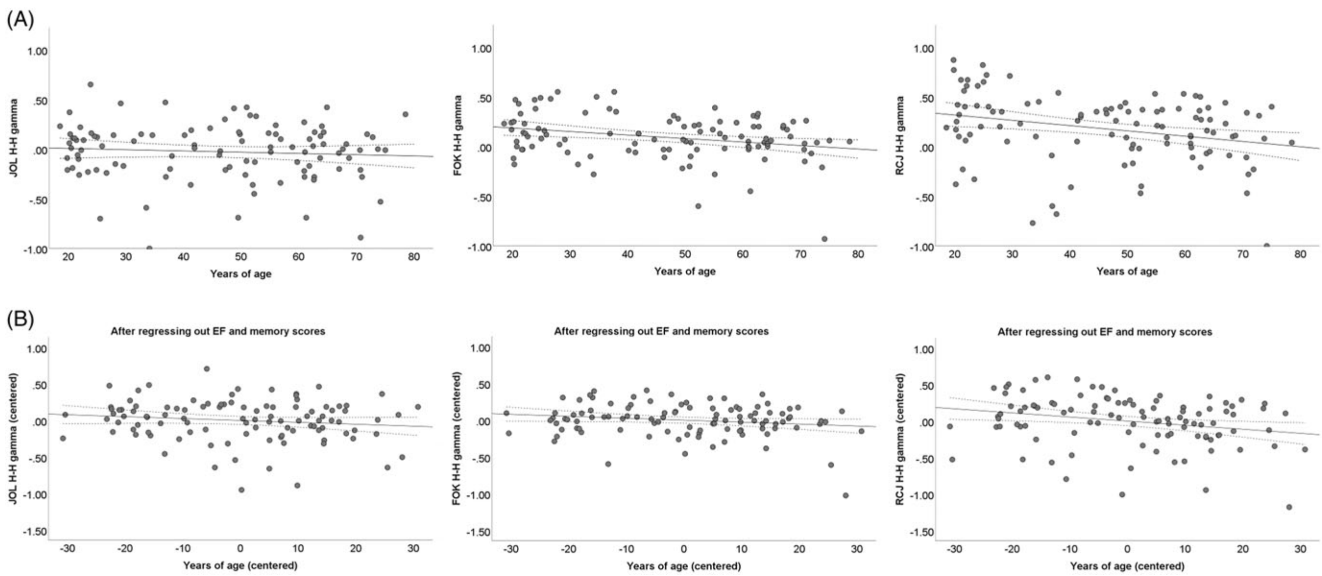

Figure 2. Relationships between age and metamemory accuracy. EF = executive function, FOK = feeling-of-knowing judgment, JOL = judgment of learning, RCJ = retrospective confidence judgment. The scatterplots show the relationships between age and Higham–Higham (H–H) gamma coefficients (A) before and (B) after regressing out EF and memory scores. A regression line with the 95% confidence interval was fitted to each plot.

To understand the mechanisms underlying the relationship between age and episodic memory, a mediation analysis was performed with EF and metamemory variables that were significantly associated with age (independent variable) and mean recognition accuracy (outcome variable) as mediators. The analysis was done using the PROCESS macro (version 4.2; Hayes, 2017) for IBM SPSS Statistics for Windows, Version 28.0 (IBM Corp., Armonk, NY). The model number was four, and the 95% confidence intervals were determined based on 10,000 bootstrap samples. The alpha level was 0.05.

Results

Sample characteristics

The descriptive statistics of the demographic and task variables are presented in Tables 1 and 2. An independent-sample *t* test and a Pearson's correlation test showed that age neither significantly differed between males and females nor significantly correlated with years of education, $ps > .15$. In addition, as expected, age significantly negatively correlated with both the composite EF *Z*-score, $r(102) = -.47$, $p < .001$, and mean recognition accuracy, $r(102) = -.45$, $p < .001$. As such, the EF and memory scores were covaried in all subsequent analyses.

