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The Time Course of Encoding Specific and Gist Episodic Memory Representations Among Young and Older Adults

Nathaniel R. Greene[1, 2] and Moshe Naveh-Benjamin[1]
[1] Department of Psychological Sciences, University of Missouri
[2] Department of Psychology, University of Pennsylvania

How rapidly can we encode the specifics versus the gist of episodic memories? Competing theories have opposing answers, but empirical tests are based primarily on tasks of item memory. Few studies have addressed this question with tasks measuring the binding of event components (e.g., a person and a location), which forms the core of episodic memory. None of these prior studies included older adults, whose episodic memories are less specific in nature. We addressed this critical gap by presenting face–scene pairs (e.g., an old man with a park) at various encoding presentation rates to 80 young ($M = 21.83$ years) and 86 older ($M = 68.62$ years) adults. Participants completed associative recognition tests featuring old/intact (e.g., the old man with the same park), similar (e.g., the old man with a different park), and unrelated (e.g., the old man with a kitchen) pairs. Multinomial-processing-tree model analyses revealed that young and older adults encoded each pair's gist representation more rapidly than its specific representation, supporting fuzzy-trace theory. No age-related differences in gist representations were obtained at any presentation rate, but older adults required more time to encode specific representations commensurate with those of younger adults. However, older adults' abilities to retrieve these representations were cue-dependent, as they were more susceptible than younger adults to experiencing vivid false memories of similar lures. These phantom recollections were remediated with further increases in encoding time. Thus, slower speed of encoding partially underlies age-related declines in episodic memory specificity, but retrieval mechanisms also play a role.

Public Significance Statement

The present study provides novel insights into the speed with which specific (detailed) and gist (meaning-based) representations of episodic memories can be encoded among young and older adults. These insights constrain leading theories of information processing and have implications for understanding why older adults are less likely to remember the specific details of past episodes. Providing older adults with more time to learn new information may be one solution for fostering stronger and longer-lasting memories that are rich in specific details.

Keywords: adult aging, specificity, gist, episodic memory, speed of processing

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Episodic memories bind events in specific spatiotemporal contexts (Tulving, 1983, 2002), enabling us to remember where we parked our car today compared to yesterday or whether we took our morning dose of medicine. Beyond molding the autobiographical narratives of our lives (Levine et al., 2002), episodic memories also shape our day-to-day experiences by influencing what we attend to in the present moment (Cowan et al., 2024; Henderson et al., 1999) and how we plan for future experiences (Brewer & Marsh, 2010; Einstein & McDaniel, 2005; Schacter & Addis, 2007; R. E. Smith, 2003). Despite the importance of episodic memory to daily functioning, these mental records of our past experiences are rarely perfect portrayals of what transpired. We tend to retain the general essence/meaning (or "gist") of past events, while representations of the more specific details of those events erode with time and interference

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Nathaniel R. Greene https://orcid.org/0000-0001-6758-6761

The ideas discussed in this article have not been disseminated previously. Data and analysis scripts are available at https://osf.io/98anb/.

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Correspondence concerning this article should be addressed to Nathaniel R. Greene, Department of Psychological Sciences, University of Missouri, 9J McAlester Hall, Columbia, MO 65211, United States, or Moshe Naveh-Benjamin, Department of Psychological Sciences, University of Missouri, 106 McAlester Hall, Columbia, MO 65211, United States. Email: ngreene@mail.missouri.edu or nrgreene@sas.upenn.edu or navehbenjaminm@missouri.edu

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(Brainerd & Reyna, 1990, 2002; Craik, 2002a, 2002b; Greene & Naveh-Benjamin, 2022a, 2022b; Sachs, 1967; Sekeres et al., 2016; Thorndyke, 1977). In many situations, remembering the gist is necessary and sufficient for comprehension and can be more important than retaining specific details that are less relevant to the core meaning of an episode (Greene & Naveh-Benjamin, 2023d). For instance, in reading, remembering what a story was about (the gist of the narrative) is more critical to comprehension than is remembering details like how the text was structured (Kintsch & van Dijk, 1978; Morrow et al., 1989; Radvansky & Dijkstra, 2007; Radvansky et al., 2001). Yet, there are also many instances where failures to remember specific details can result in catastrophic mistakes. For example, in eyewitness testimony, relying on gist rather than specific representations can lead to false recollections of what transpired during a crime (Brainerd & Reyna, 2002; Devitt & Schacter, 2016; Gallo, 2006; Norman & Schacter, 1997).

Many factors could explain why an individual remembers the gist but not the specifics of an episode, including how old the individual is (Abadie et al., 2021; Brainerd & Reyna, 2015; Craik, 2002a; Greene & Naveh-Benjamin, 2020, 2023a; Koutstaal & Schacter, 1997; Schacter et al., 1997; Tun et al., 1998), how attentionally demanding it is to encode or retrieve specific versus gist representations (Greene & Naveh-Benjamin, 2022b, 2022d, 2023b; Luo & Craik, 2009; Odegard & Lampinen, 2005; Rabinowitz et al., 1982), and how much time has elapsed between encoding and subsequent retrieval (Andermane & Bowers, 2015; Greene & Naveh-Benjamin, 2022a, 2022b, 2023c; Sachs, 1967; Sekeres et al., 2016; Thorndyke, 1977). One critical mechanism that may mediate these other factors is the amount of time required to encode the gist versus the specifics of an episode (Ahmad et al., 2017; Greene & Naveh-Benjamin, 2023e; Navon, 1977; Tatler et al., 2003). Differences in the speed of encoding each type of representation may underlie why, more so than younger adults, older adults often fail to retain specific details of their past experiences (Greene & Naveh-Benjamin, 2023a), in line with cognitive slowing theories of aging (Light, 1991; Myerson et al., 1990; Salthouse, 1996). Furthermore, representations that can be encoded more rapidly may require less sustained attention during encoding by being quickly off-loaded into passive (i.e., attention-freeing) storage (cf., Cowan, 1988, 2019; Cowan et al., 2014, 2024; Rhodes & Cowan, 2018).

Examining whether there are differences in the speed with which individuals encode specific and gist representations can constrain competing theories of information processing. This can have far-reaching implications for understanding how we process complex events, such as the order in which we extract meaning versus verbatim/exact details from written text (Kintsch & van Dijk, 1978; Moravcsik & Healy, 1995; Morrow et al., 1989, 1997; Perfetti, 2007; Radvansky & Dijkstra, 2007), spoken language (Johnson-Laird, 1983; Kintsch, 1988; Sachs, 1967; Wallace et al., 1998), images (e.g., of scenes; Ahmad et al., 2017; Melcher, 2006; Potter, 1976; Potter & Levy, 1969; Tatler et al., 2003), continuous or evolving sequences of events (e.g., films; Kurby & Zacks, 2008; Radvansky & Copeland, 2006; Richmond & Zacks, 2017; J. M. Zacks et al., 2006), and displays of emotion (Barrett, 2017; Gendron & Barrett, 2018). Perhaps of greatest importance, however, is understanding the rates and order in which we encode specific and gist representations of a core feature of episodic memories—the associative binding of multiple components of an episode (Tulving, 1983; Underwood, 1969; Zimmer et al., 2006), such as a person and the location where one encountered that person (e.g., Gruppuso et al., 2007). This associative binding is critical for successful memory. For example, remembering not only that you have a car (item memory) but where you parked it (item-context binding) is essential to finding it in a crowded parking lot. As a more dramatic example, accurate eyewitness testimony requires one to remember not only that they previously saw a weapon (item memory) and a person (item memory) but that the person wielded the weapon (item-item binding). Despite the importance of associative binding to episodic memory, our current understanding of how rapidly individuals can encode specific or gist representations is mostly limited to studies of item memory (e.g., with words or pictures of scenes; but see Greene & Naveh-Benjamin, 2023e).

A related limitation of the current literature is that prior studies have not considered the rate of encoding of specific and gist representations among older adults, who have generally poorer episodic memory capabilities than younger adults (Fraundorf et al., 2019; Light, 1991; Naveh-Benjamin & Old, 2008; Rhodes et al., 2019; R. T. Zacks et al., 2000). Age-related declines in episodic memory are most pronounced for the associative binding of components of an episode (Boywitt et al., 2012; Chalfonte & Johnson, 1996; Chen & Naveh-Benjamin, 2012; Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2003, 2004; for meta-analyses, see Old & Naveh-Benjamin, 2008; Spencer & Raz, 1995), but these associative memory failures may be limited to specific but not gist representations, at least for some episodic associations (Castel, 2005; Greene & Naveh-Benjamin, 2020, 2022a; Greene et al., 2022). For example, older adults can remember that a face had been associated with a park rather than a kitchen scene (general/gist representation) but often fail to remember which exact park scene had been associated with the face (specific representation; Greene & Naveh-Benjamin, 2020). In addition, older adults can rely on preexisting knowledge to encode the gist of novel associations, such as using knowledge of the real-world price of grocery items to aid with remembering whether a studied item was fairly priced or overpriced (Castel, 2005; Castel et al., 2007, 2013; cf., Lindenberger & Mayr, 2014; McGillivray & Castel, 2010; Mohanty et al., 2016; Peterson et al., 2017; Umanath & Marsh, 2014). Despite their well-preserved gist representations, older adults often forget the specific details of their past experiences (Abadie et al., 2021; Brainerd et al., 2009; Koutstaal, 2003; Koutstaal & Schacter, 1997; Koutstaal et al., 2003; Morrow et al., 1992; Radvansky et al., 2001; Rankin & Kausler, 1979; Reder et al., 1986; Stark et al., 2013; Stine & Wingfield, 1988; Trelle et al., 2017; Tun et al., 1998; for reviews, see Brainerd & Reyna, 2015; Greene & Naveh-Benjamin, 2023a; Grilli & Sheldon, 2022). Examining the time course of encoding specific and gist representations among older adults, relative to younger adults, may shed light on mechanisms underlying why older adults' episodic memories are fuzzier or less specific (cf., Greene & Naveh-Benjamin, 2023a; Salthouse, 1996).

In what follows, we first lay out the predictions of competing theories regarding the time course of encoding specific and gist representations. We then review findings from studies with young adults that have constrained these theories. Next, we consider whether the same theory that best accounts for the data of young adults could also account for the rates under which older adults encode specific and gist representations of episodic associations. Finally, we consider whether age-related slowing in the encoding of specific representations can explain why older adults' episodic memories are representationally less specific than those of younger adults.

Competing Theoretical Positions on the Rate of Encoding Specific and Gist Representations

Competing theories stake opposing positions regarding the rates and (in)dependency of encoding specific and gist representations. Early theories of reading and discourse comprehension—sometimes termed gist macroprocessor theories (Johnson-Laird, 1983; Kintsch, 1988; Kintsch & van Dijk, 1978; van Dijk & Kintsch, 1983; cf., Reder, 1982)—proposed that the gist of a stream of information is encoded after a specific representation has been laid down (specific-gist serial dependency model; see Figure 1A). These theories argue, for example, that the meaning of a sentence is extracted after natural pauses (e.g., at the end of a clause), as existing knowledge structures (gist macroprocessors) comb through the specific/verbatim stream of information (for a similar account based on the reading systems framework, see Perfetti, 2007; Perfetti & Stafura, 2014). Specific-gist serial dependency models also feature in theories of event segmentation in episodic memory (e.g., Richmond & Zacks, 2017). Accordingly, events (e.g., different scenes in a movie) are discretized only after a high-level, meaning-based representation has been extracted from lower-order, specific sensory or perceptual representations of ongoing events (cf., Baldassano et al., 2017; Kurby & Zacks, 2008; J. M. Zacks et al., 2009, 2010).

An alternative view is maintained by fuzzy-trace theory (Brainerd & Reyna, 1990, 2004; Reyna & Brainerd, 1995), which asserts that specific and gist representations are encoded independently (i.e., parallel trace model; see Figure 1B). Because each representation is encoded independently, neither representation depends on the other type of representation having been established. Fuzzy-trace theory predicts, however, that gist representations can be encoded more rapidly than specific representations. This position is compatible with studies of visual perception showing that global features of visual stimuli are processed prior to the encoding of local, specific features (Navon, 1977). It is also consistent with connectionist models of memory proposing that knowledge stored in long-term memory can be activated rapidly to create a "semantic tag" of new episodic information during the early stages of encoding (Estes, 1988; McClelland & Rumelhart, 1985).

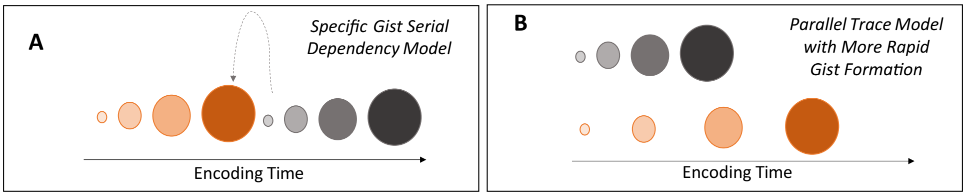
Serial Dependency Versus Parallel Encoding of Specific and Gist Representations: Evidence From Studies With Younger Adults

It is well-established that, when given more time to encode information, young adults retain more of that information (Brady et al., 2016; Hirshman & Hostetter, 2000; Li et al., 2020; McDermott & Watson, 2001; Potter & Levy, 1969; Roberts, 1972; Shepherd et al., 1991; Waugh, 1967). However, under very short presentation durations, young adults often can extract the gist of information, even as they may fail to encode specific representations. A classic example comes from the semantic priming procedure of Draine and Greenwald (1998) in which participants were tasked with judging whether target names were typically male or female. Unbeknownst to participants, prior to the target name presentation, a prime was presented rapidly for between 30 and 50 ms. When the prime was semantically congruent with the target (e.g., "Jane" as the prime and "Mary" the target), young adults were faster and more accurate in classifying the target, compared to situations in which the prime was semantically incongruent with the target (e.g., "Dave" as the prime and "Carol" the target). These results suggest that during the rapid presentation of the prime, young adults encoded its gist. Remarkably, despite this apparently rapid gist formation, young adults were unaware that they saw a prime (i.e., they had no specific/verbatim memory for the primes; cf., Balota, 1983).

Studies of visual perception for images of scenes have also found that young adults rapidly extract general features (i.e., semantic representations of what the scene depicts), even under very brief presentation durations (e.g., within about 100–200 ms; Potter, 1976; cf., Melcher, 2006; Navon, 1977; Tatler et al., 2003). This gist encoding of scene images unfolds more rapidly than the encoding of specific representations of those scenes (Ahmad et al., 2017; Tatler et al., 2003). For example, in the procedure by Tatler et al. (2003), young adults studied images of scenes at rates ranging from 1 to 10 s per scene. Immediately after scene presentation, participants answered questions about what type of scene they saw (i.e., questions about

Figure 1

Theoretical Models for the Rate of Encoding Specific and Gist Episodic Memory Representations



Note. In each panel, specific and gist representations are depicted as orange (light gray) and dark gray circles, respectively. With increases in encoding time, the circles increase in size and clarity (depicted by a darkening of the respective color) to illustrate that each type of representation becomes more fleshed out with longer encoding time. (A) A specific-gist serial dependency model (e.g., Kintsch & van Dijk, 1978). The curved arrow represents a "gist macroprocessor" interpreting the meaning (gist) of the earlier-established specific representation. (B) A parallel trace (simultaneous processing) model in which specific and gist representations are encoded independently and in parallel. The depiction here shows that gist representations are completely fleshed out more rapidly than specific representations are, as predicted by fuzzy-trace theory (Brainerd & Reyna, 1990), but the processing of both representations proceeds in parallel. See the online article for the color version of this figure.

