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Does age affect metacognition? A cross-domain investigation using a hierarchical Bayesian framework

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ABSTRACT

According to previous research, the accuracy of metacognitive judgments in aging depends on the cognitive domain involved in the task, the experimental design, and the metacognitive index used. Older adults are frequently less accurate than younger adults in judging their episodic memory, while no difference is typically observed for semantic metamemory. In addition, age-related changes in metaperception appear to be highly task-dependent. Other metacognitive domains (such as metacognition of executive functioning) have been seldom explored. This study aimed to integrate methodological and theoretical advances in the study of metacognition to answer the question of whether metacognition is impaired in healthy aging. Data were collected in a large sample ($n = 443$) of participants aged 18 to 79. Participants provided retrospective confidence judgments in four domains: episodic memory, semantic memory, executive functioning, and visual perception. Our measure of accuracy, metacognitive efficiency, was estimated using a hierarchical Bayesian implementation of the meta-*d'* model. Results showed that metacognitive efficiency decreased with age in the episodic task and increased with age in the semantic task. There was no effect of age on metacognitive efficiency in the executive and perception tasks. Moreover, metacognitive efficiency appeared to rely on a domain-general process in older adults. Explaining the episodic metamemory deficit in aging could help understand the difficulties of older adults to use inferential processes for memory search and retrieval as well as their difficulties to implement memory strategies.

1. Introduction

Metacognition, the capacity to monitor and control cognitive functions, such as memory (metamemory; Flavell, 1971; Nelson & Narens, 1990), perception (metaperception; Mamassian, 2016; Rahnev, 2021) or motor skills (e.g., Metcalfe & Greene, 2007; Wen, Charles, & Haggard, 2023) is of critical importance in understanding the cognitive function of older adults. With impaired metacognitive function, older adults will fail to implement appropriate cognitive strategies and allocate resources efficiently (e.g., Bastin & Van der Linden, 2005; Souchay & Isingrini, 2004), and thus will not adapt their cognitive processes according to the cognitive changes they experience. Whilst there is a rather well-developed literature on metacognition in aging, it tends to be piecemeal, focusing on one domain or another as a micro-level explanation of age-related decline (e.g., Park & Schwarz, 2012) and there are inconsistencies in results according to the domain and type of metacognitive measure used. Moreover, most approaches overlook a key conceptual issue which could shed light on such a pattern of results: the notion that metacognition might be organized in a domain-general fashion (Ais, Zylberberg, Barttfeld, & Sigman, 2016; Faivre, Filevich, Solovey, Kühn, & Blanke, 2018; Lee, Ruby, Giles, & Lau, 2018; Lund, Correa, Fardo, Fleming, & Allen, 2023; Mazancieux, Fleming, Souchay, & Moulin, 2020; Rouault, McWilliams, Allen, & Fleming, 2018), and therefore may be ubiquitously impaired (or maintained) in healthy

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aging. Our aim in this paper was thus to consider more recent models of metacognition and methods to address the question of whether metacognition is impaired in healthy aging across a number of different domains in the same individuals. Before discussing the existing literature on metacognition in older adults, we review the key elements of cognitive changes in aging.

Aging does not affect all cognitive processes in the same way; with some processes experiencing age-related change, and others remaining relatively stable. The cognitive components related to reasoning and cognitive control decrease (Horn & Cattell, 1967; Khammash, Rajagopal, & Polk, 2023; Park et al., 2002). In particular, executive functions, encompassing problem solving and carrying out non-automatic tasks such as working memory, attention, inhibition, or planning (Diamond, 2013) decrease with aging (see Reuter-Lorenz, Festini, & Jantz, 2021 for a review). In contrast, semantic processes (i.e., verbal and general knowledge) improve or remain stable across the lifespan (Khammash et al., 2023). This dissociation is reflected in memory, with differences observed between episodic and semantic memory (Cosgrove, Kenett, Beaty, & Diaz, 2021; Mitchell, 1989; Nyberg, Bäckman, Erngrund, Olofsson, & Nilsson, 1996). Episodic memory (i.e., memory of personal experiences, containing the temporal and spatial context of learning; Tulving, 1972) declines with age (Mitchell, 1989; Tromp, Dufour, Lithfous, Pebayle, & Després, 2015), whereas semantic memory (i.e., memory of knowledge about the world; Tulving, 1972) improves or remains stable (Kavé & Halamish, 2015; Mitchell, 1989). The episodic memory decline may be due to weaker encoding (Friedman, Nessler, & Johnson, 2007; Giffard, Desgranges, & Eustache, 2001; Gutchess, Ieuji, & Federmeier, 2007; Morcom et al., 2010), or difficulty in retrieving spatiotemporal information from memory (i.e., a recollection deficit; Giffard et al., 2001; Healey & Kahana, 2016). Moreover, some memory processes appear to be more age-sensitive than others. For instance, familiarity (i.e., the feeling that something has been seen before without contextual information being retrieved) seems less impaired by aging than recollection (Koen & Yonelinas, 2014).

For other cognitive domains, such as visual perception (i.e., the ability to perceive and categorize visual stimuli; Lieberman, 1984), age-related changes depend on the cognitive load induced by the task (Faubert, 2002): an age-related decline is observed in perception tasks involving a high cognitive load, whereas there is no age effect in tasks inducing a lower cognitive load. These differences associated with cognitive load could result from the age-related changes observed in visual perception. For instance, older adults have difficulty to process temporal information and require more time than younger adults to process visual stimuli (Owsley, 2011). Thus, performance of older adults depends on the complexity of the neural network involved in the task (Faubert, 2002). Perception tasks that involve simultaneous processing or complex stimuli rely on complex neural networks that are more likely to be altered by aging.

One of the main questions in the field of metacognition in aging is to understand how age-related changes in cognitive processes influence metacognitive processes (Hertzog, Dunlosky, & Sinclair, 2010; Morson, Moulin, & Souchay, 2015; Sacher, Isingrini, & Taconnat, 2013). To assess metacognition, cognitive performance (also termed first-order performance) can be compared to metacognitive judgments, with the relationship between first-order performance and metacognitive judgments being termed second-order performance. Measuring the gap between first- and second-order performance allows us to estimate the accuracy of metacognitive judgments. There are a number of different paradigms which have been used to address this question, which we reviewed briefly here because it is pertinent to our understanding of the differences across tasks, domains and paradigms.

A first distinction in the types of metacognitive paradigms can be made between global and local judgments (Seow, Rouault, Gillan, & Fleming, 2021). For global metacognitive judgments, participants are asked to predict the number of items they would answer correctly. For local metacognitive judgments, on which we focused, participants are asked to judge their performance on each item separately. Different types of local metacognitive judgments can be used such as Judgments of Learning (JOLs; Arbuckle & Cuddy, 1969), Feelings of Knowing (FOK; Hart, 1965), or Retrospective Confidence Judgments (RCJs; e.g., Hertzog & Dunlosky, 2011). During JOLs, participants are asked to predict whether an episodic item (or a list of episodic items) will be later recalled or forgotten. FOK judgments are made prior to a memory task and assess the capacity to predict correct recognition using episodic or semantic material.

For studies aiming to test metacognition more broadly, RCJs tend to be used because they constrain the conceptual space to a decision about the correctness of a decision for any type of task (see Mazancieux et al., 2023). We use RCJs in the current study. They have been used to evaluate metacognition in several cognitive domains such as visual perception (e.g., Filippi, Ceccolini, Periche-Tomas, & Bright, 2020; Fleming, Ryu, Golfinos, & Blackmon, 2014; Palmer, David, & Fleming, 2014), short-term memory (McWilliams, Bibby, Steinbeis, David, & Fleming, 2023), episodic memory (e.g., Dodson, Bawa, & Krueger, 2007; Fleming et al., 2014; Hertzog, Curley, & Dunlosky, 2021; Palmer et al., 2014; Voskuilen, Ratcliff, & McKoon, 2018; Weidemann & Kahana, 2016), semantic memory (e.g., Lachman, Lachman, & Thronesbery, 1979), or executive functioning (Mazancieux et al., 2020). RCJs are based on several cues such as the familiarity of the cue, the fluency of the response, or the accessibility of the target (Castel, Middlebrooks, & McGillivray, 2015).