Metamemory accuracy

Next, the effect of aging on metamemory accuracy was analyzed. The relationships between age and the H–H gamma coefficient before and after regressing out the EF and memory scores are depicted in Figure 2. A repeated measures ANOVA, with judgment type as a within-subject factor, and age, composite EF *Z*-score, and mean recognition accuracy as continuous predictors, was

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Table 3. Repeated measures ANCOVA results for the Higham–Higham gamma coefficients

	ANCOVA Results			
	df	*F*	*p*	η_p^2
Judgment (JOL, FOK, RCJ)	1.8, 183	20.38	<.001***	.17
Age	1, 100	6.66	.011*	.062
Memory	1, 100	0.11	.74	.001
Executive function	1, 100	0.49	.49	.005
Judgment × Age	1.8, 183	1.25	.29	.012
Judgment × Memory	1.8, 183	1.33	.27	.013
Judgment × Executive function	1.8, 183	0.32	.71	.003

FOK = feeling-of-knowing judgment, JOL = judgment of learning, RCJ = retrospective confidence judgment.
*$p < .05$.
***$p < .001$.

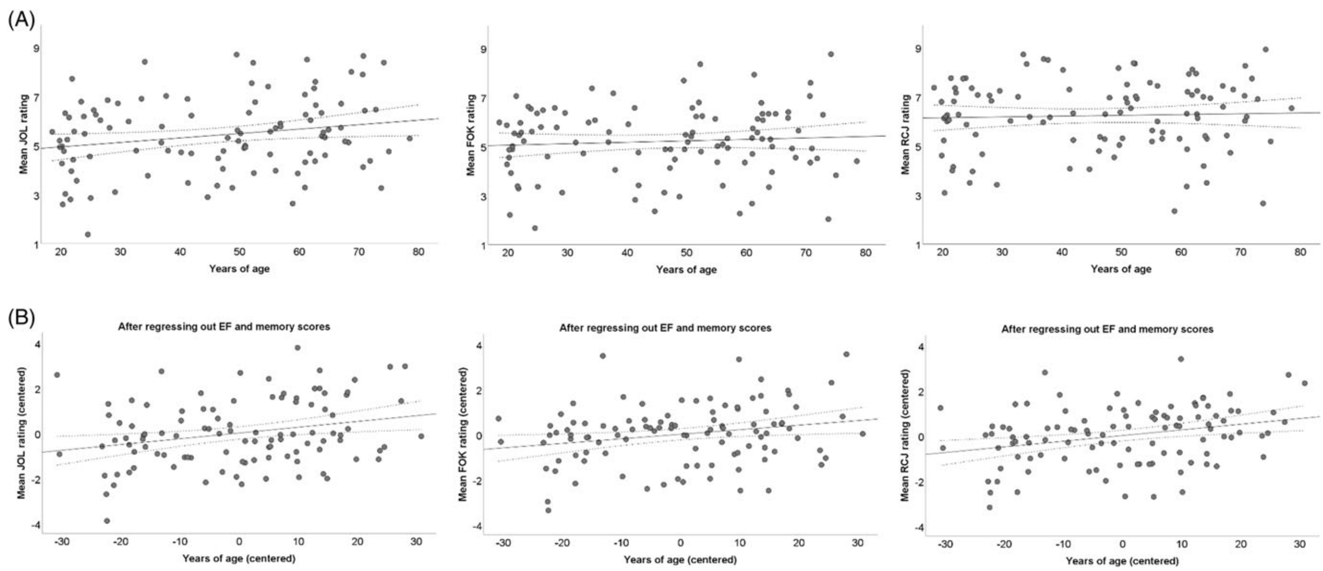

Figure 3. Relationships between age and mean confidence ratings. EF = executive function, FOK = feeling-of-knowing judgment, JOL = judgment of learning, RCJ = retrospective confidence judgment. The scatterplots show the relationships between age and mean confidence ratings (***a***) before and (***b***) after regressing out EF and memory scores. A regression line with the 95% confidence interval was fitted to each plot.

conducted on the H–H gamma coefficients. The test results are shown in Table 3.

The effect of age was significant, $F(1, 100) = 6.66$, $p = .011$, $\eta_p^2 = .062$, but age did not significantly interact with judgment type, $F(1.8, 183) = 1.25$, $p = .29$, $\eta_p^2 = .012$. These results suggest poorer metamemory accuracy with increasing age across different types of judgment. In addition, the effect of judgment type was highly significant, $F(1.8, 183) = 20.38$, $p < .001$, $\eta_p^2 = .17$. Bonferroni tests ($p < .05$) revealed that the RCJ gamma was significantly higher than the other two gamma estimates, and that the FOK gamma was significantly higher than the JOL gamma. None of the effects involving EF or memory was significant, $ps > .27$.