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the scene's gist) or about specific features of the scene (e.g., what shapes, objects, or colors were depicted in the scene). Young adults were highly accurate (>80%) in responding to the gist questions at all rates, with no difference in accuracy between the 1 and 10 s rates. However, for questions about specific details of the scenes, young adults performed poorly at the 1 s rate (~30% correct), but their accuracy by 10 s of encoding time improved to as high as 80%. Similarly, in a long-term memory procedure, Ahmad et al. (2017) presented young adults with images of scenes at rates of 1 or 4 s each and found no encoding rate difference on participants' abilities to later discriminate studied scenes (e.g., a lake) from categorically unrelated scenes (e.g., a garage)—tests of gist memory. However, their ability to discriminate studied scenes from similar scenes (e.g., a different lake)—tests of specific memory—was inferior for scenes that were studied for just 1 s versus those that were studied for 4 s.

These item memory studies with young adults support fuzzy-trace theory's position of independent encoding of specific and gist representations, with more rapid formation of the latter (Brainerd & Reyna, 1990, 2004). To date, only one study has examined how rapidly young adults can encode specific and gist representations of episodic associations. Greene and Naveh-Benjamin (2023e) presented young adults with pictures of faces paired with pictures of scenes (e.g., an old man paired with a park) at various rates of presentation (0.75, 1.5, or 4 s per pair). In tests of long-term memory, participants discriminated studied pairs from similar pairs (e.g., the old man with a different park) and unrelated pairs (e.g., the old man with a bedroom). Using mathematical modeling (Stahl & Klauer, 2008), Greene and Naveh-Benjamin (2023e) showed that young adults' abilities to remember the specific face–scene pairing (e.g., whether the old man had been paired with the first or the second park scene) improved with each increase in encoding time. Meanwhile, young adults' abilities to remember the gist of the face–scene pair (e.g., whether the old man had been paired with a park or a bedroom) improved from 0.75 to 1.5 s of encoding time, with sometimes no further improvement from 1.5 to 4 s of encoding time. These results also align with the parallel trace model (Brainerd & Reyna, 1990) and are opposed to the specific-gist serial dependency model (Kintsch & van Dijk, 1978).

Which Model Best Accounts for How Older Adults Encode Specific and Gist Representations?

The parallel trace model appears to best capture the data from younger adults with respect to how rapidly they encode specific versus gist representations on tasks of item and associative memory. However, it remains unknown whether this model could also account for rates of encoding specific and gist representations among older adults. It may seem logical to assume that older adults can encode gist representations as rapidly as, if not more rapidly than, specific representations, given that they have well-preserved gist but not specific representations, compared to younger adults (Brainerd & Reyna, 2015; Devitt & Schacter, 2016; Greene & Naveh-Benjamin, 2023a; Grilli & Sheldon, 2022). Older adults may be able to rely upon their extensive knowledge base (i.e., semantic memory; Baltes et al., 1999; Nyberg et al., 1996) to rapidly encode the gist of new information (cf., Lindenberger & Mayr, 2014; Umanath & Marsh, 2014).

Alternatively, a variant of the specific-gist serial dependency model (Kintsch & van Dijk, 1978) may better account for how older adults encode specific and gist episodic memory representations, even as this model fails to account for empirical data of younger adults. That is, older adults may need to initially lay down a partially established specific representation before they can begin to encode a gist representation. To compensate for age-related sensory decline (e.g., Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Naveh-Benjamin & Kilb, 2014), older adults may devote much of their effort during early stages of encoding to deciphering their degraded sensory/perceptual representations of incoming information. For example, older adults may need to process at least some of the specific details of an image (e.g., "this scene has a bench, a gazebo, and trees") before they can infer the meaning of the image (e.g., "this scene is a park"). This potential need to first attend to the specific, perceptual features of information during early stages of encoding may tax older adults' abilities to also begin rapidly encoding the gist, due to their more limited attentional capabilities (Craik & Byrd, 1982; Hasher & Zacks, 1988). However, once older adults can begin extracting the gist, they may not devote much additional attentional resources to fleshing out their partially established specific representations, given the processing advantages of relying on gist representations (Greene & Naveh-Benjamin, 2023d). By this account, older adults' specific representations formed under shorter encoding rates may be commensurate with those formed under longer encoding rates, whereas their gist representations may flesh out with increases in encoding time. Thus, there is a sound argument to be made in favor of the specific-gist serial dependency model, and against the parallel trace model, in explaining how older adults encode specific and gist representations.

Can Age-Related Cognitive Slowing Explain Why Older Adults Have Impoverished Specific Memory Representations?

Examining the rates under which older adults encode specific and gist representations, particularly of episodic associations, may shed insight into why older adults' episodic memories are representationally less specific in nature than those of younger adults (e.g., Greene & Naveh-Benjamin, 2023a). Specifically, older adults may require more time than younger adults to encode specific representations. Theorists have long proposed that older adults' slower processing of information, as evident by their slowed reaction time in tasks of processing speed (Hale & Myerson, 1996; Salthouse, 1998, 2000; Schaie, 1989), underlies their deficits in numerous aspects of cognition, including episodic memory (Light, 1991; Myerson et al., 1990; Salthouse, 1996). According to the processing speed theory of aging (Salthouse, 1996), age-related differences in performance on complex tasks like associative recognition are at least partially attributable to a limited-time mechanism (cf., Salthouse, 1980, 1982, 1985), whereby slowing of early operations in a sequence (e.g., slower initial sensory/perceptual registration of stimuli) restricts older adults' time to perform later operations (e.g., employing effective strategies to commit the stimuli to memory).

It is possible, however, that older adults' slower processing speed is not attributable to a slowing in cognitive processing, but rather to slowing of nonmnemonic processes. Using a diffusion modeling analysis (Ratcliff, 1978), Ratcliff et al. (2001, 2004) found that age-related differences in reaction time on two-choice discrimination tasks (e.g., old/new item recognition) were explainable by older adults' slower nondecision time (i.e., the time representing noncognitive processes, like preparing a motor response). However,

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old/new recognition tasks are not sensitive to isolating the underlying contributions of specific versus gist representations to task performance (Brainerd et al., 1999, 2019). In a traditional old/new recognition task, new items (e.g., the word "broom") are unrelated to studied items (e.g., the words "chair," "hat," and "pillow") at both specific and gist levels of representation (i.e., "broom" does not resemble the exact content nor the semantic/meaning content of any studied item). Thus, participants could rely on either type of representation of studied items to reject new items, such that older adults could have comparable mnemonic processing time as younger adults on these tasks by responding often on the basis of their intact gist representations.

The Present Study

Here, we aimed to characterize how rapidly young and older adults can encode specific and gist representations of the associations between components of an episode that are core to episodic memory (Tulving, 1983; Underwood, 1969; Zimmer et al., 2006). To do so, we employed a modified variant of the associative specificity task of Greene and Naveh-Benjamin (2020), in which participants studied face–scene pairs (e.g., an old man paired with a park), simulating remembering people in different locations (e.g., Gruppuso et al., 2007), and later completed conjoint associative recognition tests (cf., Brainerd et al., 1999; Stahl & Klauer, 2008). The conjoint recognition tests featured previously studied pairs (e.g., the old man paired with the same park), related lure pairs (e.g., the old man paired with a different park), and unrelated pairs (e.g., the old man paired with a hallway). Thus, unlike in classic old/new recognition, our recognition tests featured a mix of new lures that resembled studied pairs at gist but not specific levels of representation (related pairs) and those that were unlike studied pairs at specific and gist levels of representation (unrelated pairs). This enabled us to isolate the contributions of specific and gist representations to young and older adults' recognition responses with mathematical measurement models (Brainerd et al., 1999, 2001; Stahl & Klauer, 2008, 2009).

The critical manipulation of the present study involved a systematic variation of the encoding rate of presentation of each face–scene pair (cf., Greene & Naveh-Benjamin, 2023e). In previous studies that found age-related differences in specific but not gist memory on this task (Greene & Naveh-Benjamin, 2020, 2022a), young and older adults alike had 4 s to encode each pair. Here, we employed a fast–medium–slow encoding rate manipulation on a within-subject basis, creating conditions where participants had very little time (i.e., fast rates), a moderate amount of time (i.e., medium rates), or a lot of time (i.e., slow rates) to encode each pair. We varied these rates between young and older adults such that, at the slowest presentation rates, older adults had more time (6 s per pair) than younger adults (4 s per pair) to encode each pair.

Our manipulations of the encoding rate of presentation and the similarity of the recognition probes enabled us to address important unresolved questions about the nature of episodic memory representations, in general, and the potential source of age-related differences in these representations, more specifically. First, does the same theoretical model that can explain the rates of encoding specific and gist associative episodic memory representations apply to young and older adults alike? Second, can slowing in the speed of encoding specific representations explain why older adults have more impoverished representations of the specific details of their past experiences (e.g., Greene & Naveh-Benjamin, 2023a)?

Regarding the first question, we hypothesized that, among younger adults, the parallel trace model advocated by fuzzy-trace theory (Brainerd & Reyna, 1990) would better account for the rates under which specific and gist representations are encoded, compared to an alternative specific-gist serial dependency model (Kintsch & van Dijk, 1978). That is, we expect to find improvements in young adults' abilities to remember the specifics of face–scene pairs with increases in encoding time, but young adults' abilities to remember the gist of these pairs would be as established at the fast (or, at minimum, at the intermediate) rate as at the slow encoding rate. This hypothesis is consistent with the results of numerous prior studies of item memory (Ahmad et al., 2017; Draine & Greenwald, 1998; Melcher, 2006; Tatler et al., 2003) and with one prior study of associative memory (Greene & Naveh-Benjamin, 2023e; see Method for important differences between the present study and this precursor). Among older adults, however, there is reason to anticipate that either the parallel trace model or the specific-gist serial dependency model could explain the rates and order of encoding specific and gist representations. The parallel trace model could apply because older adults may be able to rely upon their extensive knowledge base (Baltes et al., 1999; Nyberg et al., 1996) to rapidly begin encoding the gist of a face–scene pair. Alternatively, the serial dependency model could apply because older adults, with more diminished sensory/perceptual processing capabilities (e.g., Baltes & Lindenberger, 1997), may need to devote much of their attention during the early stages of encoding to deciphering the specific details of a face–scene pair before they can begin to interpret its meaning. In this case, we would expect to find that older adults' specific representations established under fast presentation rates would be commensurate with those formed under the intermediate (and possibly the slow) rate, whereas their gist representations would improve with increases in encoding time.

Regarding our second question, we hypothesize that when encoding time is equated between young and older adults, older adults would have poorer memory for the specific details of face–scene pairs, but there would be no age-related differences in gist memory, at least at the standard (4 s) encoding rate, in line with previous studies (Greene et al., 2022; Greene & Naveh-Benjamin, 2020, 2022a). If older adults' reduced memory specificity, relative to younger adults, is attributable to age-related cognitive slowing (e.g., Salthouse, 1996), then we would expect that with more time to encode face–scene pairs for older adults (6 s per pair) compared to younger adults (4 s per pair), age-related differences in specific representations should be reduced or disappear. If, however, age-related slowing has more to do with nonmnemonic processes, like the time it takes to execute a response (e.g., Ratcliff et al., 2001, 2004), then even with more time to encode face–scene pairs, older adults' specific representations could still be less well-established than those formed by younger adults under shorter encoding durations.

Method

The present study consisted of two experiments. However, due to the similar methods and obtained results (see below), we present our analyses collapsed across experiments.

Participants

The target sample size for each experiment was 40 participants per age group. This sample size has been found to be well-powered (>80%

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sensitivity) by a Bayesian design analysis for detecting a medium-sized age-related effect ($d \sim 0.70$) in the associative specificity paradigm in prior work (Greene et al., 2022) and is consistent with the typical sample sizes used in this paradigm (Greene & Naveh-Benjamin, 2020, 2022a, 2022b, 2022d, 2023b, 2023c, 2023e). However, 46 older adults participated in Experiment 1, so the final sample size, collapsed across the two experiments, was 80 younger adults and 86 older adults. Demographic information is listed in Table 1.

Most participants, except for 17 young adults in Experiment 2, were recruited from the crowdsourcing platform Prolific (n.d.) and received monetary compensation ranging from \$8.00 to \$9.00 USD. The remaining 17 young adults were recruited from introductory psychology classes at the University of Missouri and received research credits toward the course requirement. All participants completed the study online. Participants on Prolific were eligible to participate if they (a) were aged between 18 and 26 years (for young adults) or 65–80 years (for older adults); (b) were fluent in English; (c) reported no history of cognitive impairment or dementia; (d) reported drinking no more than five to nine alcoholic beverages per week; (e) had an approval rating of $> 85\%$ based on prior studies completed on the site; (f) had competed no more than 300 prior studies on Prolific; and (g) had obtained an educational level of no higher than a Master's degree or equivalent.

As indicated in Table 1, the samples of young and older adults in both experiments were majority female and, at least in the combined dataset, had similar levels of education. There was no significant difference in the proportion of young and older adult participants identifying as female in Experiment 1, $\chi^2(1) = 0.01$, $p = .940$; in Experiment 2, $\chi^2(1) = 0.00$, $p = 1.00$; nor combined across the two experiments, $\chi^2(1) = 0.01$, $p = .922$. For completed years of formal education, there was no significant difference between young and older adults in Experiment 1, $t(82.12) = -1.28$, $p = .204$, nor in the combined sample, $t(159.38) = -0.60$, $p = .547$. However, in Experiment 2, the older adults were slightly more highly educated than the young adults, $t(73.60) = -2.07$, $p = .042$, but the younger adult sample consisted of 17 undergraduate students, many of whom would likely go on to obtain a college degree. The 23 young adults in Experiment 2 who were recruited from Prolific had completed an average of 15.04 years of formal education, which is similar to the educational attainment of the older adults.

Table 1

Demographic Statistics of the Young and Older Adults

Age group	*n*	*M* Age (*SD*)	*M* YoE (*SD*)	%Female, %Male
Exp 1 (YA)	40	22.55 (2.43)	15.08 (2.00)	57.5, 42.5
Exp 1 (OA)	46	68.39 (3.90)	14.42 (2.70)	54.3, 46.7
Exp 2 (YA)	40	21.10 (2.73)	13.99 (2.18)	65.0, 35.0
Exp 2 (OA)	40	68.88 (3.97)	15.15 (2.80)	65.0, 35.0
All (YA)	80	21.83 (2.67)	14.53 (2.15)	61.3, 38.7
All (OA)	86	68.62 (3.92)	14.76 (2.75)	59.3, 40.7

Note. All indicate the combined samples from Exp 1 and Exp 2. Age is given in years. Participant sex was assessed with the question "what is your sex?" Participants responded by selecting "female," "male," "intersex," or "prefer not to say." The last column (%female, %male) only depicts the percentage of participants responding with the options "female" or "male," as no participants chose the remaining options. Regarding racial composition, 95.3% of older adults across the two experiments identified as being White, compared with 75% of younger adults (12.5% Asian, 5% Black, and 7.5% identifying as either multiracial, Latinx/Hispanic, or other). YoE = years of formal education; Exp 1 = Experiment 1; YA = young adult; OA = older adult; Exp 2 = Experiment 2.