Given the predominance of memory deficits in aging, metacognition research has focused on metamemory (e.g., Dodson et al., 2007; Eakin, Hertzog, & Harris, 2014; Hertzog et al., 2010; Morson et al., 2015; Souchay, Isingrini, & Espagnet, 2000; Souchay, Moulin, Clarys, Taconnat, & Isingrini, 2007). The literature has shown so far that older adults are as accurate as younger adults using JOLs (see Castel et al., 2015 for a review). However, episodic metamemory judgments of older adults are less accurate than those of younger adults using FOKs (Castel et al., 2015; Devaluez, Mazancieux, & Souchay, 2023; Hertzog et al., 2010; Morson et al., 2015; Perrotin, Isingrini, Souchay, Clarys, & Taconnat, 2006; Perrotin, Tournelle, & Isingrini, 2008; Sacher et al., 2013; Souchay et al., 2007; Thomas, Bulevich, & Dubois, 2011) and RCJs (Dodson et al., 2007; Voskuilen et al., 2018). Nevertheless, the age effect on episodic FOK is not always found (e.g., Eakin et al., 2014). In contrast, there is no age difference on metamemory accuracy in semantic tasks using FOK (Allen-Burge & Storandt, 2000; Castel et al., 2015; Devaluez et al., 2023; Eakin et al., 2014; Lachman et al., 1979; Marquié & Huet, 2000; Morson et al., 2015; Souchay et al., 2007) and RCJs (Dahl, Allwood, & Hagberg, 2009; Dodson et al., 2007).

Moreover, the age effect on metamemory accuracy differs according to whether the confidence level is low or high. For example, older adults seem to be less accurate than younger adults for high confidence responses, but they are as accurate as younger adults for low confidence responses (Chua, Schacter, & Sperling, 2009; Dodson et al., 2007; Fandakova, Shing, & Lindenberger, 2013; Greene, Chism, & Naveh-Benjamin, 2022). The memory-constraint hypothesis argues that the age difference observed in metacognition might be due to the memory deficit rather than to a monitoring deficit (Hertzog et al., 2010). It is therefore essential to differentiate memory performance from metacognitive processes when assessing metamemory in order to explore the dissociation between first- and second-order processes in older adults.

Metacognition related to other cognitive domains has received less attention in the aging literature. We summarized here the few studies that have focused on visual perception and executive functioning. The metacognitive component linked to visual perception, *metaperception,* refers to the ability to judge the quality and the accuracy of our perceptions (Mamassian, 2016). Older adults appear to be less accurate when judging their perception on contrast discrimination tasks (using Gabor patches; Klever, Mamassian, & Billino, 2022; Palmer et al., 2014), but they are as accurate as younger adults when judging their perception on feature discrimination tasks (Filippi et al., 2020; McWilliams et al., 2023). These contradictory results suggest that metacognition in aging can be influenced by the nature of the perceptual decision.

Prior investigations of metacognition related to executive functioning in older adults have focused on metacognition for working memory tasks, with equivocal findings. Bertrand, Moulin, and Souchay (2017) and Bertrand et al. (2019) showed that metacognition is preserved in working memory tasks in both normal and pathological aging, whereas Bunnell, Baken, and Richards-Ward (1999) found that metacognition was impaired in working-memory with healthy older participants. Of note, these previous studies used global judgments (Bertrand et al., 2017; Bertrand et al., 2019; Bunnell et al., 1999). No study using local judgments has been carried out to test metacognition of processes related to executive functioning in aging. Local and global judgments are based on different processes (Seow et al., 2021), and are affected differently by aging (Castel et al., 2015; McWilliams et al., 2023).

The contradictory findings for local metacognition in aging might be due to limitations in the methods used to assess accuracy (Fleming et al., 2014). Metacognitive accuracy refers to the ability of the participant to discriminate between their correct and incorrect responses in the second-order responses they give. Most of the above studies have estimated metacognitive accuracy with correlational methods (e.g., Soderstrom, McCabe, & Rhodes, 2012; Souchay et al., 2007; Thomas et al., 2011; Vannini et al., 2019). For instance, the gamma correlation (Goodman & Kruskal, 1979) estimates metacognitive accuracy as a difference in the number of congruent responses (e.g., high confidence and right answer) compared to incongruent responses (e.g., high confidence and wrong answer). Nonetheless, gamma correlations (1) do not consider metacognitive bias (i.e., the tendency to be more or less confident overall), and (2) are influenced by first-order performance (Guggenmos, 2021; Masson & Rotello, 2009; Vuorre & Metcalfe, 2021). In older participants, metacognitive bias appears to depend on the task and on the type of confidence judgment used. Older adults are frequently overconfident in episodic tasks (Castel et al., 2015; Hertzog et al., 2021; Lovelace & Marsh, 1985; Soderstrom et al., 2012) and semantic tasks (Kavé & Halamish, 2015). Nevertheless, they give lower confidence judgments than younger adults in short-term memory tasks (Bertrand et al., 2017; McWilliams et al., 2023, but see Culot et al., 2023, developed below).

Whatever the direction of the effect, it seems important to have a measure of metacognitive accuracy that cancels out the effect of age on metacognitive bias. Moreover, given the dependence between first- and second-order performance when using correlational indices (Fleming & Lau, 2014; Guggenmos, 2021; Vuorre & Metcalfe, 2021), the effect of age on metacognition could be an artefact due to age-related decline of episodic memory. The measures of metacognitive accuracy may fail to distinguish between cognitive deficits and the metacognitive processes we seek to assess. Indeed, the age-related decline of the episodic FOK is not observed when older adults with high recognition performance are compared to younger adults with low recognition performance (Devaluez et al., 2023), suggesting that the first-order episodic deficit influences the metacognitive scores. To overcome these limitations, recent studies have suggested using model-based estimations of metacognitive accuracy based on signal detection theory (SDT; Barrett, Dienes, & Seth, 2013; Fleming & Lau, 2014). The *meta-d'* framework (Maniscalco & Lau, 2012, 2014) is based on an ideal observer model, computing an ideal first-order performance value (*d'*) from the observed confidence judgments (i.e., type-2 area under receiver operating characteristic curve, AUROC). This ideal *d'* or *meta-d'* can be then compared to the observed *d'* of a participant using the ratio between these two values known as *metacognitive efficiency* (M_{ratio}). A M_{ratio} of 1 is considered as ideal metacognitive efficiency as the participant used all available information from first-order performance to make their confidence judgments. However, a precise and reliable estimation of M_{ratio} per participant requires many trials (at least 400 trials per participant; Guggenmos, 2021). Studies with lower numbers of trials can take advantage of the ability to compute M_{ratio} at the group level using hierarchical Bayesian modeling (the *HMeta-d* model, Fleming, 2017). Thus, the *HMeta-d* limits the impact of participants with a high level of uncertainty by taking into account this uncertainty as well as between-subject uncertainty at the group level, providing more reliable group estimates of metacognitive efficiency when the number of items is limited (Fleming, 2017; Guggenmos, 2021).

Compared to other measures of metacognition, metacognitive efficiency using M_{ratio} provides estimates that have better (but not perfect) independence from first-order performance (Guggenmos, 2021; Rahnev, 2023; Shekhar & Rahnev, 2021), which is critical for exploring the domain generality of metacognition. Indeed, a major issue in the field of metacognition is to understand whether metacognition relies on one process common to all metacognitive domains (i.e., domain-general metacognition), on several metacognitive processes which differ according to the cognitive domain involved in the task (i.e., domain-specific metacognition), or whether metacognition is based on a more complex architecture (see Mazancieux et al., 2023). The most common method for studying the domain generality of metacognition is to explore the correlations of metacognitive accuracy between different domains (e.g., Lund et al., 2023; Mazancieux et al., 2020). Thus, if metacognition is domain general, metacognitive accuracy would be correlated across cognitive domains. A participant who makes accurate judgments in one task should make accurate judgments in another task. In younger adults, previous studies have found that metacognition seems to rely on a joint process between cognitive domains (i.e., domain-general metacognition; Lee et al., 2018; Lund et al., 2023; Mazancieux et al., 2020; McCurdy et al., 2013; West, Harrison, Matthews, Mattingley, & Sewell, 2023). Nevertheless, the conclusions on the domain generality of metacognition may be highly dependent on the tasks used (Lee et al., 2018; Rouault et al., 2018). For instance, the domain-generality of metacognition was observed with discrimination tasks (i.e., two-alternative forced-choice paradigm), but not with detection tasks (i.e., yes/no paradigm) (Lee et al., 2018).

The question of the domain specificity and generality has also been raised in the context of aging in order to detect a general factor that might explain age-related decline as a whole. In addition to the cerebral changes, other factors that could explain cognitive aging have been explored, such as genetic factors, general state of health, the decline of sensory systems (vision, hearing, etc.), or lifestyle (e.g. Deary et al., 2009; Lindenberger & Baltes, 1997; Ritchie et al., 2016). A small number of variables explain the inter-individual variability observed in aging (Ritchie et al., 2016). Age-related cognitive changes seem to be linked across various domains (Tucker-Drob, Brandmaier, & Lindenberger, 2019). Thus, the degree of decline in one cognitive domain is predictive of cognitive changes in other cognitive domains (Tucker-Drob et al., 2019). Thus, it could be proposed that a general process may explain part of the cognitive aging (Salthouse, 2000; Tucker-Drob, 2011; Tucker-Drob et al., 2019). Nevertheless, the age-related decline is also due to the decline of domain-specific factors, which explains the difference observed between different cognitive domains (Ritchie et al., 2016). Concerning metacognition, the variety of results observed between the different cognitive domains suggested a possible domain-specificity of metacognition. In other words, there could be different metacognitive processes, which might be more or less involved depending on the nature of the task, and the effect of age on these processes may differ. To our knowledge, no study has previously explored the domain-specificity of metacognition in aging using cross-task correlations.