A repeated measures ANOVA was also repeated using the G–K gamma. None of the results significantly changed. That is, significant results were obtained only for the effect of age, $p = .035$, and the effect of judgment type, $p < .001$.

Metamemory confidence

The effect of aging on mean confidence ratings was then analyzed. The relationships between age and mean confidence ratings before and after regressing out the EF and memory scores are presented in Figure 3. A repeated measures ANOVA was conducted with judgment type as a within-subject factor, and age, years of education, composite EF *Z*-score, and mean recognition accuracy as continuous predictors. The test results are shown in Table 4.

The effect of age was significant, $F(1, 100) = 8.55$, $p = .004$, $\eta_p^2 = .079$, but age did not significantly interact with judgment type, $p = .57$. These results implied a positive relationship between age and mean rating across judgment types. In addition, the main effect of judgment type was significant, $F(1.7, 167) = 74.04$, $p < .001$, $\eta_p^2 = .43$. Bonferroni tests ($p < .05$) showed that confidence rating was significantly higher for RCJ than for other judgment types. The rating was also significantly higher for JOL than for FOK.

The effect of memory was significant, $F(1, 100) = 24.38$, $p < .001$, $\eta_p^2 = .20$. Because memory also significantly interacted with judgment type, $F(1.7, 167) = 5.60$, $p = .007$, $\eta_p^2 = .053$, multiple regression with age, memory, and EF scores as predictors and mean rating as the DV was performed separately for each judgment type. The results are shown in Table 5. For each judgment type, both age and memory score significantly predicted the rating, whereas the EF score did not, $ps > .05$. Based on the beta estimate, the relationship between confidence rating and memory performance was strongest for RCJ.

Table 4. Repeated measures ANCOVA results for mean confidence ratings

	ANCOVA Results			
	df	*F*	*p*	η_p^2
Judgment (JOL, FOK, RCJ)	1.7, 167	74.04	<.001***	.43
Age	1, 100	8.55	.004**	.079
Memory	1, 100	24.38	<.001***	.20
Executive function	1, 100	0.48	.49	.005
Judgment × Age	1.7, 167	0.50	.57	.005
Judgment × Memory	1.7, 167	5.60	.007**	.053
Judgment × Executive function	1.7, 167	2.58	.089	.025

FOK = feeling-of-knowing judgment, JOL = judgment of learning, RCJ = retrospective confidence judgment.
**$p < .01$.
***$p < .001$.

Table 5. Linear regression results for mean confidence ratings

	Metamemory Judgment											
	JOL				FOK				RCJ			
	B	*SE*	*t*	*p*	*B*	*SE*	*t*	*p*	*B*	*SE*	*t*	*p*
Age	0.025	0.009	2.69	.008**	0.020	0.009	2.35	.021*	0.025	0.008	3.06	.003**
Memory	0.038	0.012	3.30	.001**	0.046	0.011	4.37	<.001***	0.062	0.010	6.18	<.001***
Executive function	−0.11	0.082	−1.38	.17	−0.034	0.075	−0.46	.65	0.001	0.071	0.02	.98

FOK = feeling-of-knowing judgment, JOL = judgment of learning, RCJ = retrospective confidence judgment.
*$p < .05$.
**$p < .01$.
***$p < .001$.

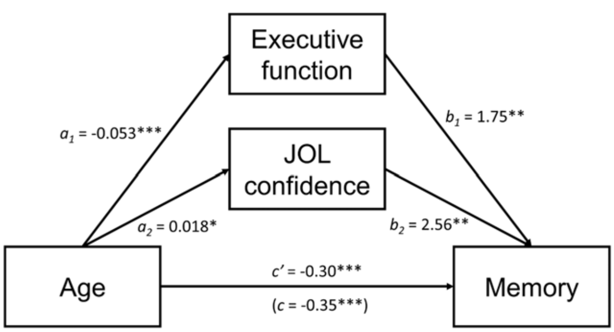

Figure 4. Mediating effects of judgment of learning (JOL) confidence and executive function in the relationship between age and episodic memory. All presented effects are unstandardized. *$p < .05$, **$p < .01$, ***$p < .001$.