Design

A 2 (Age: Young vs. Older Adult) × 3 (Presentation Rate at Encoding: Fast, Intermediate, or Slow) × 3 (Type of Memory Probe: Intact, Related, or Unrelated) mixed design was used, with encoding presentation rate and type of memory probe manipulated within-subject. Presentation rates at encoding varied by block in a random order for each participant, with three blocks studied under each presentation rate. The encoding presentation rates differed slightly for the young (1, 2, or 4 s per pair) and older adults (2, 4, or 6 s per pair). The primary outcome variables were model-based estimates of specific and gist memory representations.

The presentation rates for young adults differed slightly from those used in the precursor to the present study (Greene & Naveh-Benjamin, 2023e), which employed a between-subject manipulation with encoding presentation rates of 0.75, 1.5, or 4 s per pair. We adjusted the rates for the young adults so they would be on a more common scale with the presentation rates administered to older adults. We also used a within-subject manipulation to better control for individual differences among participants within an age group (e.g., Cherry & Park, 1993).

Materials

We paired 120 unique faces from the FACES database (Ebner et al., 2010) with 120 unique scene images from a categorized scene pool (Konkle et al., 2010). Pairs were presented centrally on a computer screen, with the face to the left and the scene to the right. Each image was presented at a resolution of 312 × 389 pixels. All faces were White and depicted neutral emotions. Faces were divided evenly among young and old and male and female faces (30 faces per each combination of age and sex group). The 120 scenes were drawn from 60 scene categories, each with two unique exemplars (e.g., two parks and two kitchens). Each exemplar from a given scene category was presented in the same block but was paired with a different face. The experiment was programed and automated for online testing via PsyToolkit (Stoet, 2010, 2017).

Procedure

All procedures were approved by the Institutional Review Board at the University of Missouri. In each experiment, participants completed three short practice blocks (one under each encoding rate of presentation) followed by nine experimental blocks (three each per encoding presentation rate, with the order randomized by participant). Each block consisted of a study phase, a period of unrelated interpolated activity, and a test phase (see Figure 2). The only between-experiment difference occurred in the interpolated activity period, as discussed below.

Prior to the first practice block, participants were informed that they would see pictures of faces paired with scenes under various rates of presentation and that their memory for these face–scene pairs would be tested. They were also informed about the different types of memory probes they would see and were given examples of intact, related, and unrelated pairs. During the practice blocks (which featured just four studied pairs each), participants received feedback about their recognition responses, but they received no

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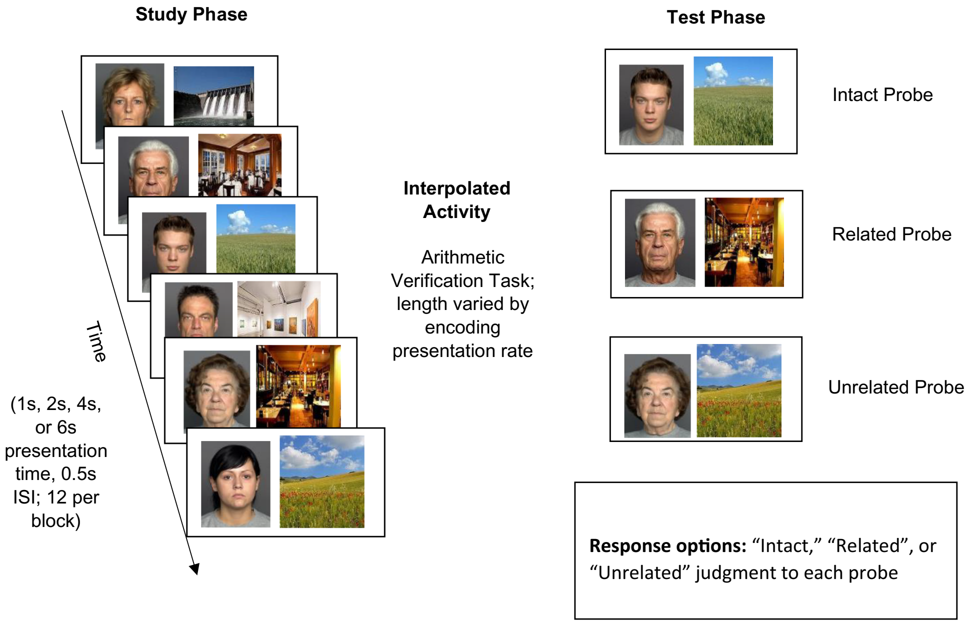
Figure 2

Schematic of the Procedure



Note. Faces depicted in this figure are from the FACES Database (Ebner et al., 2010), https://faces.mpdl.mpg.de, reproduced with permissions per the FACES platform release agreement. Participants studied 12 unique face–scene pairs per block (only six depicted here). The encoding presentation rate (1, 2, 4, or 6 s) was the same for all pairs in a block but varied across blocks (only young adults studied pairs at the 1 s rate, and only older adults studied pairs at the 6 s rate; both groups studied pairs at the 2 and 4 s rates). After studying all pairs in a block, participants completed an arithmetic verification task for 60–120 s. The length of this interpolated activity task was based on the encoding presentation rate to equate the total amount of time from the beginning of the study phase to the beginning of the test phase across all blocks. During the test phase at the end of each block, participants saw an equal number of intact, related, and unrelated pairs. ISI = interstimulus interval. See the online article for the color version of this figure.

feedback during the main experimental blocks. They then proceeded to the nine experimental study-test blocks, presented in a random order for each participant.

Study Phase

Each study phase featured 12 sequentially presented unique face–scene pairs. All pairs in a block were presented at the same rate during encoding. Each pair was separated by a 0.5 s interstimulus interval. Within the study phase of a given block and across all blocks, no two pairs were identical, but the two exemplars of a given scene category (e.g., the two field scenes depicted in Figure 2) both appeared in the same block, each paired with a unique face.

Interpolated Activity During Retention Interval

After the study phase of each block, participants completed an arithmetic verification task for a minimum of 60 s before beginning the test phase. Participants indicated whether simple arithmetic problems were solved correctly (e.g., "3 × 4 = 12?") or incorrectly (e.g., "5 + 7 = 13?") by pressing the "1" or "0" key, respectively. To ensure that the total block length prior to the start of the test phase was equal across all encoding presentation rates (e.g., Glanzer & Cunitz, 1966; Greene & Naveh-Benjamin, 2023e), the length of this interpolated activity task depended on the presentation rate during the study phase (see Table 2). This ensured that the average amount of time between encoding and retrieval for any face–scene pair were equivalent across all presentation rates. This is critical given that specific representations may decay rapidly after encoding (e.g., Greene & Naveh-Benjamin, 2022a, 2022b), such that if the length of the retention interval was the same across all blocks,

Table 2

Length of Study Phases and Interpolated Activity-Filled Retention Intervals Based on Rate of Presentation at Encoding

Encoding rate (s)	Study phase (s)	Retention interval (s)	Total time before test phase (s)
1	18	120	138
2	30	108	138
4	54	84	138
6	78	60	138

Note. The length of the study phase is calculated as 12 Pairs × (Encoding Rate + 0.5 s), with the 0.5-s term corresponding to the interstimulus interval. Using a minimum retention interval that spanned 60 s, the total time from the beginning of the study phase to the beginning of the test phase (total time before test phase) was 138 s in the 6 s encoding rate condition. We equated the total time before test phase across all other encoding rates by subtracting the respective study phase length from 138 s to determine the respective length of the retention interval.

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there would have been potential for more erosion of specific representations in blocks with slower presentation rates.

The main difference between experiments was whether the total number of arithmetic problems was also equated across encoding presentation rates. Because the length of the retention interval was longer for blocks with faster encoding rates (see Table 2), the number of arithmetic problems shown to participants could depend on the encoding rate. We controlled for this potential source of nonstudy-specific interference (i.e., interference from the interpolated activity task rather than from the face–scene task) only in Experiment 2. In Experiment 1, participants could solve as many problems as possible within the retention interval, as a new problem appeared immediately after the response to the previous problem. As a result, participants solved more problems in blocks with faster encoding rates (see Table S1 in the online supplemental materials). In Experiment 2, there were 20 arithmetic problems per block, regardless of the length of the retention interval. Here, participants had 3,000 ms to respond to each problem. If they responded before the end of the 3,000 ms window, a string of plus signs (“++++”) appeared onscreen until the end of the trial. This string remained onscreen for an additional 1,200, 2,400, or 3,000 ms after the response window for the 4, 2, and 1 s encoding time conditions, respectively. This ensured that the total length of the retention interval and the total number of arithmetic problems presented was equivalent across all blocks.

Despite these differences between experiments, there were no credible between-experiment effects on recognition accuracy (see Figures S1 and S2 in the online supplemental materials). There were also comparable model-based estimates of specific and gist memory across experiments for both young and older adults (see Tables S2–S5 in the online supplemental materials), but we did detect subtle between-experiment differences in the retrieval processes of older adults at the 4 s encoding rate (discussed in the Analyses section). Nevertheless, given the overall comparability in results obtained across experiments, we combined the data from the two experiments in subsequent analyses.

Test Phase

After the end of the interpolated activity, participants’ memory for the pairs studied earlier in that block was assessed with associative recognition tests featuring intact pairs (i.e., the same face with the same scene from study; see Figure 2 for example) and recombined pairs (i.e., the face from one pair repaired with the scene from another pair). There were no new (i.e., unstudied) faces or scenes during the test phase, ensuring that all items shown at test had the same level of familiarity based on prior exposure in the study phase. The recombined pairs were further divided into related pairs and unrelated pairs. Related pairs retained the gist but not specific representation of the original pairing (e.g., in Figure 2, the old man was paired with the same type of scene—a restaurant—in the study and test phases, but the specific restaurant scene changed between study and test). Unrelated pairs were unlike original pairs at both specific and gist levels of representation (e.g., in Figure 2, the old woman appeared with a restaurant at study but with a field at test). There were an equal number (four each) of intact, related, and unrelated pairs per block. Participants had up to 50 s to click on one of three labeled responses (“intact,” “related,” or “unrelated”) appearing below each pair. However, there were no trials in which participants failed to respond within 50 s.

Analyses

We sought to characterize the effects of encoding time and participant age on associative recognition accuracy and the underlying quality of memory representations supporting accurate and inaccurate responses. Thus, our main analyses concentrated on recognition accuracy, rather than reaction time, but exploratory analyses of reaction time data can be found in Table S6 in the online supplemental materials.

Analysis of Variance (ANOVA) on Associative Recognition Proportion Correct and Lure Discrimination Index

We first measured whether there were differences in accuracy on the associative recognition task—defined as the proportion of correct responses to each type of memory probe—as a function of age group, presentation rate at encoding, and type of memory probe, using ANOVA models estimated in *JASP* (JASP Team, 2023). Tests of between-experiment differences in accuracy were also conducted (see the online supplemental materials).

In addition to these basic accuracy analyses, we also conducted analyses on a metric derived from mnemonic similarity tasks (Stark et al., 2019), which share many similar features to our task but have traditionally been employed with tests of item memory. Specifically, we computed a lure discrimination index (LDI), which provides a behavioral metric of pattern separation, the ability to orthogonalize similar representations from different events (cf., Stark et al., 2013). LDI is a bias-correction metric for “related” responses, computed as the difference between correct “related” responses to related probes and erroneous “related” responses to unrelated probes, that is, $\text{LDI} = p(\text{“related”}|\text{related}) - p(\text{“related”}|\text{unrelated})$. Higher values of LDI are assumed to reflect an enhanced ability to retrieve specific details of studied events, enabling one to disambiguate similar lures from those events. LDI metrics were submitted first to repeated measures ANOVA models within each age group to test for effects of encoding time on lure discrimination separately among young and older adults. Next, we submitted the LDI metrics to independent samples *t* tests across age-matched encoding presentation rates (2 and 4 s) and the slowest presentation rates (4 s for younger adults vs. 6 s for older adults) to test for age-related differences in lure discrimination as a function of encoding presentation time.

A limitation of these analyses is that they provide limited insight into the underlying cognitive (e.g., retrieval of specific and/or gist representations) and noncognitive (e.g., guessing) mechanisms contributing to recognition accuracy (see Greene & Rhodes, 2022). For example, correct responses to a given probe could arise from a memory process (which may involve the retrieval of specific details, or just the gist of a previous event) or from guessing. Although the LDI purportedly corrects for some of the bias in “related” responses, it cannot cleanly separate the contributions of different memory representations (e.g., specific vs. gist) involved in correct responses, nor can it test for differences in the ability to retrieve these representations based on the type of test probe (e.g., intact vs. related pairs). These are important considerations in understanding the effects of presentation time at encoding on age-related differences in episodic memory specificity, given emerging evidence suggesting a dynamic interplay between encoding and retrieval conditions (Greene & Naveh-Benjamin, 2022a, 2023a). Thus, our principal conclusions were based on a model-based estimation of specific and gist memory, as discussed next.

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Multinomial-Processing-Tree (MPT) Model Analyses

To decompose participants' recognition responses into the latent cognitive and guessing processes that contributed to these responses, we used an empirically validated MPT model of specific and gist memory based on the simplified conjoint recognition paradigm (Stahl & Klauer, 2008, 2009). MPT models consist of a series of mathematical equations that define the probabilities that unique, latent processes (e.g., the retrieval of a specific representation) were involved in a participant's recognition response to a memory probe (for reviews, see Batchelder & Riefer, 1999; Erdfelder et al., 2009; for a tutorial, see Schmidt et al., 2023). The MPT model from the simplified conjoint recognition paradigm (Stahl & Klauer, 2008), featuring an extended parameter structure based on Stahl and Klauer (2009) to model illusory recollection for related probes—dubbed phantom recollection (Brainerd et al., 2001)—is depicted in Figure 3.

Overview of the Model. Participants' responses to different memory probes are modeled to arise from the contributions of specific and gist memory retrieval and guessing. Intact probes are identical to studied pairs and are thus strong elicitors of those pairs' specific representations (Brainerd et al., 1999, 2001, 2019; Brainerd & Reyna, 1990; Stahl & Klauer, 2008, 2009; cf., encoding-specificity principle, Tulving & Thomson, 1973). Thus, when shown an intact probe, participants may retrieve the specific details of the original pair (with probability V_i) and correctly respond "intact." If a participant fails to remember the specifics (with probability $1 - V_i$), they may still have access to the pair's gist (with probability G_i). Because both intact and related probes match the gist of studied pairs (see Figure 2), when the gist is retrieved, a participant must guess whether the probe is "intact" (with probability a) or "related" (with probability $1-a$). If a participant fails to remember the specifics and the gist of a studied pair, they can still guess (with probability b) that a pair could be either "intact or "related," or otherwise (with probability $1-b$), they will endorse the pair as "unrelated."