In order to overcome the limitations of previous studies resulting from metacognitive measures and extend research to more cognitive domains, our study tested for the first time the effect of age on metacognition using the *HMeta-d* framework in four domains: episodic memory, semantic memory, executive functioning, and visual perception. It thus helps to understand whether metacognitive decline in older adults is the result of age-related cognitive changes in first-order processes, or whether it is the result of declining metacognitive monitoring.

We had two main aims: First, we wanted to estimate the age effect on performance, metacognitive bias, and metacognitive efficiency within different cognitive domains using a regression-based approach. We expected to observe an age-related decline of episodic memory (Mitchell, 1989; Tromp et al., 2015), executive functioning (Park et al., 2002), and visual perception (Faubert, 2002); whereas semantic memory should remain stable with age (Kavé & Halamish, 2015; Mitchell, 1989; Park et al., 2002).

Previous findings on the age effect on metacognitive bias are equivocal. We expected that participants would be more overconfident in episodic (Castel et al., 2015; Hertzog et al., 2021; Lovelace & Marsh, 1985; Soderstrom et al., 2012) and semantic (Kavé & Halamish, 2015) tasks. In line with studies using working memory tasks, we predicted that participants would be more underconfident with age in the executive task (Bertrand et al., 2017; McWilliams et al., 2023). For metaperception, using a similar tasks, a numerosity judgment and with the first-order performance held constant for age (fixed at ~70 % of correct responses with a staircase procedure), one study has shown that mean confidence decreased with age (McWilliams et al., 2023), whilst another study has shown that older adults were more confident than younger adults (Culot et al., 2023). We therefore formulated a nondirectional hypothesis for this task; predicting that we would observe an age effect on metacognitive bias in the visual task.

Concerning metacognitive efficiency, we expected to observe an age-related decline for the episodic component (Devaluez et al., 2023; Morson et al., 2015; Sacher et al., 2013; Souchay et al., 2000, 2007), but not for the other cognitive domains: semantic memory (Devaluez et al., 2023; Morson et al., 2015; Souchay et al., 2007), executive functioning (Bertrand et al., 2017), and visual perception (McWilliams et al., 2023). Our second aim was to test the domain-generality of metacognition by estimating cross-task correlations, and by comparing cross-task correlations in two age groups (i.e., younger and older participants). Considering the dissociations observed in metacognition of older adults between episodic and semantic tasks (Devaluez et al., 2023), and between episodic and perception tasks (Palmer et al., 2014), we expected to observe greater involvement of domain-specific processes for older adults than for younger adults.

Two different versions of the *HMeta-d* framework were used to meet the two objectives of the study. To assess the influence of age on metacognitive efficiency, we first used a version that estimates the regression parameters related to *Mratio* as a function of one or more covariates, such as age (called *RHmeta-d*; Harrison et al., 2021). To assess the domain generality of metacognition, we then used a version that estimates the correlation parameters between the *Mratios* of different tasks (Mazancieux et al., 2020).

2. Method

The de-identified data on which the study conclusions are based, the analytic design and materials are available on the OSF (See Meunier-Duperray et al., 2022). The study design, analysis and hypothesis were preregistered. We report below how we determined our sample size, any data exclusions, all manipulations, and all measures.

2.1. Participants

Our initial sample size was based on the number of participants estimated for cross-task correlations in Mazancieux et al. (2020) (i.e., 181 young adults). Considering the spread of ages across the lifespan, we preregistered three times this number (reflecting broadly younger, middle-aged and older adults). In a paper published subsequent to our preregistration with the same approach (McWilliams et al., 2023) a model converged with 304 participants of all ages (*mean* = 42.20; *sd* = 20.50), thus the sample size was revised downwards since preregistration. Data were collected from 442 participants aged 18 to 79. Three hundred and thirty-height participants completed the experiment online (age mean = 39.90; *sd* = 20.20), and 104 participants completed the experiment in-person (age mean = 49.50; *sd* = 20.00) at the University of Grenoble-Alpes or at the University of Tours. Fig. 1 shows the number of participants for each age in the online (in grey) and in-person (in black) test conditions. Given that no effect of testing type was found for task performance, metacognitive bias, and metacognitive efficiency (see supplemental material, Appendix A), analyses were collapsed across the entire sample. All participants were native French speakers and reported having no neurological or psychiatric disorders. The study received a favourable ethical opinion from the University Grenoble Alpes (i.e., Comité d'Ethique pour les Recherches de Grenoble-Alpes; CERGA) for the project named "Understanding metamemory in healthy aging (AGEFOK)" (protocol number CERGA-Avis-2022-12). Data were collected in France and Belgium, in French, between 2022 and 2023, online and in person.

2.2. Procedure and materials

The four tasks were adapted from Mazancieux and colleagues' study (Mazancieux et al., 2020) on PsychoPy (v2021.2.3) and were presented in fully random order. To avoid ceiling effects in younger adults, the presentation time was shortened for the executive and perception tasks.

The episodic memory task was composed of two phases. In a first phase, participants saw a 500-ms fixation cross followed by pairs of unrelated words (a cue and a target) presented one by one in random order for 2500 ms each. Following this encoding phase, a second phase displayed a 500-ms fixation cross followed by the same cues presented one by one in random order. Participants had to choose between two propositions, composed of the target word and a new word not previously presented (i.e., a distractor), which word was presented with the cue in the first phase without a time limit. The words (cues, targets, and distractors) were a noun or an adjective composed of six letters and two syllables extracted from the French Lexique database (New et al., 2004). Number of occurrences had been fixed between 20 and 100 per million.

For the semantic memory task, in each trial, participants saw a 500-ms fixation cross followed by a general knowledge question (e.g., *Which painter is the leading exponent of Cubism?*) and had to choose their response between two propositions without a time limit (e.g., *Picasso* or *Rubens*). These questions were adapted from the original experiment (Mazancieux et al., 2020) to suit the different ages of the sample. Seventy questions, including the 40 questions from the original experiment and 30 new questions, were tested with French samples of 43 young adults, 57 middle age, and 16 older adults. We selected 40 questions that participants of all ages were able to answer.

For the perception task, for each trial, participants saw a 500-ms fixation cross followed by two circles containing dots (see Fig. 2). One of the two circles always contained 50 dots, while half of the distractors contained between 25 and 49 dots, and the second half between 51 and 75 dots. The location of the dots for targets and distractors and the exact number of dots for the distractors were defined randomly (see Mazancieux et al., 2020). After a 1000-ms presentation, participants had to choose which circle contains the most dots.

The executive functioning task involved both attention and working memory. Participants will see a 500-ms fixation cross followed by sequences of five numbers and letters for 900 ms. The sequences had been randomly created before the experiment. Half of the trials contained two numbers and three letters whereas the other half contained three numbers and two letters. Participants had to choose between two propositions whose response corresponded to the sum of all numbers and to the sequence of letters presented before. The distractors differed from the target either by one letter or by the sum of the numbers. For instance, if the participants saw the sequence "1A1A7", the correct answer was "9AA", and the distractor would be either "9 AM" or "12AA".

For all tasks, participants chose their answer by pressing "F" to select the answer that appeared on the left of the screen, or "H" to select the