Mediating effects of learning confidence and EF on the relationship between aging and episodic memory

These analyses revealed significant relationships among age, EF, and memory, and among age, confidence ratings, and memory. To better understand the mechanisms underlying the relationship between age and memory, a mediation analysis was performed with age as the independent variable, mean recognition accuracy as the outcome variable, and mean JOL confidence rating and composite EF *Z*-score as mediators. The JOL rating was chosen because it represented the level of confidence during the encoding or memory formation stage.

The mediation results are shown in Figure 4. Age was associated with poorer EF ($a_1 = -0.053$, $p < .001$), and poorer EF was subsequently related to poorer memory ($b_1 = 1.75$, $p = .009$). The indirect effect through EF, holding JOL confidence constant, was significantly below zero, 95% CI [−0.17, −0.03]. In addition, age was associated with higher confidence during learning ($a_2 = 0.018$, $p = .031$), and a higher confidence of learning was subsequently related to better recognition performance ($b_2 = 2.56$, $p = .001$). A 95% confidence interval based on 10,000 bootstrap samples suggested that the indirect effect through JOL confidence, holding EF constant, was significantly above zero, 95% CI [0.004, 0.14]. The relationship between age and memory remained significant after controlling for age's indirect effect through the two mediators ($c' = -0.30$, $p < .001$), indicating partial mediation effects.

Discussion

This study aimed to examine the effect of aging on metamemory monitoring and the roles of metamemory and EF in age-associated memory decline. A paired-associate learning task that probed JOL, FOK, and RCJ was administered to adults aged 18–79 years. There were two major findings. First, aging was associated with a decline in metamemory accuracy and an increase in confidence across judgment types. These changes remained significant after accounting for EF and memory performances. Second, both confidence of learning and EF ability partially mediated the relationship between aging and memory, such that higher confidence during encoding and better EF skills predicted better memory with increasing age. These findings have clarified the effect of aging on metamemory monitoring and the psychological mechanisms underlying the aging of episodic memory.

The relationship between aging and metamemory accuracy has been elusive. Most previous studies examined only one judgment type at a time, and differences among studies in sample and task features made it difficult to infer the nature of the age difference in metamemory monitoring. Kuhlmann and Undorf (2018) have found preservation of JOL for familiarity (i.e., recognition), but not for recollection, with aging. Other studies have found an association between aging and impaired FOK accuracy (Souchay et al., 2000; Souchay et al., 2007), whereas

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others have not (Eakin & Hertzog, 2012; Eakin et al., 2014; Hertzog et al., 2010; MacLaverty & Hertzog, 2009). In addition, while Wong et al. (2012) found that aging negatively affected RCJ accuracy, Eakin et al. (2014) reported null age effects. The merit of the present study is its use of a within-subject design and a moderately large sample to compare the age effects on different kinds of metamemory judgment. The isomechanism framework of metacognition posits that all metacognitive judgments are based on the same processes of inferences about available cues, although the cues differ partly across judgment types (Dunlosky & Tauber, 2013). Accordingly, the lack of a significant interaction between age and judgment type suggests an age-related decline in inference-based processes rather than a specific decline in activating or utilizing certain cues.

To explain the conflicting reports of age effects on FOK accuracy, Eakin et al. (2014) argued that the significant age effects reported in some previous studies (Souchay et al., 2000, 2007) might be due to the recruitment of older adults with lower cognitive functioning and lower education level compared to younger adults. The present study found that the relationship between aging and reduced metamemory accuracy existed even after controlling for the two cognitive functions known to be vulnerable to decline over age (i.e., EF and memory). Thus, there is a unique negative relationship between aging and metamemory accuracy that cannot be explained by age differences in EF or memory.

The present study compared two gamma estimation methods in light of the recent finding that the H–H gamma, using ROC curves and the trapezoidal rule, deviates less from the true value of gamma compared to the traditional G–K gamma (Higham & Higham, 2019). Our recent study compared the internal consistencies of the two gamma estimates and found the H–H gamma to have higher internal consistency overall (Yeung, 2022). In the present study, after covarying potential confounds, a significant age effect on metamemory accuracy emerged, regardless of the method used to estimate gamma. Indeed, the H–H gamma was as sensitive, if not more sensitive, in revealing the age difference in metamemory accuracy. Since this gamma is proven to be more accurate (Higham & Higham, 2019) and internally consistent (Yeung, 2022), compared to the traditional one, the present study supports the use of the ROC-based gamma in future aging studies.