Related probes are less effective retrieval cues for a studied pair's specific representation (e.g., Brainerd et al., 2019). However, a participant may remember the specifics of the original pair (with probability V_r) and use that specific representation to reject the related probe. This recollection rejection process (Brainerd et al., 1999, 2003; Stahl & Klauer, 2008) results in a correct "related" response to related probes. Participants rarely engage in recollection rejection in conjoint recognition tasks (Brainerd et al., 2022), but they can still respond correctly if they retrieve the gist (with probability G_r) and guess "related" rather than "intact." Due to the high similarity between related probes and studied pairs, it is possible that a participant may experience a vivid, illusory recollection of having seen the related pair before. This phantom recollection process (Brainerd et al., 2001; Stahl & Klauer, 2009) results in erroneous "intact" responses to related pairs. Phantom recollection is theorized to arise from situations with impoverished (or inaccessible) specific representations but preserved gist representations that can be so strong that they generate false specific representations at retrieval (Brainerd et al., 2001; Lampinen et al., 2005; Singer & Remillard, 2008).

Finally, unrelated probes match original pairs at neither specific nor gist levels of representation (see Figure 2). Accordingly, retrieval of any representational information of the originally studied pair would be sufficient to correctly classify these probes. The model depicted in Figure 3 does not include separate specific or gist memory parameters for unrelated probes, as the modeled pathway $1 - b$ (which leads to correct "unrelated" responses) already corresponds to a state of believing that the memory probe does not at all resemble a studied pair. That is, this pathway models the probability that a participant thinks, "I do not remember this face being paired with this type of scene, so this is an 'unrelated' pair."

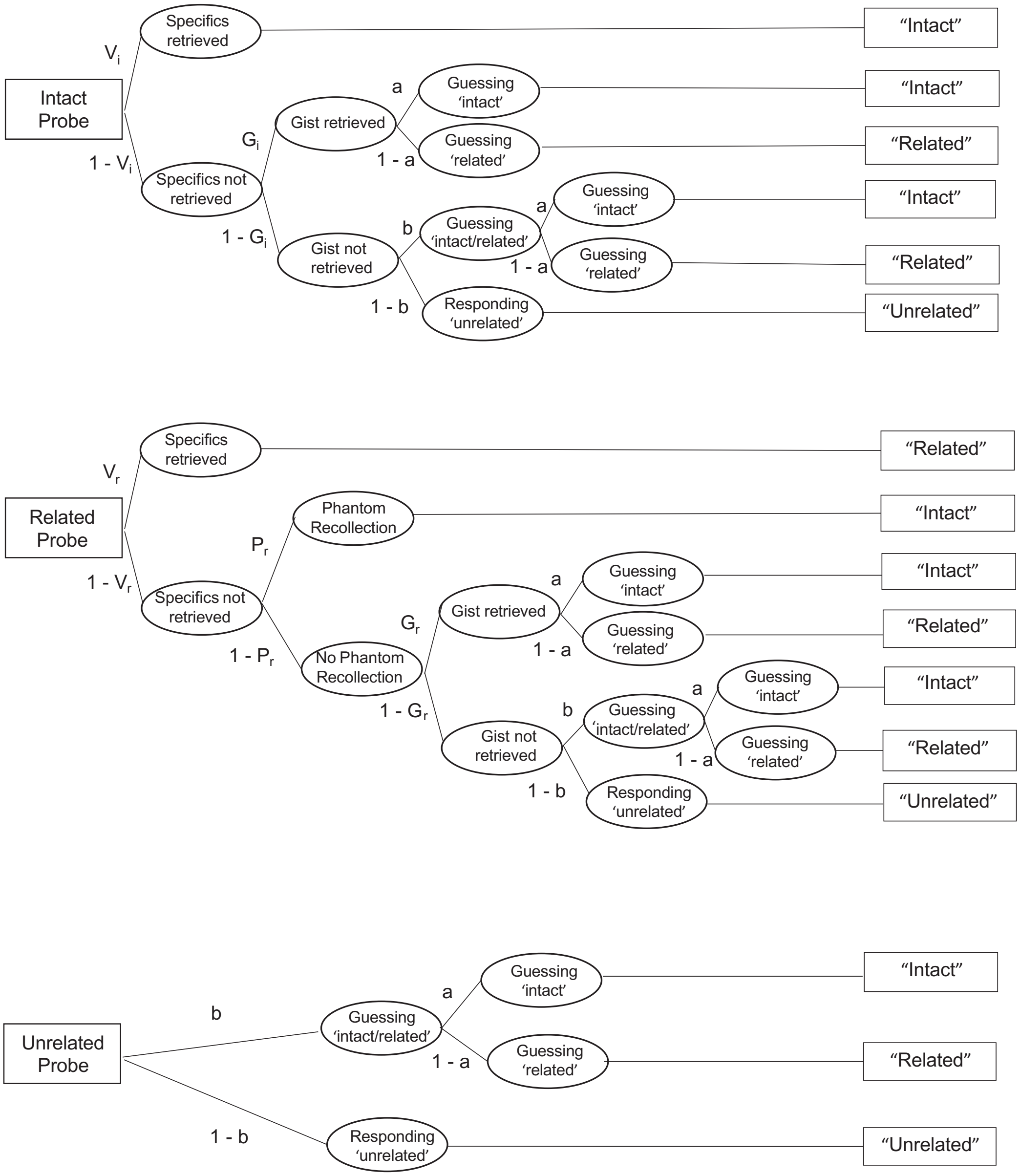
Model Estimation Procedures. We fit the model separately to the young and older adult data using a hierarchical Bayesian estimation routine with latent-trait prior specifications (Klauer, 2010) in the TreeBUGS package for R (Heck et al., 2018; R Core Team, 2022). In each group, we modeled within-subject effects of encoding rate by allowing each parameter to freely vary across fast, intermediate, and slow presentation rates. We used the program's default, weakly informative priors, which follow recommendations in the literature (Klauer, 2010; Matzke et al., 2015). Hierarchical MPT models account for heterogeneity in parameters across participants by partially pooling individual-level estimates toward group-level means (Schmidt et al., 2023). Traditional estimation approaches (e.g., fitting an MPT model to aggregated frequencies across participants) may overlook this important source of variability, which can lead to biased parameter estimates and goodness of fit statistics (J. B. Smith & Batchelder, 2010; Klauer, 2006; but see Erdfelder et al., 2023). Information about model sampling routines, convergence diagnostics, and goodness of fit assessments can be found in the online supplemental materials. The constrained models (discussed below) satisfactorily fit the data of young and older adults.

The model depicted in Figure 3 has seven free parameters, but the data structure (three types of memory probes crossed with three types of responses) has only six degrees of freedom. Thus, the saturated model is not identifiable. Following recommendations from Stahl and Klauer (2009), we constrained the recollection rejection parameter (V_r) to 0 in both groups, allowing us to freely estimate the remaining six parameters. There were several justifications for this decision. First, in a meta-analysis of conjoint recognition procedures, Brainerd et al. (2022) found that the mean estimate of V_r was 0.13 ($SD = 0.17$) across 424 item memory tasks with young adults, indicating that young adults rarely rely upon recollection rejection in these procedures. Second, estimates of V_r are often even lower in associative memory tasks, especially among older adults. For example, V_r was estimated to be 0.05 among young adults at the 4 s encoding rate of Greene and Naveh-Benjamin (2023e) and is often indistinguishable from 0 among older adults in tests of long-term memory (Greene & Naveh-Benjamin, 2022a). Third, when we allowed V_r to be freely estimated in the present study, by instead constraining the phantom recollection parameter to 0, the model did not satisfactorily fit the data of the older adults. This alternative model also provided reduced (but still reliable) fit to the data of younger adults, compared to the model with phantom recollection as a free parameter. Mean group-level posterior estimates [lower 2.5th percentile, upper 97.5th percentile] of V_r in this alternative parameterization of the model were low among young adults (1-s rate: 0.01 [0.00, 0.05]; 2-s rate: 0.03 [0.00, 0.09]; 4-s rate: 0.06 [0.00, 0.16]) and older adults (2-s rate: 0.01 [0.00, 0.03]; 4-s rate: 0.01 [0.00, 0.04]; 6-s rate: 0.01 [0.00, 0.05]). Thus, young and older adults alike rarely engaged in recollection rejection of related probes in the present study.

Model-Based Statistical Tests of Our Hypotheses. All statistical tests were based on comparisons of posterior estimates of each model parameter between two different conditions (e.g., comparing V_i between young and older adults at a specified encoding rate). For

Figure 3

Simplified Conjoint Recognition MPT Model



Note. When shown a memory probe (boxes on the left), a participant may arrive at their response (boxes on the right) in different ways, depicted by the branching pathways in the middle, where the ovals describe latent cognitive or guessing processes. Each parameter models the probability that the specified process occurs during the recognition period. The two *V* parameters correspond to the probability that participants retrieve the specific (denoted verbatim in fuzzy-trace theory) representation of an association given either an intact probe (V_i) or a related probe (V_r). Related probes can elicit a false but vivid recollective phenomenology of having experienced that probe before, and this is captured by the phantom recollection parameter P_r, which results in endorsing related probes as "intact." The two *G* parameters correspond to the conditional probabilities that participants retrieve the gist of an association for intact probes (G_i) or related probes (G_r), given that they have not retrieved more specific representations and, in the case of related probes, that they have not experienced phantom recollection. If participants retrieve only a gist but not specific representation, they then guess whether the probe is "intact" (with probability a) or "related" (with probability $1 - a$). If a probe elicits no specific or gist information for a participant, then the participant can still guess that the probe is "intact" or "related" with probability b. Otherwise, participants respond "unrelated" with probability $1 - b$. MPT = multinomial-processing-tree model; V_i = probability of remembering a specific representation when shown an intact probe; G_i = probability of remembering a gist representation when shown an intact probe; a = probability of guessing "intact"; b = probability of guessing either "intact" or "related"; V_r = recollection rejection parameter; P_r = probability of experiencing a phantom recollection when shown a related probe; G_r = probability of remembering a gist representation when shown a related probe.

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each parameter s in the set $S = \{1, \ldots, n_S\}$, we subtracted the posterior samples of s estimated in one condition from the posterior samples of s estimated in a different condition. Our use of hierarchical Bayesian methods minimizes the need to correct for multiple comparisons as adjustments for multiplicity are an inherent feature of such models (Gelman et al., 2012; Kruschke & Liddell, 2018). Within each age group, we tested for differences in each parameter across encoding rates with three sets of comparisons (slow–fast, slow–intermediate, intermediate–fast). Across age groups, we tested for age-related differences in each parameter as a function of the encoding presentation time with three sets of comparisons (young 2 s–old 2 s, young 4 s–old 4 s, young 4 s–old 6 s). We also compared parameter estimates within each age group across the two experiments and obtained mostly similar estimates (see Tables S2–S5 in the online supplemental materials). The only exception was that parameter G_r in the 4 s encoding rate among older adults was estimated to be slightly higher in Experiment 1 than Experiment 2. However, in both experiments, we detected no credible age-related differences in G_r at the 4 s encoding rate, and the comparability in the remaining parameters justified our decision to combine the data across experiments.

The subtraction method produces a posterior mean difference score and 95% Bayesian credible interval (CI) of the difference. In a Bayesian framework, a 95% CI conveys the range of values in which we can be 95% certain that the “true” difference in the population can be found. If the 95% CI of the difference score excludes 0, then this provides 95% certainty that a true difference exists between these conditions (see J. B. Smith & Batchelder, 2010). In addition, for each parameter s, we computed the proportion of posterior samples of s that were estimated to be higher in one condition/group (e.g., among young adults) than another condition/group (e.g., among older adults). We deemed that there was credible evidence for a difference in s across the two conditions when $> 95\%$ of posterior samples were estimated to be higher in one condition than the other. Importantly, if the posterior probability of a difference was $< 95\%$, we remained agnostic as to whether a true difference existed, which is analogous to obtaining a nonstatistically significant p value in the frequentist approach.[1]

Transparency and Openness

Neither experiment was preregistered. Deidentified data and analysis scripts are publicly available at https://osf.io/98anb/ (Greene & Naveh-Benjamin, 2023f). Face stimuli were from the FACES Database (Ebner et al., 2010) and can be accessed at https://faces.mpdl.mpg.de. Scene stimuli were drawn from categorized stimulus sets from Konkle et al. (2010) and are publicly available at https://bradylab.ucsd.edu/.

Results

Associative Recognition Accuracy

Figure 4 depicts the proportion of correct responses to each type of memory probe among young and older adults (see Figures S1 and S2 in the online supplemental materials for results separated by experiment). Young and older adults' average proportions of all responses to each memory probe at each encoding rate are listed in Table 3.

As depicted in Figure 4, within each age group, there were some improvements in accuracy with increases in encoding presentation time, though these improvements differed across the types of memory probes. Furthermore, across age groups, there were differences in recognition accuracy at each encoding rate that appeared to depend on the type of memory probe. To assess whether these visual trends were statistically reliable, we partitioned our ANOVA analyses into two separate sets of statistical tests aimed at addressing each aim of our study in isolation. First, we analyzed whether there were effects of encoding presentation rate within each age group. This first set of analyses did not include age as a between-subject factor because the encoding presentation rates were not identical between young (1, 2, and 4 rates) and older (2, 4, and 6 s rates) adults. Thus, an age difference at the fast (1 vs. 2 s) and intermediate (2 vs. 4 s) presentation rates would not be informative for our hypotheses.[2] Our second set of analyses focused on our a priori defined age-related comparisons at matched encoding presentation rates (2 and 4 s) for young and older adults and at the slowest rates (4 s for young adults compared to 6 s for older adults).

Effects of Encoding Presentation Rate Within Each Age Group

We fit a separate 3 (Presentation Rate at Encoding: Fast, Intermediate, or Slow) × 3 (Type of Memory Probe: Intact, Related, or Unrelated) repeated measures ANOVA to the proportion correct data of young and older adults. In each age group, there was a significant main effect of encoding presentation rate—young adults, $F(2, 158) = 48.24$, $p < .001$, older adults, $F(2, 170) = 35.24$, $p < .001$—with improvements in accuracy with each increase in the encoding rate (all $p_{\text{Holm}} \leq .005$). There was also a significant main effect of type of memory probe among young adults, $F(2, 158) = 99.89$, $p < .001$, and older adults, $F(2, 170) = 116.72$, $p < .001$, which was driven by a similar gradient of recognition accuracy across memory probes (related < intact < unrelated) in each group, all $p_{\text{Holm}} \leq .003$.