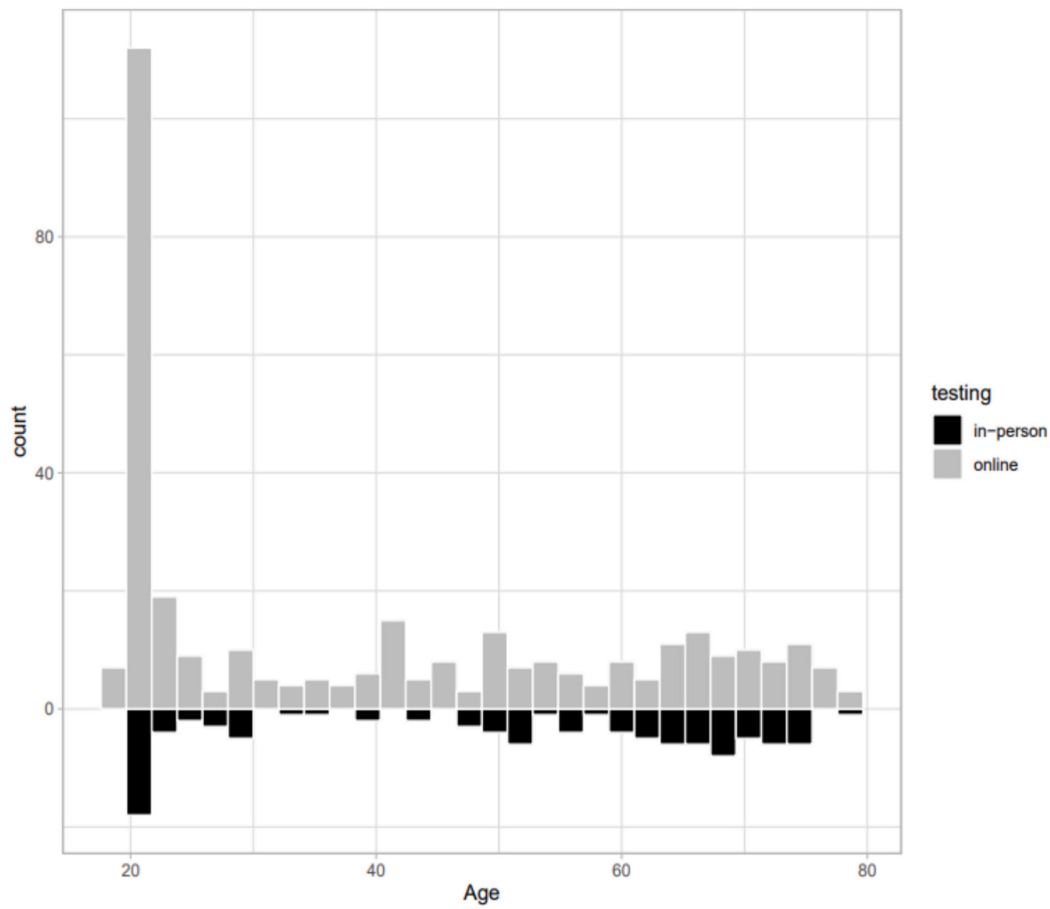

Fig. 1. Number of participants for each age in the online and in-person test conditions.

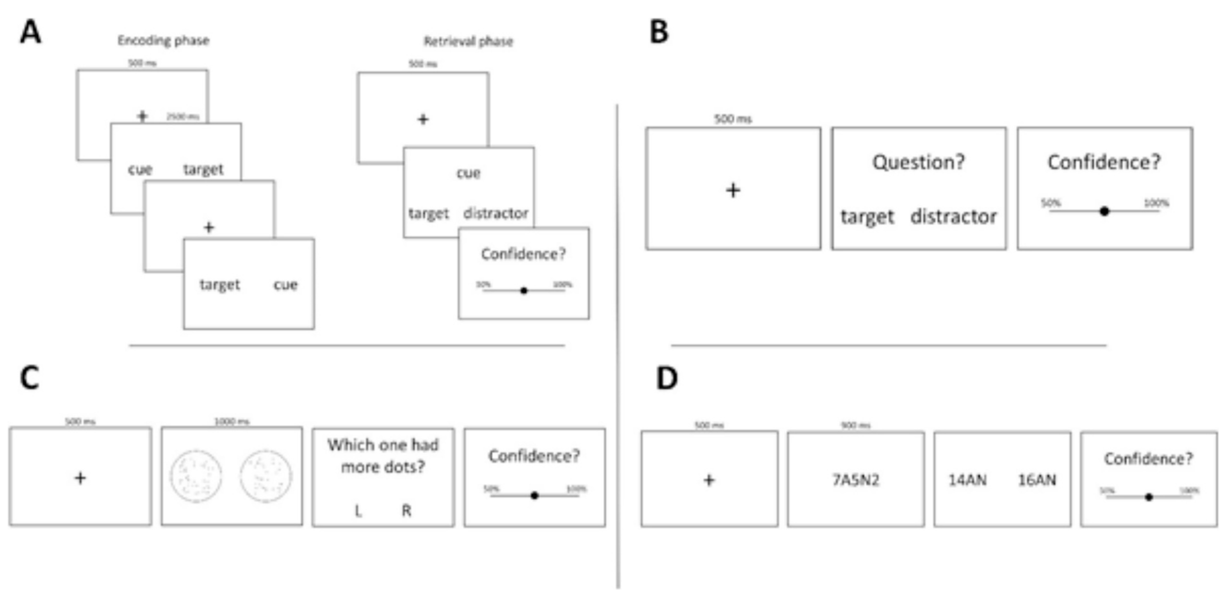

Fig. 2. Procedure and example stimuli of the four tasks: episodic, semantic, perception, and executive tasks.
Note. Figure adapted from "Is there a G factor for metacognition? Correlations in retrospective metacognitive sensitivity across tasks", by Mazancieux et al., 2020). *Journal of Experimental Psychology: General,* 149(9), 1788–1799 (https://doi.org/10.1037/xge0000746). A. The episodic task was composed by an encoding and retrieval phase of word pairs (i.e., one target and one distractor); B. The semantic task presented general knowledge questions and two proposed answers; C. The perception task consisted in choosing from two proposals the circle that contained the most dots; D. The executive task presented a series of letters and numbers, and consisted in choosing between two propositions the one that corresponded to the addition of the numbers followed by the letters. Confidence judgments were asked after each response.

answer that appeared on the right. A confidence judgment on the response given followed each trial of each task. Participants raised their confidence on a 6-point scale from 50 % (random response) to 100 % (very confident in the response given) using the mouse, with no limit of time. Each task contained 40 trials.

Fig. 2 summarizes the procedure of the four tasks. After the experiment, the participants gave their age and their educational level. In addition to their biological age, participants could indicate their subjective age. Participants also carried out an online survey about cognitive reserve (the Cognitive reserve Index questionnaire; Nucci et al., 2012). These two exploratory variables will not be presented here.

2.3. Data analyses and exclusions

Data were analyzed along two axes: First, regression parameters were estimated to test the age effect on cognition, metacognitive bias, and metacognitive efficiency with age as a continuous variable in the four cognitive domains independently. Second, cross-task correlations tested the domain-generality hypothesis, first on the sample as a whole, then on the sample divided into two age groups (i.e., younger participants under 60 and older participants over 59). Considering the recent development of the *HMeta-d* version which estimates regression parameters on metacognitive efficiency (Harrison et al., 2021), only the analysis of cross-task correlation was preregistered. To remain consistent with the Bayesian framework of *HMeta-d*, Bayesian analyses were also performed for task performance and metacognitive bias. Details of pre-registered frequentist analyses are given in the supplementary material (Appendix B).

2.3.1. Age effect on cognition, metacognitive bias, and metacognitive efficiency

Task performance was estimated with a sensitivity index (*d'*). The following hierarchical model was applied to estimate the effect of age on cognitive performance (*d'*) in each task:

$d' \sim \text{age}^{*}\ \text{task}$

For prior specifications, we assumed that recognition performance would decrease with age in the episodic (mean $= -0.3$, $sd = 1$), executive (mean $= -0.2$, $sd = 1$), and perception (mean $= -0.2$, $sd = 1$) tasks; whereas it would increase with age in the semantic task (mean $=$ 0.2, $sd = 1$).

Metacognitive bias was estimated by the difference between mean confidence and mean performance (i.e., percentage of correct responses). Thus, participants with a score close to zero had no or low bias, participants with positive scores overestimated their performance, and participants with negative scores underestimated their performance. The following hierarchical model was estimated:

$\text{bias} \sim \text{age}^{*}\ \text{task}$

Given the conflicting results regarding the age effect on metacognitive bias in visual perception (see Culot et al., 2023; McWilliams et al., 2023), we used default priors for this task.

Metacognitive efficiency was estimated using an extended version of the *HMeta-d* model, which was developed to estimate metacognitive efficiency integrating within- and between subject uncertainty in parameter estimates (Fleming, 2017). The *HMeta-d* sampling procedure is based on Markov chain Monte Carlo (MCMC) simulation and is implemented in JAGS (http://mcmc-jags.sourceforge.net), providing posterior distributions of parameter estimates. The extended version we used was adapted to estimate regression parameters (beta) linking predictor variables such as age to metacognitive efficiency (the *RHMeta-d*; Harrison et al., 2021). This model was adapted on R 4.2.2 using the same parameters and priors as for the original *RHMeta-d* (see Harrison et al., 2021). As preregistered and to avoid extreme and unreliable values of metacognitive efficiency (Guggenmos, 2021), participants whose *d'* was below 0.2 or above 3 were removed from the next analyses in each task independently. Indeed, simulation of the relationship between first- and second-order performance showed that low and high *d'* decrease the estimation of M_{ratio} using the *HMeta-d* (see Fig. 2H in Guggenmos, 2021).