Both age and memory performance predicted higher confidence across judgment types. The positive link between memory and confidence in one's memory was expected and supported the validity of the rating scale. In addition, the positive relationship between age and confidence level occurred despite the decrease in memory performance with increasing age. This finding aligns with the previous finding of the overestimation of subsequent memory performance at the time of study in older adults compared to younger adults (Connor et al., 1997). However, it contrasts with the previous finding of similar episodic FOK confidence judgments and lower episodic RCJ in older adults (Eakin et al., 2014). The present study found no significant interaction between age and judgment type for confidence ratings. The effect was very small ($\eta_p^2 = .005$). The FOK and RCJ in both Eakin et al. (2014) and this study were based on recognition memory performance. Therefore, the type of memory task does not appear to explain the discrepancy. Nevertheless, the present study used a Likert scale of varying confidence levels, whereas Eakin et al. (2014) used the percentage likelihood of correct recognition. Further investigation is needed to determine whether this methodological difference explains the discrepant FOK and RCJ findings.

To understand whether age-related changes in metamemory confidence explained the age difference in memory above and beyond EF, a mediation analysis was performed. This analysis gave us important insights into the mechanism underlying the link between the increased confidence and declined memory that occurred with increasing age. There was an indirect relationship between age and memory, such that aging was associated with an increase in confidence during learning, and greater confidence was subsequently related to better recognition performance. These occurred after controlling for EF, a known mediator of the age-related decline in memory (also replicated in this study) (Crawford et al., 2000; Lee et al., 2012). Thus, the increased confidence of learning represents a compensatory mechanism that mitigates the age-related decline in memory. The present findings have important practical implications as they suggest that boosting confidence during learning (e.g., correcting negative self-beliefs) and enhancing EF might be memory intervention strategies for older adults. Nevertheless, future experimental work is needed to ascertain the causal effect of boosting one's confidence of learning on subsequent memory performance.

Although this study contributes to the literature by clarifying the effect of aging on metamemory monitoring and the roles of metamemory and EF in the age-related decline in memory, it has limitations. First, it examined only episodic metamemory. Some evidence suggests that the effect of aging on episodic and semantic metamemory judgments differ (Eakin et al., 2014). Thus, future work would benefit from comparing the different kinds of metamemory judgment between episodic and semantic memory tasks. Second, while a distinction between metamemory monitoring (i.e., confidence judgments) and metamemory control (i.e., study strategies) has been made, the present study was designed to investigate monitoring processes only. According to Nelson and Narens (1990), monitoring and control processes interact and influence each other throughout the acquisition process. Thus, although the present study failed to find a link between metamemory accuracy and memory performance, the possibility remains that metamemory monitoring influences control processes, which then determine memory performance. Third, the face-scene task required the recognition rather than free recall of items. Because recognition and recall may rely on different neurocognitive processes (Brown et al., 2010), whether the present findings are generalizable to recall tasks remains to be determined. Fourth, the present study was based on a highly educated sample. More research is needed to determine whether the findings could be generalized to the less educated population.

Accumulating evidence suggests that accelerated memory decline is one of the early signs of dementia and one of the best neuropsychological predictors of dementia development (Gainotti et al., 2014; Tromp et al., 2015). It would be worthwhile to examine whether the present findings are generalizable to the mild cognitive impairment and dementia populations, and whether boosting confidence during learning and improving EF skills could facilitate learning and memory in individuals at risk of dementia. In addition, the prefrontal cortex and associated circuits have been implicated in metamemory, EF, and memory (Chua et al., 2014; Eichenbaum, 2017; Friedman & Robbins, 2022). Altered prefrontal cortex functioning is a hallmark feature of healthy aging (Cabeza & Dennis, 2013; West, 1996), and this change is particularly evident among older adults with memory problems (Li et al., 2015; Yeung et al., 2016, 2022). Future work would benefit from unraveling the neural basis of the present behavioral findings to devise better memory intervention methods for aging.

Data availability statement. The task and data on which the present results and study conclusion were based are available on OSF (https://osf.io/f3cxb/).

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