These main effects, however, were qualified by significant two-way interactions among young adults, $F(4, 316) = 7.26$, $p < .001$, and older adults, $F(4, 340) = 10.42$, $p < .001$. Follow-up one-way repeated measures ANOVAs detected significant main effects of encoding presentation rate on accuracy to all test probes in both groups, all $p < .004$. However, post hoc tests revealed important differences in this effect. In both age groups, accuracy to intact probes improved with each increase in encoding time (all $p_{\text{Holm}} < .001$), and accuracy to unrelated probes improved from the fast to intermediate rates (both $p_{\text{Holm}} < .001$) but not from the intermediate to slow

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[1] From a frequentist approach, our sample, combined across experiments, yields 87.8% power to detect mean differences of as small as 0.05 on the probability scale (the natural scale of each parameter) if the MPT model were fitted to aggregated response counts across participants, as estimated from a power analysis in the multiTree program (Moshagen, 2010). However, we did not perform a simulation-based method with the hierarchical model and thus, rather than quantifying evidence for a null effect, we appropriately remain agnostic in these instances.

[2] Because older adults' presentation rates were slower than those of younger adults at each level of the encoding rate factor, it is possible that the model would detect no age differences. Age differences may be present at matched encoding rates (i.e., the 2 and 4 s rates), but these rates map on to different levels of the encoding presentation rate factor for young and older adults. Moreover, two of our planned age-related comparisons involved the 4 s rate for younger adults (once in comparison with the matched 4 s rate for older adults, and once in comparison with the longer 6 s rate for older adults).

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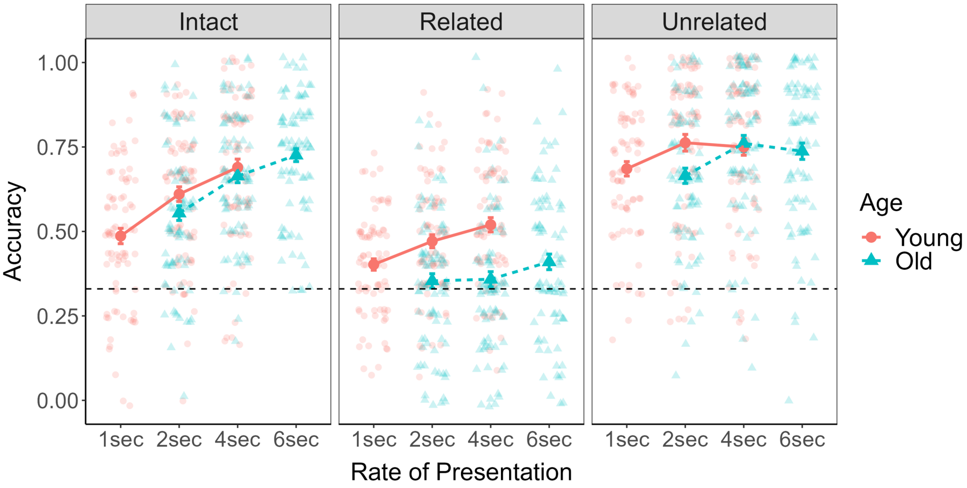
Figure 4

Proportion Correct on the Associative Recognition Test Combined Across Experiments 1 and 2



Note. Results depict the mean proportion of correct "intact," "related," and "unrelated" responses to intact, related, and unrelated probes, respectively. Large circles and triangles correspond to group averages for young and older adults, respectively. Error bars represent ±1 *SEM*. Individual participants' data are overlaid as small, faded circles and triangles. Lines connecting group means across the rate of presentation depict changes at the group level with increases in presentation time at encoding, but the data are measured on a discrete scale. Horizontal dashed line corresponds to chance-level performance (33% correct). Performance below chance to intact or related probes can still be informative in this paradigm. *SEM* = standard error of the mean. See the online article for the color version of this figure.

rates (both $p_{\text{Holm}} > .200$). Accuracy to related probes improved with each increase in encoding time among young adults only (all $p_{\text{Holm}} < .001$) but did not significantly differ between the fast (2 s) and intermediate (4 s) rates among older adults, $p_{\text{Holm}} = .795$.

We also submitted the LDI metrics (Table 4) to a separate one-way repeated measures ANOVA within each age group to test for effects of encoding presentation rate on bias-corrected lure discrimination. Among young adults, the main effect was significant with a Greenhouse–Geisser correction, $F(1.69, 133.10) = 15.74$, $p < .001$. Young adults' lure discrimination improved from 1 to 2 s of encoding time ($p_{\text{Holm}} < .001$) but did not significantly differ between 2 and 4 s of encoding time, $p_{\text{Holm}} = .134$. We also detected a significant effect of encoding presentation rate on older adults' LDI, $F(2, 170) = 7.14$, $p = .001$. Older adults' lure discrimination was higher at 6 s relative to 2 s of encoding time ($p_{\text{Holm}} < .001$) and was marginally higher at 4 s relative to 2 s as well ($p_{\text{Holm}} = .065$) but did not significantly differ between 4 and 6 s rates ($p_{\text{Holm}} = .110$).

Age-Related Effects as a Function of Encoding Presentation Rate

We fit a separate 2 (Age: Young vs. Older Adult) × 3 (Type of Memory Probe: Intact, Related, or Unrelated) mixed ANOVA to the proportion correct data obtained at age-matched encoding presentation

Table 3

Average Proportion of Responses to Each Memory Probe by Age Group and Encoding Rate of Presentation

	Younger adults			Older adults		
Response	1-s rate	2-s rate	4-s rate	2-s rate	4-s rate	6-s rate
		Intact probes			Intact probes	
P("intact")	0.49 (0.02)	0.61 (0.02)	0.69 (0.03)	0.55 (0.02)	0.66 (0.02)	0.73 (0.02)
P("related")	0.24 (0.02)	0.19 (0.02)	0.16 (0.02)	0.23 (0.02)	0.14 (0.01)	0.15 (0.01)
P("unrelated")	0.27 (0.02)	0.20 (0.02)	0.15 (0.02)	0.21 (0.02)	0.20 (0.01)	0.13 (0.01)
		Related probes			Related probes	
P("intact")	0.32 (0.02)	0.30 (0.02)	0.25 (0.02)	0.43 (0.02)	0.44 (0.02)	0.37 (0.02)
P("related")	0.40 (0.02)	0.47 (0.02)	0.52 (0.02)	0.35 (0.02)	0.36 (0.02)	0.41 (0.02)
P("unrelated")	0.28 (0.02)	0.23 (0.02)	0.23 (0.02)	0.22 (0.02)	0.21 (0.02)	0.22 (0.02)
		Unrelated probes			Unrelated probes	
P("intact")	0.12 (0.02)	0.09 (0.01)	0.10 (0.02)	0.15 (0.02)	0.10 (0.02)	0.12 (0.02)
P("related")	0.20 (0.02)	0.15 (0.02)	0.15 (0.02)	0.18 (0.02)	0.13 (0.02)	0.14 (0.01)
P("unrelated")	0.69 (0.02)	0.76 (0.03)	0.75 (0.02)	0.67 (0.02)	0.77 (0.02)	0.74 (0.02)

Note. Values represent the mean (*SE*) *P* of each response. Rate refers to the presentation duration in seconds of the face–scene pairs at encoding. *P* = proportion.

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rates (2 and 4 s rates) and to age-dependent slowest encoding presentation rates (4 s for young adults compared to 6 s for older adults). There was a significant main effect of Age (young > older adults) on proportion correct at the matched 2 and 4 s rates, both $F(1, 164) \geq 6.05$, $p \leq .015$. However, when older adults had more time (6 s) than younger adults (4 s) to encode face–scene pairs, the main effect of age on proportion correct was not significant, $F(1, 164) = 1.34$, $p = .249$. In each model, there was also a significant main effect of type of memory probe, all $F(2, 328) \geq 123.47$, all $p < .001$, which followed the pattern described previously (related < intact < unrelated).

At the 2 s rate, there was no significant Age × Type of Memory Probe interaction, $F(2, 328) = 1.31$, $p = .270$, such that older adults were less accurate than younger adults in classifying all types of memory probes. However, this interaction was significant at the age-matched 4 s rate and at the age-dependent slowest rates, both $F(2, 328) \geq 8.70$, $p < .001$. Follow-up independent samples *t* tests fitted to each probe separately revealed that older adults were less accurate than younger adults in responding to related probes at both the age-matched 4 s rate and at the slowest rates (6 vs. 4 s), both $t(164) \geq -3.50$, $p < .001$, but there were no age differences in accuracy to intact or unrelated probes at either encoding rate, all $p \geq .243$. Thus, regardless of the amount of time available to encode face–scene pairs, there were age-related differences in accuracy to related probes, but age-related differences in accuracy to intact and unrelated probes were only present at the 2-s encoding presentation rate. Results of the LDI comparisons between young and older adults support a similar conclusion: older adults had lower lure discrimination than younger adults at all encoding rates (see Table 4), all $t(164) \geq 2.39$, $p \leq .018$.

Associative Recognition Accuracy Summary

The accuracy results appear to be consistent with the hypothesis that young and older adults encode gist representations more rapidly than they encode specific representations. Indirect support for this hypothesis comes from the finding that accuracy to unrelated probes (which could be discriminated by remembering the gist of a studied pair) was similar at intermediate and slow encoding presentation rates in each age group, whereas accuracy to both intact and related probes (for which successful discrimination may require the retrieval of specific representations of studied pairs) continued to improve across these encoding presentation rates. The ANOVA results also appear to suggest that, compared to young adults, older adults may have less well-established specific and gist representations under speeded encoding times, as evident by age-related differences in accuracy to unrelated probes at the 2 s rate. With longer encoding time, age differences appear to be limited to specific representations, as age-related differences in accuracy were only present for related probes when older adults had 4 or 6 s to encode each pair. However, these age-related effects on specific representations may be cue-dependent at retrieval, as there were no age differences in accuracy to intact probes (which perfectly matched studied pairs) at the age-matched 4 s rate nor at the age-dependent slowest (6 s vs. 4 s) rates. These claims are indirect, however, because ANOVA cannot determine what processes gave rise to participants' recognition responses. Our MPT analysis was equipped to measure the latent cognitive and noncognitive processes that contributed to the patterns of responses shown in Figure 4 and Table 3.

Table 4

Lure Discrimination Indices for Young and Older Adults Across Encoding Presentation Rates

	Encoding presentation time in seconds			
Age group	1	2	4	6
Young adults	0.20 (0.03)	0.32 (0.03)	0.37 (0.03)	—
Older adults	—	0.17 (0.03)	0.23 (0.03)	0.27 (0.03)

Note. Values are mean (*SEM*). LDI is computed as the mean difference in the proportion of correct "related" responses to related probes and the proportion of erroneous "related" responses to unrelated probes, that is, LDI = *p*("related"|related) − *p*("related"|unrelated). Higher LDI is assumed to represent an increased ability to retrieve specific details of studied events (Stark et al., 2019). LDI = lure discrimination index; *SEM* = standard error of the mean.

MPT Model Results

Group-level posterior parameter estimates of the hierarchical Bayesian MPT model, split by encoding rate within each age group, are listed in Table 5.

Effects of Encoding Presentation Rate on Young Adults' Parameter Estimates

Difference scores for each MPT model parameter across encoding presentations rates among young adults are listed in Table 6. Bolded difference scores correspond to a credible difference in >95% of posterior samples. Figure 5 depicts the degree of overlap in the posterior distributions of each parameter across encoding presentation rates among young adults.

There are several key insights that the MPT model analysis of the young adult data provides that complement and extend upon the earlier accuracy results. First, young adults' estimates of the specific representation parameter V_i improved with each increase in encoding time, indicating that their specific representations of face–scene pairs became more established with more time to encode those pairs. Second, in contrast, young adults' estimates of the gist representation parameters G_i and G_r did not improve with each increase in encoding time. For parameter G_i, we detected no credible differences across encoding presentation rates, though the difference between the 4 and 1 s rates fell just shy of our 95% criterion (see Table 6). Parameter G_r was estimated to be higher at both the 2 and 4 s rates relative to the 1 s rate. Critically, there was no credible difference between the 2 and 4 s encoding presentation rates for either gist representation parameter, even as specific representations (parameter V_i) improved across these rates. Thus, the MPT model results provide more cast-iron support for the hypothesis that young adults encode gist representations of episodic associations more rapidly than they encode specific representations, confirming the indirect ANOVA results.

A third insight of the MPT model results is that young adults rarely experienced phantom recollection (parameter P_r)—the illusory sense that related probes had been experienced previously—as estimates of this parameter were bounded toward the lower end of the probability scale (see Figure 5). However, at the fastest (1 s) rate, young adults were marginally more likely to experience this vivid, false recollection than they were at the slowest (4 s) encoding

Table 5

Group-Level MPT Parameter Estimates Under Each Encoding Rate Among Young and Older Adults

Parameter	1-s rate	2-s rate	4-s rate	6-s rate
		Young adults		
V_i	0.33 [0.26, 0.40]	0.50 [0.42, 0.57]	0.61 [0.51, 0.69]	—
G_i	0.35 [0.23, 0.45]	0.41 [0.32, 0.49]	0.45 [0.34, 0.55]	—
G_r	0.53 [0.44, 0.61]	0.65 [0.57, 0.71]	0.66 [0.58, 0.74]	—
P_r	0.11 [0.04, 0.17]	0.07 [0.01, 0.14]	0.04 [0.00, 0.10]	—
a	0.32 [0.25, 0.39]	0.31 [0.23, 0.37]	0.28 [0.20, 0.34]	—
b	0.31 [0.27, 0.35]	0.20 [0.15, 0.25]	0.22 [0.17, 0.27]	—
		Older adults		
V_i	—	0.32 [0.22, 0.40]	0.57 [0.50, 0.63]	0.62 [0.54, 0.69]
G_i	—	0.49 [0.40, 0.58]	0.38 [0.29, 0.46]	0.55 [0.43, 0.65]
G_r	—	0.58 [0.48, 0.65]	0.65 [0.58, 0.72]	0.64 [0.57, 0.71]
P_r	—	0.13 [0.03, 0.22]	0.20 [0.11, 0.27]	0.09 [0.01, 0.18]
a	—	0.45 [0.37, 0.53]	0.40 [0.31, 0.49]	0.38 [0.30, 0.47]
b	—	0.32 [0.27, 0.37]	0.19 [0.15, 0.24]	0.23 [0.18, 0.28]

Note. Estimates represent the group-level (i.e., "population-level") posterior mean [lower 2.5th percentile, upper 97.5th percentile] of each parameter. MPT = multinomial processing tree; V_i = probability of remembering a specific representation when shown an intact probe; G_i = probability of remembering a gist representation when shown an intact probe; G_r = probability of remembering a gist representation when shown a related probe; P_r = probability of experiencing a phantom recollection when shown a related probe; a = probability of guessing "intact"; b = probability of guessing either "intact" or "related.".

presentation rates (see Table 6). Finally, relative to the 1 s rate, with 2 or 4 s of encoding time, young adults were less likely to respond "intact" or "related" (parameter b) when they believed that the test pair did not resemble any pair they remembered studying. In these situations, young adults were more likely to classify the test pairs as being "unrelated."

