EXAMINING THE TIME COURSE UNDER WHICH SPECIFIC AND GIST EPISODIC MEMORY REPRESENTATIONS ARE ESTABLISHED AT ENCODING AMONG YOUNG AND OLDER ADULTS

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by

NATHANIEL R. GREENE

Dr. Moshe Naveh-Benjamin, Dissertation Supervisor

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The undersigned, appointed by the dean of the Graduate School,

have examined the dissertation entitled

EXAMINING THE TIME COURSE UNDER WHICH SPECIFIC AND GIST EPISODIC MEMORY REPRESENTATIONS ARE ESTABLISHED AT ENCODING AMONG YOUNG AND OLDER ADULTS

Presented by Nathaniel R. Greene

A candidate for the degree of

Doctor of Philosophy

And hereby certify that, in their opinion, it is worthy of acceptance.

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Dr. Moshe Naveh-Benjamin

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Dr. Nelson Cowan

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Dr. Judith Goodman

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Dr. Edgar Merkle

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Abstract

One of the most pervasive adult age-related declines in episodic memory is in the ability to remember associations between components of an episode, such as between a person and a location where the person was encountered, particularly at specific but not general/gist levels of representation. Yet, the reasons why older adults' episodic memory representations are less specific or detailed than those of younger adults remain to be fully elucidated. In the present study, across two experiments (with a combined *n* of 80 young and 86 older adults), I tested whether age-related differences in the speed of encoding specific and gist representations may in part explain these deficits. Participants encoded face-scene pairs under one of three rates (fast, intermediate, or slow) and were later administered conjoint recognition tests involving discriminating intact/studied pairs from similar and dissimilar pairs. Results, interpreted with a multinomial-processing-tree (MPT) model of specific and gist memory, showed that increases in encoding time resulted in consistent improvements in specific but not general representations among both young and older adults. Moreover, when older adults had even more time than younger adults to encode the face-scene pairs, the age deficits in specific representations disappeared, though the nature of the memory probe influenced whether this occurred. These results indicate that speed of processing at encoding appears to be one important factor in accounting for age differences in the representational specificity of episodic memories, but this mechanism likely interacts with other mechanisms, such as those at retrieval, to account for why older adults' episodic memories are representationally less specific than those of younger adults.

CHAPTER 1

GENERAL INTRODUCTION

One hallmark of the natural aging process, particularly in older adulthood from about the sixth decade of life onwards, is a decline in the efficiency and precision of episodic memory (Light, 1991; Naveh-Benjamin & Old, 2008; Zacks et al., 2000), or memory for events ("episodes") occurring in specific times and places (Tulving, 1983, 2002). These age-related declines in episodic memory occur even in the absence of pathological impairments like those due to dementia and can lead to forgetting of past experiences ("retrospective memory failures") and failures to remember to do future planned activities ("prospective memory failures"). Moreover, deficits in episodic memory have implications for the everyday lives of older adults as they lead to more omissions (e.g., forgetting where one parked the car when visiting the mall, or forgetting the name of a familiar person one meets at a dinner) and commissions (e.g., as an eyewitness, misidentifying who committed a robbery). Broadly speaking, age-related declines in episodic memory are a concern not only for the older adults who experience them directly, but also for society, given the growing population of older adults aged 65 and older in many countries, including the United States (U.S. Census Bureau, 2018). Therefore, it is important to understand the mechanisms underlying *why* older adults exhibit deficits in episodic memory, which may inform future therapeutic interventions, pharmacological or behavioral, that may assist older adults with episodic memory complaints, given the importance of episodic memory to everyday functions like remembering personal, important details of one's life (Levine et al., 2002).