2.3.2. Domain-generality of metacognition

Domain generality was explored with Bayesian estimations of cross-task correlations for task performance, metacognitive bias, and metacognitive efficiency. Given the uneven age distribution, and in particular the low proportion of middle-aged participants, we did not perform the cross-task correlations in three age groups as preregistered (i.e., 18–39 y.o., 40–59 y.o., and 60–79 y.o.). First, analyses were conducted in the whole sample, then in the sample divided into two age groups: younger participants (aged 18 to 59) and older participants (aged 60 to 79). Cross-task correlations of metacognitive efficiency were estimated using the adapted version of *HMeta-d* (see Mazancieux et al., 2020). This model estimates posterior distributions over parameters of the group-level covariance matrix governing correlations between tasks. Parameters and priors were the same as in the original model (see Fleming, 2017). We also used the same model extension proposed in Mazancieux et al. (2020) which specifies that each participant's log M_{ratio} in the four tasks (*M1, M2, M3, M4*) was drawn from a bivariate Gaussian.

For correlational hypothesis, the decision rule was based on the 95 % highest density interval (HDIs; Kruschke, 2010), concluding to a high evidence for a correlation when this HDI did not overlap with zero. Participants whose task performance was at the chance level (i.e., $d' \leq 0$ - *and not* ≤ 0.2 *as above*) in at least one task were excluded from the analyses of domain generality. Similarly, high evidence for an effect of a parameter (i.e., age) was concluded when the 95 % HDI did not overlap with zero.

3. Results

3.1. Testing age effect on cognition, metacognitive bias, and metacognitive efficiency

Table 1 summarizes mean and standard deviations of percentage of correct recognition, cognitive performance (*d'*), magnitude of judgments, and metacognitive bias in the four tasks for participants under 60 and over 59 independently, as well as for the sample as a whole. For M_{ratio} analyses, the exclusion criteria based on first-order performance are not the same for the regression model (section 3.1.3.) and the correlational model (section 3.2.) (see Method).

3.1.1. First-order performance

Cognitive performance was estimated computing a sensitivity index for each participant (*d'*). Performance declined with age in episodic (age beta mean: -0.010; HDI: [−0.013; −0.006]), executive (age beta mean: -0.015; HDI: [−0.018; −0.011]), and visual tasks (age beta mean: -0.011; HDI: [−0.015; −0.008]). While performance in the semantic task increased with age (age beta mean: 0.007; HDI: [0.004; 0.010]). The full table of regression parameters is given in Appendix C. The same effects were obtained with frequentist analyses using a significant threshold of $\alpha = 0.05$ (see appendix B).

3.1.2. Metacognitive bias

Metacognitive bias was estimated by the difference between mean confidence and mean performance (i.e., percentage of correct responses). Results suggested that older participants were more overconfident with age in the perception task (age beta mean: 0.09; HDI: [0.02; 0.15]). There was no effect of age on metacognitive bias in the episodic task (age beta mean: -0.04; HDI: [−0.11; 0.02]), semantic task (age beta mean: -0.05; HDI: [−0.11; 0.02]), and executive task (age beta mean: 0.03; HDI: [−0.02; 0.07]). The full table of regression parameters is given in Appendix C. The same effects were obtained with frequentist analyses using a significant threshold of $\alpha = 0.05$ (see appendix B).

Table 1
Means and standard deviations for percentage of hits, cognitive performance (d'), magnitude of confidence, and metacognitive bias in the four cognitive domains.

	Percentage of hits			Cognitive sensitivity (d')			Magnitude of confidence			Metacognitive bias		
	Younger adults	*Older adults*	All	*Younger adults*	*Older adults*	All	*Younger adults*	*Older adults*	All	*Younger adults*	*Older adults*	All
Episodic memory	78.90 (13.70)	75.30 (12.80)	77.86 (13.51)	1.79 (1.11)	1.48 (0.93)	1.70 (1.07)	80.70 (10.6)	75.80 (12.20)	79.30 (11.30)	1.85 (10.70)	0.46 (9.73)	1.45 (10.40)
Semantic memory	69.90 (11.80)	75.40 (10.50)	71.48 (11.71)	1.08 (0.71)	1.42 (0.71)	1.18 (0.72)	76.60 (8.31)	81.00 (8.64)	77.80 (8.64)	6.64 (11.30)	5.69 (8.68)	6.37 (10.60)
Visual perception	77.10 (8.39)	74.70 (8.07)	76.40 (8.36)	1.48 (0.52)	1.32 (0.48)	1.44 (0.51)	77.70 (70.40)	78.90 (10.80)	78.00 (10.50)	0.57 (12.70)	4.21 (12.00)	1.62 (12.60)
Executive functioning	86.90 (8.80)	80.30 (10.90)	84.98 (9.91)	2.33 (0.82)	1.81 (0.90)	2.18 (0.87)	86.80 (8.28)	81.20 (11.20)	85.20 (9.53)	−0.04 (7.77)	0.97 (8.67)	0.25 (8.04)

Note. These descriptive statistics included all participants ($n = 442$, age mean = 42.20, sd = 20.50). The group of younger participants consisted of 315 participants aged 18 to 59 (mean = 31.30, sd = 13.20). The group of older participants consisted of 127 participants aged 60 to 79 (mean = 69.00, sd = 4.82).

3.1.3. Metacognitive efficiency

Normalized regression coefficients in a model predicting metacognitive efficiency were estimated with both linear and quadratic age terms using the RHMeta-d version of *Hmeta-d* (Harrison et al., 2021). Table 2 summarizes the estimated M_{ratio} in the four tasks and Fig. 3 shows the distribution of M_{ratio} throughout the age and the tendency curve of the linear terms in the four tasks. Results did not show any age effect on metacognitive efficiency in executive functioning (age beta mean: -0.05; HDI: [−0.10; 0.004]; age-squared beta mean: -0.05; HDI: [−0.13; 0.02]) and visual perception (age beta mean: 0.02; HDI: [−0.06; 0.10]; age-squared beta mean: 0.06; HDI: [−0.05; 0.18]). Metacognitive efficiency in the episodic task linearly decreased with age (age beta mean: -0.09; HDI: [−0.15; −0.03]), while it linearly increased with age in the semantic task (age beta mean: 0.07; HDI: [0.003; 0.13]). There was no quadratic effect in either episodic (age-squared beta mean: -0.04; HDI: [−0.13; 0.04]) or semantic tasks (age-squared beta mean: 0.03; HDI: [−0.05; 0.11]), suggesting that the evolution of metacognitive efficiency in the episodic and semantic tasks is progressive throughout aging. Fig. 4 represents normalized betas and HDIs of regression parameters for linear and quadratic age terms in the four tasks.

To check whether sociodemographic variables could explain the above results, we also tested the effect of level of education on cognitive performance and metacognitive efficiency. There was no effect of level of education on either cognitive performance or metacognitive efficiency in episodic (beta mean for d': 0.001: HDI: [−0.007; 0.010]; beta mean for *Mratio* = −0.003; HDIs = [−0.008; 0.002]), semantic (beta mean for d': 0.142: HDI: [−0.980; 1.265]; beta mean for *Mratio* = 0.002; HDIs = [−0.003; 0.008]), executive (beta mean for d': 0.130: HDI: [−0.982; 1.262]; beta mean for *Mratio* = 0.001; HDIs = [−0.004; 0.005]), and visual tasks (beta mean for d': 0.429: HDI: [−0.679; 1.555]; beta mean for *Mratio* = −0.004; HDIs = [−0.011; 0.003]).

3.2. Testing domain generality: Cross-task correlations

Cross-task correlations were first estimated in the whole sample, then in two independent age groups: younger adults (aged 18 to 59) and older adults (aged 60 to 79). Starting with d', the whole sample analysis showed that performance was correlated between episodic and executive tasks, semantic and executive tasks, perception and episodic tasks, and executive and perception tasks. Evidence of a correlation between semantic and episodic performance is weak. No correlation was shown between perception and semantic tasks. Correlations of cognitive performance between tasks in the sample divided by age showed that the performance of both younger and older groups was correlated between semantic and executive tasks, and episodic and executive tasks. There was no evidence for other cross-task correlations in older adults. Evidence of a correlation between perception and episodic performance in younger adults is weak. No correlation was shown between semantic and perception tasks in younger adults. Table 3 summarizes the estimations of correlations coefficients and the lower and upper 95 %-HDIs limits of first-order performance between the four tasks for the whole sample and for both age groups. The same correlations were significant with frequentist analyses (with a significant threshold of $\alpha = 0.05/6 = 0.008$), expect for the correlation between episodic memory and semantic memory in younger adults ($r = 0.09$, $p = .02$).

For metacognitive bias, results suggested evidence for positive correlations between all tasks in the overall sample as well as in both independent age groups. Higher metacognitive bias in one task is related to higher metacognitive bias in the other tasks between episodic and semantic tasks, episodic and executive tasks, episodic and perception tasks, semantic and executive tasks, semantic and perception tasks, and executive and perception tasks, regardless of age. Table 4 summarizes the estimations of correlations coefficients and the lower and upper 95 %-HDIs limits of metacognitive bias between the four tasks for the whole sample and in both age groups. The same effects were obtained with frequentist analyses using a significant threshold of $\alpha = 0.05/6 = 0.008$ (see appendix B).