Effects of Encoding Presentation Rate on Older Adults' Parameter Estimates

Difference scores for each MPT model parameter across encoding presentations rates among older adults are listed in Table 7, with bolded difference scores indicating a credible (>95%) difference. Figure 6 depicts the degree of overlap in the posterior distributions of each parameter across encoding presentation rates among older adults.

Much as specific representations (parameter V_i) improved with each increase in encoding time among young adults, this was also generally true of older adults, though the difference in V_i between the 4 and 6 s rates fell shy of our credibility criterion (see Table 7). Nevertheless, older adults' specific representations were clearly much enhanced with either 4 or 6 s of encoding time, relative to 2 s of encoding time (see Figure 6).

As to the gist parameters, an unusual pattern was obtained with parameter G_i, which was unexpectedly higher at the fastest (2 s)

Table 6

Difference Scores for MPT Model Parameters Across Encoding Presentation Rates Among Young Adults

	Differences between encoding presentation rates		
Parameter	2–1 s	4–2 s	4–1 s
V_i	**0.17 [0.08, 0.25] (100%, 2 s > 1 s)**	**0.11 [0.02, 0.19] (99.3%, 4 s > 2 s)**	**0.27 [0.18, 0.37] (100%, 4 s > 1 s)**
G_i	0.07 [−0.06, 0.21] (85.0%, 2 s > 1 s)	0.04 [−0.10, 0.17] (69.9%, 4 s > 2 s)	0.11 [−0.04, 0.26] (92.1%, 4 s > 1 s)[a]
G_r	**0.12 [0.03, 0.21] (99.4%, 2 s > 1 s)**	0.02 [−0.06, 0.10] (68.3%, 4 s > 2 s)	**0.14 [0.04, 0.23] (99.8%, 4 s > 1 s)**
P_r	−0.04 [−0.14, 0.06] (78.7%, 1 s > 2 s)	−0.03 [−0.12, 0.06] (74.5%, 2 s > 4 s)	−0.07 [−0.14, 0.02] (94.2%, 1 s > 4 s)[a]
a	−0.01 [−0.11, 0.08] (58.1%, 1 s > 2 s)	−0.03 [−0.13, 0.06] (75.4%, 2 s > 4 s)	−0.04 [−0.14, 0.04] (82.4%, 1 s > 4 s)
b	**−0.11 [−0.15, −0.06] (100%, 1 s > 2 s)**	0.01 [−0.03, 0.06] (74.5%, 4 s > 2 s)	**−0.09 [−0.14, −0.04] (100%, 1 s > 4 s)**

Note. Values correspond to the group-level posterior mean difference score [lower 2.5th percentile, upper 97.5th percentile] of each parameter obtained by subtracting the posterior samples of that parameter estimated under a faster presentation rate from the posterior samples of that parameter estimated under a slower presentation rate. Positive difference scores indicate that the parameter was estimated to be higher under the slower than the faster rate; negative difference scores indicate the opposite. Values in parentheses denote the proportion of posterior samples that were higher in one condition than the other (50% indicates the two distributions were approximately equal). Bolded difference scores correspond to a credible difference in >95% of posterior samples. MPT = multinomial processing tree; V_i = probability of remembering a specific representation when shown an intact probe; G_i = probability of remembering a gist representation when shown an intact probe; G_r = probability of remembering a gist representation when shown a related probe; P_r = probability of experiencing a phantom recollection when shown a related probe; a = probability of guessing "intact"; b = probability of guessing either "intact" or "related".

[a] Difference scores that fell within 5% of the credibility criterion.

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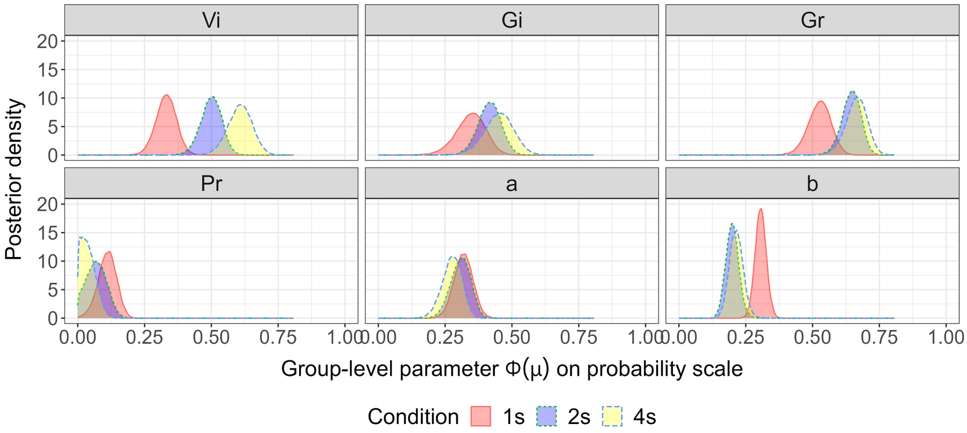
Figure 5

Posterior Distributions of Model Parameters as a Function of Encoding Presentation Rate Among Young Adults



Note. Parameters denote the probability of a given process occurring, and thus their natural estimates range from 0 to 1. The probit transform of each parameter returns the estimates from the latent-trait model to this natural scale (see Klauer, 2010). The precision of each parameter is indicated by how peaked it is on the *y* axis, as this results in a narrower width of the posterior distribution and thus more certainty in the "true" estimate of the parameter in the population. Condition describes the rate of encoding in seconds. V_i = probability of remembering a specific representation when shown an intact probe; G_i = probability of remembering a gist representation when shown an intact probe; G_r = probability of remembering a gist representation when shown a related probe; P_r = probability of experiencing a phantom recollection when shown a related probe; a = probability of guessing "intact"; b = probability of guessing either "intact" or "related." See the online article for the color version of this figure.

rate relative to the intermediate (4 s) rate but did not credibly differ between the 2 and 6 s encoding presentation rates. Meanwhile, estimates of parameter G_r were marginally higher at both the 4 and 6 s rates relative to the 2 s rate (though both difference scores fell shy of our credibility criterion; see Table 7). The distributions of parameter G_r between the 4 and 6 s rates almost completely overlay each other (see Figure 6). Although these results are perhaps somewhat less clear than those obtained with younger adults, they suggest, at minimum, a parallel formation of specific and gist representations among older adults, rather than a more protracted formation of gist representations. In fact, older adults' gist representations may be established more rapidly, given that, in some situation, estimates of gist memory were comparable between the 2 and 6 s rates (parameter G_i) or virtually identical between the 4 and 6 s rates (parameter G_r), whereas estimates of specific memory (parameter V_i) clearly improved from 2 to 4 s and trended higher at 6 s relative to 4 s of encoding time.

Older adults were occasionally prone to phantom recollection when shown related probes (parameter P_r). This susceptibility to phantom recollection was highest at the 4 s encoding presentation rate but decreased sharply with 6 s of encoding time (see Figure 6).

Regarding their bias to guess "intact" rather than "related" (parameter a), older adults were marginally more likely to do so at the 2 s rate than at the 6 s rate. Finally, older adults' tendency to endorse test pairs as being either "intact" or "related" (parameter b), even when they believed those test pairs did not resemble any pairs they remembered studying, decreased from 2 to 4 s of encoding time but was marginally higher at the 6 than 4 s rate.

Age-Related Differences in Parameter Estimates Based on Encoding Presentation Rate

Age-related differences in each model parameter under the two matched encoding presentation rates (2 and 4 s) and at the slowest rates (6 s for older adults compared with 4 s for younger adults) are listed in Table 8. Figure 7 depicts the degree of overlap in the posterior distributions of each parameter between young and older adults across these encoding rates.

There were several key findings from the age-related comparisons that go beyond what the earlier accuracy results could show. First, there were no credible age-related differences in gist memory across encoding presentation rates. Second, older adults were less likely than younger adults to access specific representations of previously studied face–scene pairs when shown intact test pairs (parameter V_i) at the 2 s encoding presentation rate. However, this age difference in V_i disappeared when older adults had 4 or 6 s of encoding time, compared to 4 s for younger adults. This finding complements the ANOVA results showing no significant age-related differences in accuracy to intact probes under these presentation rates but provides more direct evidence that older adults could establish specific representations commensurate with those of younger adults under these encoding rates. Their ability to retrieve these specific representations, however, was apparently dependent on the degree to which the test probe matched the studied pair (i.e., intact probes), given that there were age-related differences in other model-defined memory mechanisms for related pairs, discussed below.

A third important finding from the MPT model analysis is how the model accounts for the age-related differences in accuracy to

Table 7

Difference Scores for MPT Model Parameters Across Encoding Presentation Rates Among Older Adults

Parameter	Differences between encoding presentation rates		
	4–2 s	6–4 s	6–2 s
V_i	**0.25 [0.15, 0.35] (100%, 4 s > 2 s)**	0.05 [−0.03, 0.13] (89.6%, 6 s > 4 s)	**0.30 [0.20, 0.40] (100%, 6 s > 2 s)**
G_i	**−0.11 [−0.23, 0.01] (96.2%, 2 s > 4 s)**	**0.17 [0.03, 0.30] (99.1%, 6 s > 4 s)**	0.06 [−0.08, 0.19] (81.3%, 6 s > 2 s)
G_r	0.08 [−0.02, 0.18] (94.3%, 4 s > 2 s)[a]	−0.01 [−0.10, 0.07] (60.9%, 4 s > 6 s)	0.07 [−0.03, 0.16] (91.2%, 6 s > 2 s)[a]
P_r	0.07 [−0.06, 0.19] (85.5%, 4 s > 2 s)	**−0.11 [−0.22, 0.01] (96.0%, 4 s > 6 s)**	−0.04 [−0.16, 0.09] (71.9%, 2 s > 6 s)
a	−0.05 [−0.14, 0.05] (83.0%, 2 s > 4 s)	−0.02 [−0.12, 0.08] (63.9%, 4 s > 6 s)	−0.07 [−0.16, 0.02] (92.6%, 2 s > 6 s)[a]
b	**−0.13 [−0.17, −0.08] (100%, 2 s > 4 s)**	0.04 [−0.01, 0.08] (94.6%, 6 s > 4 s)[a]	**−0.09 [−0.14, −0.04] (100%, 2 s > 6 s)**

Note. Values correspond to the group-level posterior mean difference score [lower 2.5th percentile, upper 97.5th percentile] of each parameter obtained by subtracting the posterior samples of that parameter estimated under a faster presentation rate from the posterior samples of that parameter estimated under a slower presentation rate. Positive difference scores indicate that the parameter was estimated to be higher under the slower than the faster rate; negative difference scores indicate the opposite. Values in parentheses denote the proportion of posterior samples that were higher in one condition than the other (50% indicates the two distributions were approximately equal). Bolded difference scores correspond to a credible difference in >95% of posterior samples. MPT = multinomial processing tree; V_i = probability of remembering a specific representation when shown an intact probe; G_i = probability of remembering a gist representation when shown an intact probe; G_r = probability of remembering a gist representation when shown a related probe; P_r = probability of experiencing a phantom recollection when shown a related probe; a = probability of guessing "intact"; b = probability of guessing either "intact" or "related".

[a] Difference scores that fell within 5% of the credibility criterion.

unrelated probes at the 2 s rate and to related probes at all rates. With respect to the former, at 2 s of encoding time, older adults were more likely than young adults to guess that a test pair could be "intact" or "related" (parameter b) even when they did not remember seeing that type of pair (e.g., "I do not recall seeing this face with this type of scene, but perhaps I am wrong"). This led older adults, more often than young adults, to mistakenly endorse unrelated pairs as "intact" or "related" (rather than "unrelated") at the 2 s rate. Older adults' tendency to guess "intact" or "related" in this cognitive state decreased with increases in encoding time (see Table 7), resulting in no age-related differences in accuracy to unrelated probes at longer encoding presentation rates.

Regarding the age-related differences in accuracy to related probes, which were present at each encoding rate, these differences were attributed, in part, to a greater tendency of older adults to guess "intact" (parameter a) rather than "related" to these probes. However, at the age-matched 4 s encoding presentation rate, older adults were also more prone than young adults to experiencing phantom recollections of related probes (parameter P_r), leading them to erroneously conflate these probes as "intact" rather than "related." This heightened susceptibility to phantom recollection among older adults was remediated (i.e., there was no credible age-related difference) when older adults had even more time (6 s) to encode pairs compared to younger adults (4 s).

Discussion

Results of the present study constrain competing theories of information processing and human memory—fuzzy-trace theory (Brainerd & Reyna, 1990) versus gist macroprocessor theories (Kintsch & van Dijk, 1978)—and provide mechanistic insights into the causes of age-related changes in the representational specificity of episodic memories (Greene & Naveh-Benjamin, 2023a). Regarding the former, our results build on previous studies of item memory with young adults, studying words (e.g., Draine & Greenwald, 1998) or pictures of scenes (Ahmad et al., 2017; Melcher, 2006; Tatler et al., 2003), by showing that young and older adults encode gist representations of episodic associations (specifically those between faces and scenes) more rapidly than specific representations of those associations. These results extend support for fuzzy-trace theory (Brainerd & Reyna, 1990, 2004) to explaining the rate and order of encoding specific and gist representations of a core feature of episodic memory—the associative binding of multiple components of an episode (Tulving, 1983; Underwood, 1969; Zimmer et al., 2006)—among young adults (cf., Greene & Naveh-Benjamin, 2023e) and older adults alike. Regarding the second major finding, slower speed of processing of specific details during encoding may partially explain age-related declines in the representational specificity of episodic memories (Greene & Naveh-Benjamin, 2023a; cf., Salthouse, 1996). However, the nature of the retrieval cues also plays a significant role in these declines. Older adults were less accurate than young adults in classifying related test pairs (which match studied pairs at gist but not specific levels of representation), even when they had more time than younger adults to encode each pair.[3] Older adults' recognition errors of related probes were partially driven by a heightened susceptibility to phantom recollection (Brainerd et al., 2001; Stahl & Klauer, 2009), the illusory sense of believing that similar lures had been studied previously. We will soon revisit the broader implications of these findings, but first, we focus on one of the most positive outcomes of the present study: older adults could successfully remember the gist of novel face–scene pairs as well as younger adults, even under short encoding durations.

Preservation of Gist Representations in Older Adulthood

Our findings of preserved gist representations among older adults replicate prior work showing no age-related differences in gist representations of face–scene pairs under 4 s of encoding time (Greene & Naveh-Benjamin, 2020, 2022a) and is consistent with a larger body of evidence showing that older adults retain the

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[3] Moreover, older adults responded more slowly during the recognition tests (see Table S6 in the online supplemental materials) but were still less accurate than younger adults in classifying related pairs.