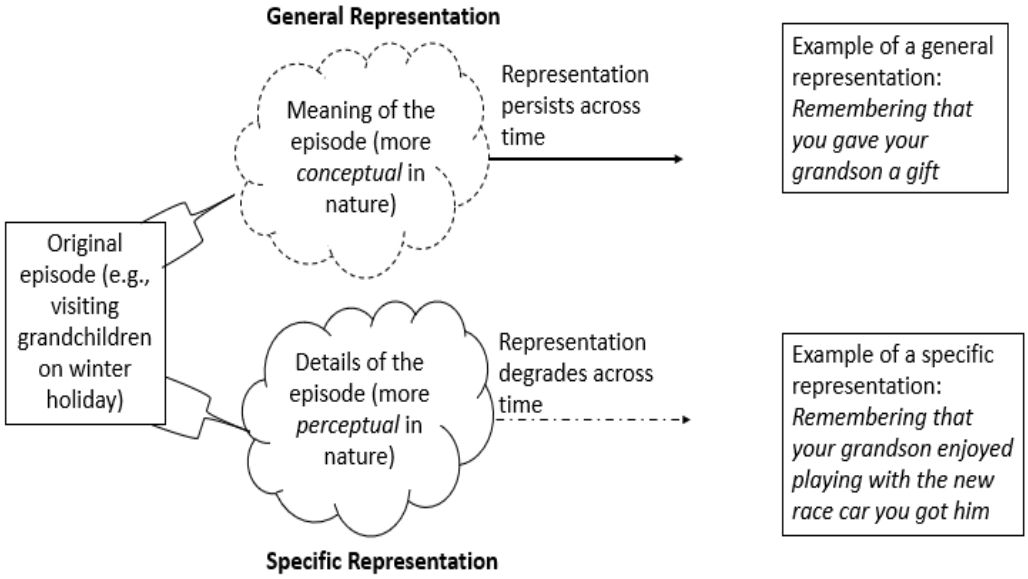
To this end, the current project focuses on an important aspect of episodic memory that differentiates young and older adults, namely, the deficient ability among older adults to remember *specific* but not general details of past experiences, and aims to gain clarity into age-related differences in the rates at which specific and general details can be encoded into episodic long-term memory (LTM). I will begin by reviewing theories that distinguish different levels of representation in episodic memory to provide a foundation upon which we can differentiate memory for specific details versus general (or "gist") details, and I will then consider the historical background of empirical studies that have attempted to assess age-related differences in the representational quality of episodic memories. Next, I will address an important gap in our current understanding of age-related differences in memory representations: the reasons why these differences emerge are not very well understood. I will describe a computational theoretic modeling framework (Greene & Naveh-Benjamin, 2023) that attempts to pinpoint different encoding, maintenance, and retrieval operations that may underpin why older adults' episodic memories are representationally less specific in nature than those of younger adults. Based on this novel mechanistic model, I will dedicate the remainder of this project to an empirical focus on one of the hypothesized mechanisms, specifically, age differences in the speed of processing specific and general representations. Here, I will present two new experiments that will involve a titration of presentation rates at encoding for younger and older adult participants on a task that is sensitive to measuring specific and general episodic memory representations. Based on the findings of these two experiments, I will end by discussing their theoretical implications for understanding whether age-related differences in the rate or speed of forming specific representations is

a viable mechanism that may, at least in part, explain why older adults' episodic memories are representationally lacking in specific details.

Theories on Levels of Representation in Episodic Memory

To provide a set of terminology for the present study, I will begin by reviewing several leading theories of episodic memory representations, each of which shares common principles with the others. The theories reviewed here differ with respect to the scales on which they operate. The first two theories – *fuzzy-trace theory* (Brainerd & Reyna, 1990, 2004) and *hierarchical representation theory* (Craik, 2002a, 2002b, 2020) – originated in the field of cognitive psychology and describe different levels of representation, along with assumptions underlying their encoding and retrieval, from a purely cognitive perspective (i.e., without attempting to identify the underlying neural processes that support these representations). The latter two theories – *trace-transformation theory* (Moscovitch et al., 2016; Robin & Moscovitch, 2017; Winocur & Moscovitch, 2011; Winocur et al., 2007, 2010) and *hippocampal pattern separation theory* (Kirwan & Stark, 2007; Stark et al., 2013; Yassa et al., 2011) – provide complementary insights into neural mechanisms that distinguish episodic memory representations as specific (or detailed) and general (i.e., "semantic" or meaning-based). At their core, all of these theories distinguish between specific, detailed representations of an episode, which capture the perceptual, surface-level details of an event; and gist, general representations of an episode, which capture the "essence" or meaning of the event (i.e., the "what" that transpired). This distinction is depicted in Figure 1 for a particular episode (visiting grandchildren on a winter holiday).

Figure 1. *Depiction of Specific and General Representations of Episodic Memory.*



Note. The cloud shape for the general representation is depicted as a fuzzier cloud than the cloud shape for the specific representation to emphasize that general representations are less precise/specific in detail than specific representations. Conversely, the arrow from the general representation is depicted as a solid arrow to convey persistence in this representation across time and decreased vulnerability to interference, whereas the arrow coming from the specific representation is a broken arrow to convey sensitivity to decay and interference.

Although the four to-be-reviewed theories differ with respect to the scales on which they operate, I argue that these theories are far more *complementary* than opposing. As noted, they all distinguish between two levels of representation – specific and general – though the terms used to describe these representations may differ, depending on the theory adopted. For instance, whereas fuzzy-trace theory uses the terms "verbatim" and "gist" to describe specific and general representations, respectively, trace-transformation theory describes these as detailed (or sometimes "peripheral") and gist (or

sometimes “central”) instead. In the present study, I will use the terms “specific” and “general” to be more theoretically neutral. Moreover, these terms are more applicable to the design of the experiments included in the present study, which relied on visual stimuli (pictures of faces and scenes), such that words like “verbatim” (meaning, “an exact reproduction of discourse”) do not accurately characterize these stimuli.