Cross-task correlations of metacognitive efficiency were estimated using an extended version of *HMeta-d* that allows estimation of group-level covariance parameters (Mazancieux et al., 2020). All parameters were close to 1 suggesting an overall good metacognitive. Whole sample analysis showed that metacognitive efficiency was correlated across all cognitive domains, except between visual perception and episodic memory (see Table 5). The same pattern was observed in participants over 60. For younger participants (i.e., between 18 and 59), metacognitive efficiency was correlated only between semantic and episodic tasks, executive and episodic tasks, and semantic and visual tasks.

Table 2
Mean and high-density intervals (HDIs) of metacognitive efficiency estimated in the four tasks with HMeta-d version for regression analyses.

	Episodic memory	Semantic memory	Visual perception	Executive functioning
n	363	402	437	351
M_{ratio}	1.19 [1.08; 1.32]	1.19 [1.07; 1.31]	0.67 [0.57; 0.77]	1.26 [1.15; 1.37]

Note. Regression analyses on M_{ratio} included only participants with a sensitivity index (d') between 0.2 and 3 for the four tasks independently.

4. Discussion

This study aimed to test the effect of age on cognition and metacognition in four domains (episodic memory, semantic memory, executive functioning, and visual perception) by incorporating methodological advances in the metacognitive field and using a large sample. Using the *Mratio* measure and the *HMeta-d* framework made it possible to estimate metacognition with a greater (but not perfect) independence from first-order performance (Guggenmos, 2021; Rahnev, 2023; Shekhar & Rahnev, 2021). This allows us to better differentiate the effect of age on cognitive and metacognitive processes

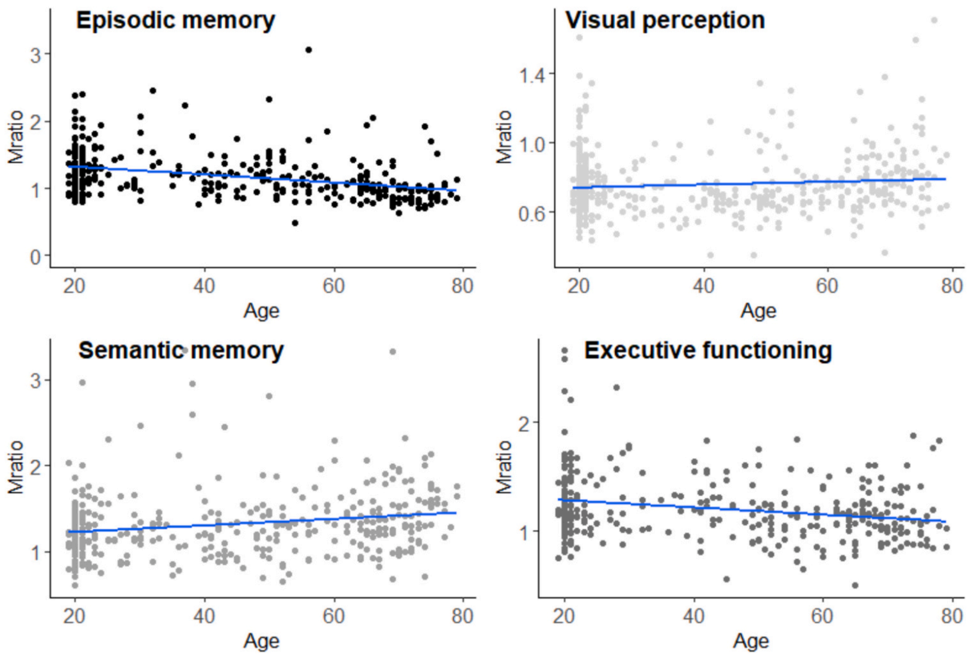

Fig. 3. Distribution of metacognitive efficiency estimates (M_{ratio}) through the age and regression line of the linear model in the four tasks.

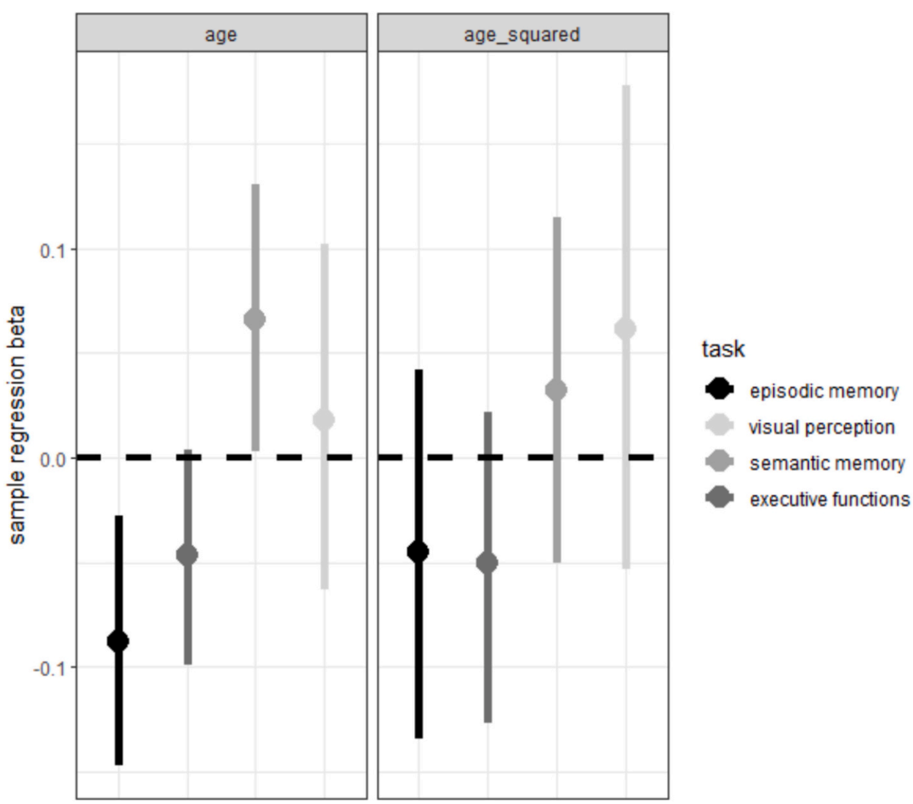

Fig. 4. Means and 95 % high density intervals (HDIs) of normalized betas estimated for linear (age) and quadratic age terms (age squared) of metacognitive efficiency (M_{ratio}) in the four tasks.
Note. There is evidence for an effect of age when the HDIs do not overlap with zero.

independently. This study also tested the domain generality of metacognition, and how it is affected by healthy aging. We first discuss our metacognitive efficiency findings before turning to the domain generality of metacognition.

As expected, cognitive performance showed age-related declines in episodic memory, executive functioning, and visual perception. In contrast, semantic memory remained stable with age. This result is consistent with the domain specificity of cognitive aging. Processes related to reasoning and cognitive control decline in aging (Horn & Cattell, 1967; Khammash et al., 2023; Mitchell, 1989; Park et al., 2002),

Table 3
Mean and 95 % (HDIs) of cross-task correlations (ρ) for first-order performance (d') for the whole sample and for the sample divided into two age groups.

	Whole sample			Younger adults			Older adults		
	Visual perception	Semantic memory	Executive functions	Visual perception	Semantic memory	Executive functions	Visual perception	Semantic memory	Executive functions
Episodic memory	**0.11 [0.02; 0.20]**	0.09 [−0.01; 0.18]	**0.26 [0.17; 0.34]**	0.09 [−0.02; 0.20]	**0.13 [0.01; 0.23]**	**0.23 [0.13; 0.33]**	0.09 [−0.08; 0.26]	0.09 [−0.09; 0.25]	**0.23 [0.06; 0.39]**
Visual perception		0.01 [−0.08; 0.10]	**0.21 [0.13; 0.30]**		0.04 [−0.07; 0.15]	**0.24 [0.13; 0.34]**		0.04 [−0.14; 0.21]	0.06 [−0.12; 0.23]
Semantic memory			**0.19 [0.10; 0.28]**			**0.27 [0.16; 0.36]**			**0.23 [0.06; 0.39]**

Note. Coefficients in bold suggest evidence for a correlation between metacognitive efficiency in the two tasks with 95 % HDI.

Table 4
Mean and 95 % (HDIs) of cross-task correlations (ρ) for metacognitive bias for the both age groups.

	Whole sample			Younger adults			Older adults		
	Visual perception	Semantic memory	Executive functions	Visual perception	Semantic memory	Executive functions	Visual perception	Semantic memory	Executive functions
Episodic memory	**0.68 [0.63; 0.73]**	**0.64 [0.58; 0.69]**	**0.72 [0.67; 0.76]**	**0.68 [0.62; 0.74]**	**0.67 [0.61; 0.73]**	**0.72 [0.66; 0.77]**	**0.65 [0.53; 0.74]**	**0.59 [0.46; 0.69]**	**0.59 [0.47; 0.69]**
Visual perception		**0.78 [0.75; 0.82]**	**0.74 [0.70; 0.78]**		**0.81 [0.76; 0.84]**	**0.77 [0.73; 0.82]**		**0.68 [0.56; 0.76]**	**0.67 [0.57; 0.75]**
Semantic memory			**0.69 [0.65; 0.74]**			**0.75 [0.69; 0.79]**			**0.65 [0.55; 0.74]**

Note. Metacognitive bias was correlated between all tasks.