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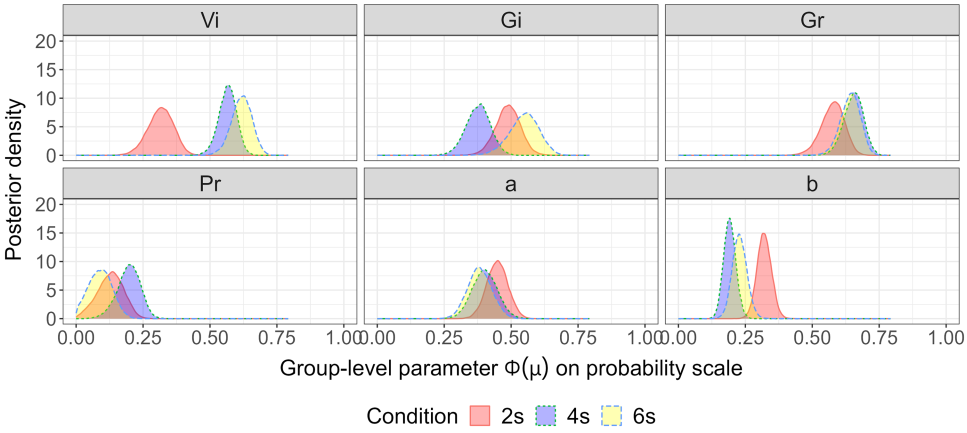
Figure 6

Posterior Distributions of Model Parameters as a Function of Encoding Presentation Rate Among Older Adults



Note. V_i = probability of remembering a specific representation when shown an intact probe; G_i = probability of remembering a gist representation when shown an intact probe; G_r = probability of remembering a gist representation when shown a related probe; P_r = probability of experiencing a phantom recollection when shown a related probe; a = probability of guessing "intact"; b = probability of guessing either "intact" or "related." See the online article for the color version of this figure.

general essence of their past experiences (for reviews, see Brainerd & Reyna, 2015; Greene & Naveh-Benjamin, 2023a; Grilli & Sheldon, 2022). Older adults' abilities to rapidly encode the gist of episodic associations may speak to the evolutionary benefit of gist representations (cf., Greene & Naveh-Benjamin, 2023d). This is so because, under speeded encoding conditions, one might expect that older adults, with impairments in associative binding (Boywitt et al., 2012; Chalfonte & Johnson, 1996; Old & Naveh-Benjamin, 2008; Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2003, 2004) and with slower cognitive processing speeds (Hale & Myerson, 1996; Light, 1991; Myerson et al., 1990; Salthouse, 1996, 1998, 2000; Schaie, 1989; but see Ratcliff et al., 2001, 2004), would struggle to encode a novel association to any degree of representation. Yet, even under such unfavorable conditions, older adults can establish gist representations commensurate with those of younger adults. Gist representations form a "semantic tag" of a new episode (Brainerd & Reyna, 1990; cf., McClelland & Rumelhart, 1985), connecting the new episodic memory to established knowledge. Our findings of preserved and rapidly formed gist representations of novel episodic associations in older adulthood are consistent with evidence that older adults rely upon prior knowledge to aid with new learning (Castel, 2005; Lindenberger & Mayr, 2014; Mohanty et al., 2016; Umanath & Marsh, 2014).

Although older adults' increased reliance on gist representations may come at the expense of their ability to remember specific details of prior experiences, contributing to false memories (Devitt & Schacter, 2016; Koutstaal & Schacter, 1997; Norman & Schacter, 1997; Tun et al., 1998), the preservation of gist representations in older adulthood can also be advantageous (Greene &

Table 8

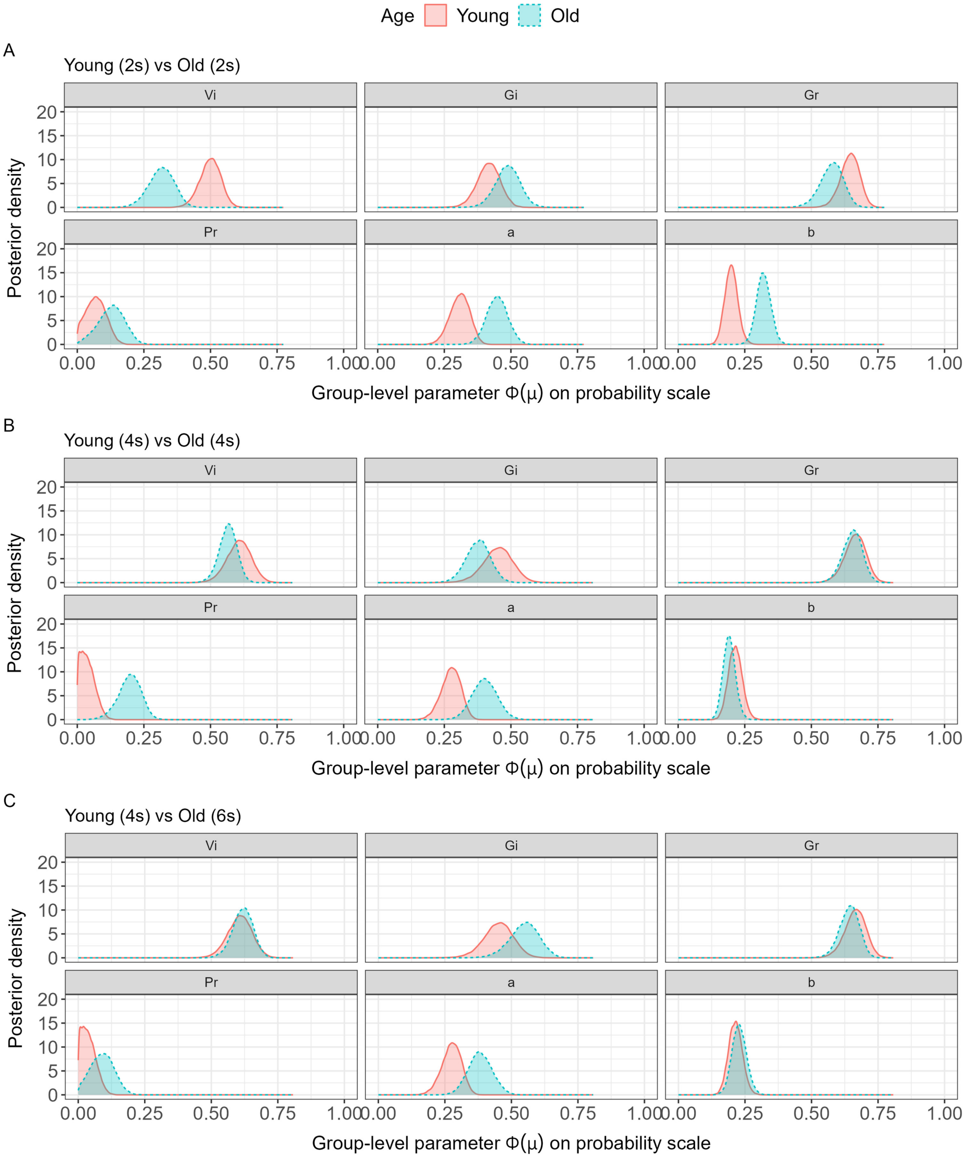
Age-Related Differences in Parameter Estimates Across Different Rates of Encoding

Parameter	Young (2 s)–old (2 s)	Young (4 s)–old (4 s)	Young (4 s)–old (6 s)
V_i	**0.18 [0.06, 0.31] (99.9% YA > OA)**	0.04 [−0.07, 0.15] (77.8% YA > OA)	−0.01 [−0.13, 0.11] (57.1% OA > YA)
G_i	−0.07 [−0.20, 0.05] (85.4% OA > YA)	0.07 [−0.07, 0.21] (85.3% YA > OA)	−0.10 [−0.25, 0.06] (89.7% OA > YA)
G_r	0.07 [−0.04, 0.18] (89.1% YA > OA)	0.01 [−0.10, 0.12] (57.3% YA > OA)	0.02 [−0.09, 0.13] (66.0% YA > OA)
P_r	−0.06 [−0.17, 0.06] (82.5% OA > YA)	**−0.16 [−0.25, −0.05] (99.8% OA > YA)**	−0.05 [−0.15, 0.04] (84.8% OA > YA)
a	**−0.14 [−0.25, −0.04] (99.7% OA > YA)**	**−0.13 [−0.25, −0.01] (98.6% OA > YA)**	**−0.11 [−0.23, 0.00] (97.0% OA > YA)**
b	**−0.12 [−0.19, −0.05] (100% OA > YA)**	0.02 [−0.05, 0.09] (74.5% OA > YA)	−0.01 [−0.09, 0.06] (64.7% OA > YA)

Note. Estimates represent the group-level (i.e., "population level") posterior mean difference score [lower 2.5th percentile, upper 97.5th percentile] of each parameter obtained by subtracting the posterior samples of the parameter estimated among older adults (at a given rate of encoding) from those of the same parameter estimated among younger adults (at a given rate of encoding). Positive difference scores indicate that the parameter was estimated to be higher among young than older adults; negative difference scores indicate the opposite pattern. Values in parentheses denote the proportion of posterior samples that were higher in YA or OA, where 50% indicates the two distributions were equal. Bolded difference scores correspond to a credible difference in >95% of posterior samples. V_i = probability of remembering a specific representation when shown an intact probe; YA = young adults; OA = older adults; G_i = probability of remembering a gist representation when shown an intact probe; G_r = probability of remembering a gist representation when shown a related probe; P_r = probability of experiencing a phantom recollection when shown a related probe; a = probability of guessing "intact"; b = probability of guessing either "intact" or "related".

Figure 7

Posterior Distributions of Model Parameters for Young and Older Adults Under Different Encoding Rates



Note. The comparisons involve the two matched encoding presentation rates for young and older adults (2 and 4 s per pair; Panels A and B) and the slowest encoding presentation rates for each age group (4 s for young adults, 6 s for older adults; Panel C). V_i = probability of remembering a specific representation when shown an intact probe; G_i = probability of remembering a gist representation when shown an intact probe; G_r = probability of remembering a gist representation when shown a related probe; P_r = probability of experiencing a phantom recollection when shown a related probe; a = probability of guessing “intact”; b = probability of guessing either “intact” or “related.” See the online article for the color version of this figure.

Naveh-Benjamin, 2023d). In many situations, such as reading or discourse comprehension, successful comprehension depends on remembering the meaning (gist) of the episode rather than more specific details like the exact syntax used (Johnson-Laird, 1983; Kintsch & van Dijk, 1978; Perfetti & Stafura, 2014), and older adults often excel at retaining the gist of narratives (Morrow et al., 1989; Radvansky & Dijkstra, 2007; Radvansky et al., 2001).

Older adults’ abilities to remember novel episodic associations at gist levels of representation may help them avoid minor inconveniences or major complications arising from their generally weaker associative memories (Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008). For example, by remembering the general locations in which they parked their cars in a crowded lot (e.g., the east as opposed to the west side of the mall), older adults can constrain their search range to

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that general location, even if they forget the specific parking spot. Most previous studies showing that older adults can remember the gist of novel episodic associations used tasks for which older adults could rely upon preexisting knowledge (or schemas) as a learning aid. For example, older adults can rely on their established schemas of the prices of grocery items to remember the gist of a novel item-price association (Castel, 2005; Castel et al., 2013) and to remember which of two novel items was better priced (Flores et al., 2017). There are some situations, however, where older adults can learn novel associations even when those associations may not be consistent with established schemas. When there is a strong value-based incentive to learning, older adults can learn the gist of novel associative information, as in remembering potential side effects associated with a medication (Friedman et al., 2015) or adverse health outcomes associated with certain foods (Middlebrooks et al., 2016).

Our findings, building on those of Greene and Naveh-Benjamin (2020, 2022a), suggest that older adults can retain the gist of novel episodic associations even in situations where preexisting knowledge or value-based incentives may play a minimal or potentially interfering role in new learning. In our procedure, older adults may have been able to rely upon schemas of encountering certain people (e.g., young women) in certain locations (e.g., gyms) to aid with remembering the gist of novel face–scene pairs that were consistent with those schemas. However, it is conceivable that many other preexisting schemas could also be consistent with the pairing (e.g., encountering young men in gyms, or encountering young women in parks), such that there was not a perfect one-to-one mapping between prior knowledge and the new information to-be-learned. That older adults could nonetheless successfully remember the gist of these novel episodic associations provides powerful support for theories proposing that older adults' memory failures are attributed more to a loss of specific rather than gist/general representations of past events (Brainerd & Reyna, 2015; Craik, 2002a; Greene & Naveh-Benjamin, 2023a). We turn now to considering the broader theoretical implications of our other major findings.

Implications for Parallel Versus Serial Encoding Models of Specific and Gist Representations

Understanding how rapidly we can encode specific and gist representations, and whether the encoding of one type of representation depends on the encoding of the other, may shed insight into why we tend more often to retain the gist than the specifics of our past experiences (Murphy & Shapiro, 1994; Sachs, 1967; Sekeres et al., 2016; Thorndyke, 1977). Yet, most prior studies on the time course of encoding specific and gist representations have relied on tasks of item memory, with young adults only. Although these studies have consistently found that gist representations can be encoded more rapidly than specific representations (Ahmad et al., 2017; Draine & Greenwald, 1998; Melcher, 2006; Tatler et al., 2003; cf., Navon, 1977), there has been very little focus on the rate and order of encoding of these representations for associations between components of an event that are core to episodic memory. A notable exception is a recent study by Greene and Naveh-Benjamin (2023e), which also found that young adults encode gist representations of face–scene pairs more rapidly than, or at least as rapidly as, specific representations. We modified this task in the present study, switching from a between-subject design to a within-subject design (with slightly modified presentation rates) to measure changes in the quality of episodic memory as a function of encoding time within an individual. Our results replicated these earlier findings. Young adults' specific representations of face–scene pairs improved with each increase in encoding time (1–2–4 s), but their gist representations were as established at the 2 s rate as at the 4 s rate. Our findings add to a growing body of studies favoring the parallel trace assumptions of fuzzy-trace theory (Brainerd & Reyna, 1990) over the serial dependency assumptions of gist macroprocessor theories (Kintsch & van Dijk, 1978).

Here, we showed that the parallel trace model (Brainerd & Reyna, 1990) also could account for the rates and order in which older adults encode specific and gist representations, at least for visual episodic associations. Older adults' estimates of the specific representation parameter V_i from our MPT model (Stahl & Klauer, 2008, 2009) increased from 2 to 4 s of encoding time. Directionally, V_i also trended higher at the 6 s than 4 s encoding rate among older adults, though the difference across these rates fell shy of our credibility criterion. These results show that older adults could later access specific details of originally studied face–scene pairs more successfully when they had more time to encode those pairs. A similar conclusion was obtained from our analyses of lure discrimination, using LDI metrics from mnemonic similarity tasks (Stark et al., 2013, 2019). Older adults' abilities to discriminate similar lure pairs from novel/unrelated distractors improved more substantially from 2 to 6 s of encoding time relative to the increase from 2 to 4 s of encoding time. Improvements in lure discrimination are thought to indicate an increased ability to successfully remember specific details of studied events (Stark et al., 2019). Thus, our findings with LDI metrics are aligned with our model-based results in showing that older adults' specific representations became more fleshed out with longer encoding time.