Table 5
Mean and 95 % (HDIs) of cross-task correlations (ρ) for metacognitive efficiency (M_{ratio}) for the whole sample and for the sample divided into two age groups.

	Whole sample			Younger adults			Older adults		
	Visual perception	Semantic memory	Executive functions	Visual perception	Semantic memory	Executive functions	Visual perception	Semantic memory	Executive functions
Episodic memory	0.13 [−0.08; 0.33]	**0.31 [0.10; 0.51]**	**0.29 [0.10; 0.46]**	0.07 [−0.17; 0.30]	**0.36 [0.10; 0.59]**	0.18 [−0.03; 0.38]	0.30 [−0.12; 0.60]	**0.38 [0.06; 0.78]**	**0.60 [0.24; 0.79]**
Visual perception		**0.29 [0.06; 0.50]**	**0.44 [0.27; 0.60]**		0.18 [−0.09; 0.42]	**0.40 [0.22; 0.61]**		**0.49 [0.15; 0.87]**	**0.54 [0.21; 0.88]**
Semantic memory			**0.30 [0.12; 0.47]**			**0.28 [0.09; 0.49]**			**0.40 [0.01; 0.75]**

Note. Coefficients in bold suggest evidence for a correlation between metacognitive efficiency in the two tasks with 95 % HDI.

as well as visual perception when the cognitive load induced by the task is high (Faubert, 2002); while the semantic component increases, or remains stable with age (Horn & Cattell, 1967; Khammash et al., 2023; Mitchell, 1989; Park et al., 2002).

Metacognitive bias indexes the tendency of participants to under or overestimate their cognitive processes. Based on previous research, we expected that participants would be more overconfident with age when judging their episodic memory (Castel et al., 2015; Hertzog et al., 2021; Lovelace & Marsh, 1985; Soderstrom et al., 2012) and semantic memory (Kavé & Halamish, 2015), but more underconfident with age in the executive task (Bertrand et al., 2017; McWilliams et al., 2023). Given the equivocal results concerning the age effect on metacognitive bias in perception tasks (Culot et al., 2023; McWilliams et al., 2023), we had no oriented hypothesis in this task. Results showed that participants were more overconfident with age in the perception task, while no effect of age on metacognitive bias was shown in the other tasks. Thus, the age effect on metacognitive bias seems to depend on the cognitive domain involved in the task.

We propose that the age effect on metacognitive bias in visual perception may depend on the degree of evidence strength accumulated during stimulus presentation. Shorter presentation times of stimuli (i.e., 1000 ms) lead to overconfidence of older adults (for instance in this current study and in Culot et al., 2023), while longer presentation times (i.e., 3000 ms) lead to underconfidence of older adults (McWilliams et al., 2023). In line with these observations, it has been shown that people are less confident of their errors when the RCJ is delayed relative to stimulus presentation than when it is immediate (Desender, Donner, & Verguts, 2021). Similarly, the overconfidence in older adults associated with short presentation times only concerns the incorrect responses (Culot et al., 2023).

We showed strong correlations between our bias measures for the four different domains. This could reflect common anchoring mechanisms being applied to each domain, meaning that each individual has a certain level of confidence which is more or less applied across tasks (for a discussion of this form of spurious domain generality see Mazancieux et al., 2023). We might imagine that some people are inherently more confident than others, regardless of the task, for instance. As such, these individual differences and large variations in between-subject confidence relate very little to trial-by-trial metacognitive sensitivity (see Kantner & Dobbins, 2019 for an example in episodic memory).

The next stage of our analyses explored metacognitive efficiency over the course of aging. Because of the psychometric advantages of *HMeta-d* (i.e., bias free, better first-order independence; Fleming, 2017; Guggenmos, 2021), age effects on metacognitive efficiency were estimated with an adapted version of this model developed for regression analyses (Harrison et al., 2021). We expected to observe an age-related decline of metacognition for the episodic component, but not for the other cognitive domains (i.e., semantic memory, executive functioning, and visual perception). The linear model indeed showed that metacognitive efficiency in the episodic task decreases in aging, consistent with people becoming less accurate at judging their episodic performance with age. Whilst the idea of a metacognitive deficit in metacognition for episodic memory is not new, this study was sufficiently powered and used a sufficiently sensitive measure to detect an age-related change for RCJs on a recognition task, something which has not been hitherto reported in smaller samples in previous studies.

One limitation of the current study is the necessary simplification of the first-order response as a single process/equal variance signal detection process, whereas, at least in episodic memory, the models of recognition such as measured here are a little more complex (i.e., the dual process model, Yonelinas, 1994 and the unequal variance signal detection model (e.g., Mickes, Wixted, & Wais, 2007)). Our analysis strategy was to invoke simple first-order models which could be common across all domains, with the limitation being that some parameter not capture in our first-order model is driving the age-related differences, and this is particularly pertinent when discussing known age-related changes in episodic memory, which rest on the possibility of recollection being impaired in older adults (e.g., Souchay et al., 2007).

In line with this finding, previous studies have shown that episodic RCJs of older adults depend on the preservation of binding abilities in episodic memory (Greene et al., 2022). According to the misrecollection account, older adults have difficulties recollecting and binding specific details of an event and are more likely to falsely recognize new elements that share features with previous elements (Dodson et al., 2007). This leads to high confidence for false recognitions, suggesting a close link between metacognitive judgments and memory processes (Fandakova et al., 2013; Greene et al., 2022). It is proposed that the interaction between executive functioning and memory processes, as well as their alteration during aging, could influence metamemory. Indeed, executive functioning sustains the recollection process of memory (Blankenship, Calkins, & Bell, 2022; Bugaiska et al., 2007; Clarys, Bugaiska, Tapia, Baudouin, & and., 2009; Parkin & Walter, 1992), and the latter is linked to metamemory performance (Brewer, Marsh, Clark-Foos, & Meeks, 2010; Cauvin, Moulin, Souchay, Kliegel, & Schnitzspahn, 2019; Hicks & Marsh, 2002; Hicks, Marsh, & Ritschel, 2002; Morson et al., 2015; Soderstrom et al., 2012; Souchay et al., 2007). In other words, metamemory performance may be related to an age-related decline in recollection. Metamemory tasks that rely mostly on recollection may be more influenced by aging than metamemory tasks that rely on other cognitive processes. However, the episodic task in the current study could be performed exclusively on the basis of familiarity, since the distractors consisted of words that had never been seen before (and were therefore completely unfamiliar). The role of familiarity and recollection on metamemory can be captured by more sophisticated models and tasks which allow calculating estimates of recollection and familiarity separately, and would require more advanced fitting of first-order performance than described here.

This could explain the dissociations observed in older adults' metamemory. For instance, older adults are less accurate than younger adults in judging their episodic memory using global judgments-of-learning (JOL) and feeling-of-knowing judgments (FOK), but they have been found to be as accurate as younger adults using local JOLs and RCJs (see Castel et al., 2015 for a review). Global JOLs and FOK judgments are mostly based on cues from recollection such as accessibility of partial information (Hicks & Marsh, 2002; Koriat, 1993; Koriat & Levy-Sadot, 2001; Leibert & Nelson, 1998; Thomas et al., 2011); whereas local JOLs and RCJs are also based on familiarity as well as recollection: notably the fluency of the response (Benjamin, Bjork, & Schwartz, 1998; Castel et al., 2015; Fleming, Massoni, Gajdos, & Vergnaud, 2016; Koriat & Helstrup, 2007; Weidemann & Kahana, 2016). Similarly, the metacognitive processes involved in the semantic task do not rely on the recollection process which may explain why the semantic component of metamemory is not negatively impaired by aging (Devaluez et al., 2023; Souchay et al., 2007).

Indeed, our results suggested that metacognitive efficiency related to a semantic task increased with age. Previous studies showed no effect of age on semantic metamemory (Dahl et al., 2009; Eakin et al., 2014; Kavé & Halamish, 2015;Marquié & Huet, 2000; Morson et al., 2015; Souchay et al., 2007). Nevertheless, some of these studies observed that metamemory judgments of older adults were more accurate than those of younger adults in semantic tasks using RCJs (Dahl et al., 2009; Eakin et al., 2014) and FOK judgments (Marquié & Huet, 2000; Morson et al., 2015; Souchay et al., 2007), without the difference between age groups reaching significance. Thus, the limitations of the metacognitive measures used in previous studies (i.e., gamma index) may not have allowed to highlight the positive effect of age on semantic metamemory. It should be noted that the effect of age on M_{ratio} in the semantic task in the current paper was very small (age beta mean: 0.07; HDI: [0.003; 0.13]). It seems essential to test the effect of age on semantic metamemory using the *HMeta-d* framework in further studies to test the reproducibility of this effect.

Interestingly, the age effect on metacognitive efficiency in the two memory tasks is in the same direction as the age effect observed on first-order performance (decline of episodic memory and increase of semantic memory). Thus, metamemory abilities could rely on memory processes. Since first-order performance dependency is not completely eliminated with M_{ratio} (Rahnev, 2023), this could raise questions about the independence of *HMeta-d* estimates from age-related memory changes. Another method to avoid bias from first-order performance is to control performance across participants, with a staircase procedure for instance (e.g., Culot et al., 2023; Lund et al., 2023). However, these types of procedures are mainly used in metaperception studies, as episodic memory performance is difficult (if not impossible) to control in the same way online because of the need for distinct study and test phases. Although it seems difficult to have the same level of performance between participants when tasks involve episodic memory, future studies that compared metacognitive performance across different domains should consider the possibility of controlling intra-individual performance, or perhaps taking a separate measure of episodic memory which is not confounded by the metacognitive task. Thus, episodic memory performance could be matched to the level of performance on other tasks that are easier to control, so that a participant has the same level of performance across the various cognitive domains (e.g., Rouy et al., 2023). Nevertheless, the staircase procedure is sometimes contested, since increasing variability of difficulty between stimuli influences estimates of metacognitive ability (Rahnev & Fleming, 2019).

Although metacognitive efficiency in both memory tasks followed age-related changes of first-order performance in these tasks (i.e., decrease of episodic memory and increase of semantic memory), we also observed a negative effect of age on executive functioning and visual perception, without observing any effect of age on metacognitive efficiency in these two tasks. The M_{ratio} of participants in the perception task could be influenced by the heterogeneity of the stimuli combined with the age-related decline observed in this task. In other words, the difficulty of stimuli varied with the age of the participants (e.g., easy trials may be perceived as more difficult by older adults), impacting the proportion of random trials. Consequently, RCJs of older adults may be as accurate as those of younger adults, since it is easier to judge their confidence in random trials. This further highlights the importance of controlling first-order performance in future studies.

Nevertheless, these results could also suggest that while first-order performance in a cognitive domain may be impaired, second-order performance within the same domain can be preserved. Such dissociations have already been observed in the literature in various cognitive domains, although not in such a large sample and with such measures. For instance, by varying visuo-spatial attention, the first-order performance of young participants varies, but second-order performance does not (Landry, Da Silva Castanheira, Sackur, & Raz, 2021). These dissociations suggest that first-order performance does not necessarily involve metacognitive function, but that these constructs depend on different cognitive processes. This shows us the importance of having an independent metacognitive measure of first-order performance, especially for populations likely to have either cognitive or metacognitive deficit (e.g., older adults, clinical population). Future studies could explore these dissociations between first- and second-order performance to investigate their dependency, for instance by finding a domain where the first-order is impaired but not the second-order, or vice versa (Mazancieux et al., 2023). An ideal design would be to explore first and second order performance on separate tasks, to disentangle the processes used in the second-order task from the capacity to perform on the first-order task.

Moreover, we found no evidence of quadratic effects of age on metacognitive efficiency in any of the four tasks. Previous research has also shown no effect of age on either metamemory or metaperception when using a quadratic model (McWilliams et al., 2023). Similarly, metacognitive abilities linked to working memory do not differ between younger adults and middle-aged participants (Forsberg, Blume, & Cowan, 2021). These results suggest that the age-related changes of metacognitive efficiency in episodic and semantic metamemory is progressive throughout the age. Metacognitive abilities of the other cognitive domains seem to be already mature in early adulthood and remain stable throughout the age. It has been already shown that general cognitive decline is progressive during adulthood (Tucker-Drob, 2011). With a longitudinal study, Tucker-Drob (2011) showed that the degree of cognitive decline is similar in early and late adulthood.

The second aim of the study was to test the domain generality of metacognition and its relationship with age. To begin, we conducted cross-task correlations across the entire sample to test the hypothesis of a general metacognitive mechanism that could be common to all cognitive domains, as already shown with young participants (Lund et al., 2023; Mazancieux et al., 2020). We replicated the cross-task correlations of metacognitive efficiency showed by Mazancieux et al. (2020), that is M_{ratios} were correlated between cognitive domains, except between episodic memory and visual perception. Thus, whole sample analyses suggest that metacognitive efficiency relies primarily on a somewhat domain general process, and the same pattern is observed with the whole sample and with our subsample of participants over 60 years old.

Whilst we do not seek to formally analyze the differences in correlations between young and old groups in this analysis, we should point out that the participants under 60 did not produce the same pattern as published previously. Because we aimed to reduce performance differences in tasks, we reduced the presentation times and modified stimuli in some tasks in comparison with Mazancieux et al. (2020) which could explain the differences observed in our results and theirs. Since the amount of perceptual evidence has been shown to influence metacognitive judgments (Samaha, Barrett, Sheldon, LaRocque, & Postle, 2016; Schwartz, Pillot, & Bacon, 2014; Thomas et al., 2011), changes on presentation times affect the amount of perceptual evidence, which may lead to difficulties in making appropriate judgments.

We found exactly the same pattern as the whole-sample analyses in the cross-task correlations performed only on participants over 60. Thus, contrary to our hypothesis, metacognitive efficiency appeared to rely more on a domain-general process in older adults than in younger adults. This result is in line with the dedifferentiation hypothesis claiming that age-related cognitive changes are widespread in the brain (Li & Lindenberger, 1999). Cerebral activations of older adults are less specific to the task in hand, impairing cognitive performance (Martin, Saur, & Hartwigsen, 2022). Consequently, cognitive abilities of older adults are more correlated than those of younger adults (Lindenberger & Baltes, 1997).

Nevertheless, this increase of domain generality of metacognition across age contradicts the dissociations observed on our own prior task-by-task analyses. Metacognitive efficiency appeared to change with aging in the two memory tasks, while it does not vary with age in the executive and visual tasks. Whatever the age of participants, cross-task correlations between metacognitive efficiency could be influenced by the domain generality of metacognitive bias, more consistently found across studies (Mazancieux et al., 2023). Moreover, metacognitive judgments involve cognitive processes related to task demands and decision-making processes. Thus, cross-task correlations could be influenced by shared factors involved in the tasks (e.g., attention, arousal, mood), without capturing the metacognitive component (Mazancieux et al., 2023). Another way of exploring domain generality of metacognition might be to consider reaction times. Dynamic models of metacognition argue that reaction times are used as a cue on which to base metacognitive judgments, whatever the cognitive domain concerned (Desender, Vermeylen, & Verguts, 2022; Mazancieux et al., 2023).

Importantly, this study did not take into account several demographic or health variables that could influence the course of aging. Although we have taken age and education into account, other demographic factors, such as race, appear to influence age-related decline (Rexroth et al., 2013). Moreover, cognitive functioning appears to be correlated with health status. For instance, greater cognitive decline is observed in older adults with vascular abnormalities (e.g., higher blood glucose level or diabetes, pulse pressure; Crowe et al., 2010; Dahle, Jacobs, & Raz, 2009; Ding et al., 2010), depressive symptoms (Lohman et al., 2013), and sleep disturbance (Guan et al., 2020; Yaffe, Falvey, & Hoang, 2014). The influence of demographic and health factors could explain the greater heterogeneity in the results of older adults and should be considered in future studies.

5. Conclusion

This study explored different domains of metacognition across the age range with a large sample size and a hierarchical Bayesian framework. Results showed that metacognitive efficiency (our measure of accuracy) of episodic memory declined with age, while metacognitive efficiency of semantic memory increased with age. We did not find any age effects on metacognitive efficiency in executive functioning and semantic memory. These results highlighted the special status of metamemory within metacognition of older adults, as well as the involvement of memory processes in metamemory abilities of older adults. Despite these dissociations between the different component of metacognition, metacognitive efficiency appeared to rely on a domain-general process in older adults, which is in line with the dedifferentiation hypothesis. Explaining the episodic metamemory deficit in aging could help understand the difficulties of older adults to use inferential processes for memory search and retrieval as well as their difficulties to implement memory strategies. Thus, techniques to improve metamemory could be used in cognitive remediation with healthy older adults to slow the decline in episodic memory.

CRediT authorship contribution statement

Lucile Meunier-Duperray: Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Audrey Mazancieux:** Methodology, Writing – review & editing. **Céline Souchay:** Conceptualization, Writing – review & editing, Supervision. **Stephen M. Fleming:** Software, Writing – review & editing. **Christine Bastin:** Conceptualization, Writing – review & editing. **Chris J.A. Moulin:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Lucie Angel:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2025.106089.

Data availability

Preregistration and data are available on OSF: https://osf.io/ymg96/

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