Meanwhile, regarding older adults' estimates of gist memory representations from our MPT model, we detected a marginal improvement from 2 to 4 s (and from 2 to 6 s) of encoding time in parameter G_r, corresponding to the probability of remembering the gist of an originally studied pair when shown a related test pair. However, older adults' estimates of G_r were virtually identical at the 4 and 6 s rates. We detected a credible improvement from 4 to 6 s of encoding time in older adults' estimates of the gist representation parameter G_i, corresponding to the probability of remembering the gist of a studied pair when it is presented again during the test phase. This increase in G_i from 4 to 6 s of encoding time arose from an unusual pattern (discussed at length in the next section) in which older adults' probability of relying upon gist representations to respond to intact probes decreased from 2 to 4 s of encoding time but rose again with 6 s of encoding time. Indeed, older adults' estimates of G_i did not credibly differ between the 2 and 6 s rates. These results show that older adults could occasionally establish gist representations under speeded encoding times (2 s) that were on par with those established under much longer encoding times (6 s), even as their specific representations continued to flesh out across these encoding rates.

The encoding of specific representations is more attentionally demanding than the encoding of gist representations (e.g., Greene & Naveh-Benjamin, 2023b; Rabinowitz et al., 1982). Increases in encoding time likely provide older adults, like younger adults, with sufficient time to attend to the specific, perceptual features of information, thus strengthening their specific representations. This in turn may make these newly formed specific representations more immune to

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inference from subsequent events or to temporal decay. Indeed, attending to information during initial encoding is essential for establishing new, durable long-term memory representations (Cowan et al., 2024; Forsberg et al., 2021, 2022). Due to their more severely limited attentional resource capacity (Craik & Byrd, 1982; Hasher & Zacks, 1988), older adults may especially benefit from longer time to process information during encoding.

Our findings pose a major challenge for gist macroprocessor theories, which propose that the gist of a stream of information is extracted after a specific representation has been established (Johnson-Laird, 1983; Kintsch, 1988; Kintsch & van Dijk, 1978; van Dijk & Kintsch, 1983). Although these theories originated to explain reading and discourse comprehension (cf., Perfetti, 2007; Perfetti & Stafura, 2014), recent work has extended the gist macroprocessor conception to explain event segmentation of episodic memories (Richmond & Zacks, 2017; cf., Baldassano et al., 2017). This theoretical view has already been challenged by the earlier obtained empirical results showing more rapid encoding of gist than specific representations among young adults (e.g., Ahmad et al., 2017; Draine & Greenwald, 1998; Greene & Naveh-Benjamin, 2023e; Melcher, 2006; Tatler et al., 2003). However, there was reason to believe that the specific-gist serial dependency model advocated by these theories may explain the order in which older adults encode specific and gist representations. We argued that, to compensate for potential declines in sensory/perceptual processing capabilities (e.g., Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Naveh-Benjamin & Kilb, 2014), older adults may need to direct their attention to deciphering the sensory or perceptual characteristics of stimuli before they can interpret the meaning of those stimuli. Our results suggest the opposite. Older adults can more rapidly extract the gist than the specific details of visual episodic associations.

Although our results and those of many other researchers challenge the gist macroprocessor theory, we cannot yet rule out this theory, as it may be able to account for the rate of formation of specific and gist representations for some (currently untested) types of information. This is a question for future research to address, but the present study adds to a growing body of evidence that is strongly stacked against the specific-gist serial dependency model.

Implications for Understanding Mechanisms of Age-Related Differences in the Representational Specificity of Episodic Memory

Results of the present study suggest that age-related slowing in the speed of processing (Salthouse, 1996) specific representations during encoding may be one important mechanism underlying why older adults' episodic memories are representationally "fuzzier" or less specific than those of younger adults (for a comprehensive review, see Greene & Naveh-Benjamin, 2023a). However, other mechanisms at retrieval also play a role (cf., Jacoby et al., 2005).

Older Adults' Specific Representations Become More Established With Increases in Encoding Time

Under speeded encoding times (i.e., 2 s), older adults' specific representations (captured by the MPT model parameter V_i) were less established than those of younger adults, but with more time to encode each pair (i.e., 4 or 6 s per pair), these age differences in specific representations disappeared. These results indicate that, as encoding time increases, older adults can form more durable specific representations of episodic associations that they can later access when shown those exact associations again during retrieval.

We did not detect an age difference in V_i at the 4 s encoding presentation rate, in contrast to the results of previous studies (Greene & Naveh-Benjamin, 2020, 2022a). Parameter V_i corresponds to the probability that participants can access the specific representation of a studied pair when it is presented again as an intact pair at test. Because we did not find an age-related difference in proportion correct to intact pairs at the 4 s rate, it is not surprising that the model also did not detect an age difference in V_i. Intact pairs are strong elicitors of specific representations as they are perfect matches with encoded information (Brainerd et al., 1999, 2001, 2019; Stahl & Klauer, 2008, 2009; cf., encoding-specificity principle, Tulving & Thomson, 1973). In classic old/new item or associative recognition, older adults can recognize old items or pairs usually as well as younger adults can (Fraundorf et al., 2019; Old & Naveh-Benjamin, 2008; Rhodes et al., 2019). Our finding of no age difference in accuracy to intact pairs at the 4 s rate (and no underlying difference in the ability to access specific representations when shown intact pairs) is thus in accord with most studies of recognition memory in aging. Age deficits in recognition memory are generally driven by older adults' heightened susceptibility to erroneously endorse new items or pairs as old. These false alarms are most pronounced for similar lures (test probes that resemble the gist, but not the specifics, of studied information; Greene et al., 2022; Stark et al., 2013). Indeed, in the associative specificity task, age deficits are most pronounced for related probes (Greene et al., 2022; Greene & Naveh-Benjamin, 2020, 2022a), a finding that was replicated in the present study at all encoding presentation rates.

The Retrieval Context Matters, Even When Older Adults Sufficiently Encode Specific Representations

The finding that older adults' deficits in accuracy to related probes were not offset by increases in encoding time suggests that slower speed of processing alone may not sufficiently explain age differences in the representational quality of episodic memories. Instead, factors at retrieval play a role, as well. These retrieval factors likely include the amount of environmental support provided in the retrieval cue (e.g., Craik, 1986), which is greater for intact probes (which are perfect matches to studied information) than related probes (which are only partial matches). Relatedly, the amount of effort required to reintegrate a specific representation of a studied episode differs for intact than related probes (Brainerd et al., 2019), as more attention is required to access these representations when shown similar lures rather than old items (Luo & Craik, 2009). Older adults often engage in a shallower search of the contents of their memories than younger adults do (Craik, 2002a; Jacoby et al., 2005). This may impact their ability to correctly recognize that related probes are not exact matches to studied information.

Our MPT model analysis provided key insights into how encoding time affected underlying cognitive processes contributing to older adults' recognition errors to related probes. Neither young nor older adults relied greatly upon accessing specific representations of studied pairs to reject related test pairs. Estimates of this so-called recollection rejection process (Brainerd et al., 1999, 2003) were low (near 0) among young and older adults at each encoding presentation

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rate. Moreover, attempting to estimate this recollection rejection process in our MPT model resulted in unsatisfactory fit to older adults' data. Previous studies have also reported low estimates of recollection rejection in item (Brainerd et al., 2022) and associative (Greene & Naveh-Benjamin, 2020, 2022a, 2022b, 2022d, 2023b, 2023c, 2023e) conjoint recognition tasks, which have often been found to be indistinguishable from 0 among older adults in tests of long-term memory (e.g., Greene & Naveh-Benjamin, 2022a). We thus constrained the V_r parameter of our MPT model to 0 in both groups. This allowed us to estimate the contributions of phantom recollection, the process by which seeing a similar lure elicits a false and vivid phenomenological sense of having previously encountered that lure (Brainerd et al., 2001; Lampinen et al., 2005; Singer & Remillard, 2008; Stahl & Klauer, 2009).

The present study constituted the first attempt to model phantom recollection in a task of associative recognition. Our results demonstrated that young adults rarely experienced phantom recollection, but they were somewhat more prone to this illusory recollective experience under speeded (1 s) encoding presentation rates than at slow (4 s) rates. Older adults, by contrast, became more susceptible to phantom recollection with increases in encoding time from 2 to 4 s per pair. Indeed, at 4 s of encoding time, older adults were more likely than younger adults to experience phantom recollection of related pairs, even though there was no age-related difference in the ability to access specific representations when shown intact pairs. With further increases to 6 s of encoding time per pair, older adults' susceptibility to phantom recollection of related pairs returned to the "baseline" prevalence observed at the 2 s encoding rate. Indeed, at 6 s of encoding time for older adults, relative to 4 s for younger adults, there were no age-related differences in phantom recollection, but older adults had a stronger bias overall to guess that test pairs were "intact" rather than "related."

Older Adults Are Occasionally Overconfident in Their Memories

The finding that older adults' estimates of phantom recollection to related probes peaked at 4 s of encoding time (rising from 2 s and falling again at 6 s) was mirrored by the effects of encoding time on older adults' conditional probability of responding to intact pairs based on gist representations, given that they had failed to retrieve specific representations (i.e., parameter G_i). That is, older adults' estimates of G_i plummeted from 2 to 4 s of encoding time then rose again at 6 s. Strikingly, these opposing shifts in phantom recollection of related probes and gist retrieval of intact probes from 2 to 4 s of encoding time occurred alongside an increase in the probability that older adults could retrieve the specific representation of a studied pair when it appeared as a test probe (i.e., parameter V_i). What might this peculiar pattern indicate?

A plausible interpretation of these results is that older adults are occasionally overconfident about what or how much information they have retained. This interpretation is compatible with the "misrecollection account" of Dodson et al. (2007), according to which older adults erroneously believe, often with high confidence, that they had previously experienced events that never truly occurred (cf., Fandakova et al., 2013; Greene et al., 2022, 2024). However, there are certain conditions under which older adults' erroneous misrecollections are most likely to arise. Older adults are typically excellent at evaluating the accuracy of their memories for general facts or knowledge (Marquié & Huet, 2000; Perlmutter, 1978; Pliske & Mutter, 1996) but are much poorer at evaluating the accuracy of their memories for specific episodes (Dodson & Krueger, 2006; Dodson et al., 2007; Fandakova et al., 2013). Yet even these metacognitive failures for specific episodes depend on several factors, including the degree of specific information older adults must remember about a given episode (Greene et al., 2022) and how much time has elapsed between encoding and retrieval (Greene et al., 2024). Regarding the former, older adults' recognition accuracy improves with increases in their reported confidence in their recognition responses on tests for which the retrieval of the gist of a prior episode is sufficient (e.g., in recognizing whether an unrelated probe had been studied). However, on tests for which the retrieval of specific details of a previous episode is required (e.g., in recognizing whether a related probe had been studied), older adults are prone to high-confidence recognition errors (Greene et al., 2022). Meanwhile, older adults can reliably evaluate the accuracies of their memories for specific episodes immediately after encoding but are much poorer judges when attempting to retrieve episodes from long-term memory (Greene et al., 2024).

Results of the present study suggest that older adults' metamemory failures may also arise in situations where they can compare the perceived qualities of their memories across different contexts. For instance, older adults may have good awareness that their memories were generally poorer in one context (e.g., under speeded encoding conditions) than in another context (e.g., under slower encoding conditions), but this may have an unintended consequence on their ability to successfully evaluate their memories within a specific context. When older adults have a limited amount of time to encode information (e.g., the 2 s condition of the present study), they have some awareness that they did not adequately encode the specifics of these episodes, relative to conditions where they had slightly more time (e.g., the 4 s condition) to encode each episode. Thus, under conditions with generally poorer memories (e.g., in 2 s condition), older adults rarely experience vivid false memories for related content (i.e., similar lures) because they are at least somewhat aware that they did not sufficiently encode detailed representations for most episodes.

Under somewhat more favorable conditions that foster stronger memories (e.g., the 4 s condition), older adults have some awareness that their memories in these conditions are superior to those in less favorable conditions. This can lead them to be overconfident about just what they have (or have not) retained. In these conditions, when older adults fail to remember specifically if they previously studied an intact test pair, they may decide that the test pair does not at all resemble any pair that they studied because they believe they would have remembered seeing that pair or one like it. Thus, older adults would respond to intact pairs less often on the basis of their gist representations when they failed to retrieve specific representations of those pairs. This overconfidence may also lead older adults to erroneously believe, with vivid phenomenological awareness, that they previously saw unstudied information (i.e., related lures). Strikingly, these metamemory failures can be potentially "undone" by providing older adults with better conditions that foster even stronger memories (e.g., by increasing the encoding time from 4 to 6 s). In these conditions, older adults not only form more durable specific representations, but they may also be more in tune with what they have (and have not) retained, reducing their susceptibility to vivid false memories and increasing their probability of relying on gist representations in

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situations where they failed to remember specific representations. This interpretation of our results is consistent with evidence showing that older adults have some preserved abilities to self-monitor their memories during encoding (Hertzog et al., 2010).

Conclusions

Here, we showed that young and older adults alike encode the meaning (or gist) of novel visual episodic associations somewhat more rapidly than the specific details of those associations. These findings provide powerful support for fuzzy-trace theory (Brainerd & Reyna, 1990, 2004) and are opposed to the specific-gist serial dependency model of gist macroprocessor theories (e.g., Kintsch & van Dijk, 1978). Even under speeded encoding presentation rates, older adults can establish gist representations of episodic associations that are commensurate with those of younger adults, speaking to a potential evolutionary benefit of gist representations (cf., Greene & Naveh-Benjamin, 2023d). However, older adults require more time to lay down specific representations that are on par with those of younger adults, in line with processing speed theories of aging (Salthouse, 1996). In some instances (e.g., at 4 s of encoding time), even when older adults appear to establish specific representations on par with those of younger adults, they are more susceptible to experiencing vivid false memories of related lures. These findings speak to the important role that the retrieval context plays in age-related differences in the representational quality of episodic memories (cf., Craik, 1986; Jacoby et al., 2005). Under both speeded (e.g., 2 s) and more drawn out (e.g., 6 s) encoding times, older adults are less susceptible to phantom recollection of related lures, suggesting that their occasionally heightened tendency for false memories (e.g., at 4 s of encoding time) may arise from metamemory failures (cf., Dodson et al., 2007; Greene et al., 2022). Specifically, older adults may be overconfident about their memories in conditions that are modestly favorable overall, leading them to be occasionally blinded to shortcomings in what they have (or have not) retained.

Constraints on Generality

The present study recruited young and older adult participants from an online crowdsourcing platform, and many questions remain as to how representative of the general population are the older adults who choose to participate in online studies (Greene & Naveh-Benjamin, 2022c). Participants in the present study were majority-White, particularly the older adults, and were generally highly educated. The extent to which these findings would generalize to more diverse samples, including non-White older adults and/or to older adults with lower educational attainment, remains to be determined. Moreover, the extent to which these findings would generalize to other types of associations in episodic memory remains to be addressed in future research. For example, generalizing our findings to tasks measuring young and older adults' abilities to remember who said or did what can have important implications for eyewitness testimony. In addition, generalization to tasks of prospective memory, like remembering future weather forecasts or predicted financial outcomes associated with different investment options, can shed insight into the effects of encoding conditions (e.g., amount of time available to learn information) and variations in memory quality on young and older adults' abilities to plan for important future events.

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