A second reason why these theories are complementary, rather than opposing, is that they all share a common assumption that specific and general representations can “co-exist” independently. That is, neither type of representation is inherently dependent on the other type of representation. This contrasts with earlier held views, from theories of reading and discourse comprehension (Johnson-Laird, 1983; Kintsch & van Dijk, 1978; Reder, 1982; van Dijk & Kintsch, 1983), that assumed that gist/general representations were formed as *by-products* of effortful attempts at interpreting verbatim/specific streams of information. According to this alternative verbatim-gist serial dependency model, the rate at which gist representations of an episode’s meaning are formed is slower than the rate at which specific representations can be established, as the gist must be extracted from the earlier-established specific representation. Empirical evidence refuting this position has come from studies in several domains, including studies of semantic priming effects in lexical decision tasks (e.g., Draine & Greenwald, 1998) and of effects of rate of presentation during encoding on the long-term retention of specific and general representations of scene memory (Ahmad et al., 2017) and face-scene memory (Greene & Naveh-Benjamin, 2022d) that show more rapid, or at the least equivalent, rates of formation of general relative to specific representations. I will review this evidence more extensively later, as it motivates the aims of the present study.

The idea that specific and general representations are encoded, stored, and can be retrieved independently is a central feature of fuzzy-trace theory, which adopts a dual-trace model of memory representations in which verbatim traces tagging the surface-level representation and gist traces tagging the semantic-level representation of an episode form in parallel, rather than in serial fashion (Brainerd & Reyna, 1990). In trace-transformation theory, there is assumed independence between detailed/peripheral and gist/central representations, as these representations rely on different neural substrates, and can be independently relied upon given certain task demands (Robin & Moscovitch, 2017). In Craik's hierarchical representation theory (Craik, 2002a, 2002b, 2020), the independence assumption is best reflected in the retrieval processes that result in remembering an episode at a highly specific level or only at a general level. According to this theory, the degree to which specific details of an episode can be reintegrated at retrieval depends not on the extent to which general details are first accessed, but rather on the *depth of elaboration*, that is, how deeply an individual probes the contents of their memory to reintegrate detailed-rich representations of an episode. At a shallow level of elaboration, an individual may recall "I visited my grandchildren last Christmas," but at a deeper level of elaboration, the individual may recall more specific features of the episode, such as whether it was snowy and dreary or sunny and pleasant, or whether they ate lunch before or after exchanging gifts. Likewise, in pattern separation theory (Kirwan & Stark, 2007; Stark et al., 2013; Yassa et al., 2011), different retrieval processes compete to distinguish episodes with shared general but not specific features versus equating these episodes based on their shared general features. This suggests some degree of independence, at least in the retrieval process, for specific and general representations.

A third point of commonality among the extant theories of levels of representation is that they all predict that episodic memories should be representationally less specific and more general in older adulthood. The specific reasons why each theory makes this prediction will be spelled out in more detail in the ensuing sections, dedicated to each theory. However, it is important to keep a few points in mind here. First, none of these theories originated as a theory of cognitive aging, per se. Rather, each theory makes specific assumptions about the basic nature of memory representations which, when coupled with widely held theoretical views about certain cognitive processes that worsen in older adulthood (such as depleted attentional resources, or slower processing speed), lead naturally to their predictions on why older adults tend to remember general but not specific representations. Second, a direct comparison of these theories would be a logistical challenge, given that they all make similar predictions (i.e., one would be hard pressed to find empirical data that would support one but not the other theories), and all have been formulated as verbal rather than mathematical theories (though there has been some effort to translate fuzzy-trace theory into a more mathematically explicit theory; Brainerd et al., 2009). A more mathematically explicit theory of the processes underlying the encoding, maintenance/storage, and retrieval of specific and general representations in both young and older adults is currently lacking, though Greene and Naveh-Benjamin (2023) have sketched a computational modeling framework that may pave the way for such a theory. I turn now to a closer inspection of each of the four theories, though I will discuss the two neuroscientific theories in unison because, although important, the neuroscientific angle will not be considered further in the present study.

Fuzzy-Trace Theory. According to *fuzzy-trace theory* (Brainerd & Reyna, 1990, 2004; Reyna & Brainerd, 1995), episodic memories are encoded, stored, and retrieved in two independent traces – a verbatim trace capturing the specific (often perceptual) details of an episode, and a gist trace tagging the meaning/semantic features (i.e., the "essence" or the "what" that transpired) of the episode. Both traces are assumed to be formed independently, as opposed to in a serial fashion, and each trace is subject to its own resource demands (i.e., attentional costs to encode or retrieve) and vulnerability to interference or decay across time (Brainerd & Reyna, 2002). Based on these principles, fuzzy-trace theory posits that older adults have well-preserved gist but not verbatim/specific representations (Brainerd & Reyna, 2015) as gist representations are thought to be more immune to interference (Brainerd & Reyna, 2002) and require less attentional resources to encode (Brainerd & Reyna, 1990).

Supporting evidence for these key assumptions has come from a few studies with young adults showing that, when attention is divided during encoding between studying memoranda for a later memory test and completing a secondary (or concurrent) task, such as an auditory choice reaction time task (e.g., Craik et al., 1996; Greene et al., 2021; Naveh-Benjamin et al., 2003a, 2014), young adults are less likely to remember specific but not gist/general details of past episodes (Odegard & Lampinen, 2005; Rabinowitz et al., 1982; but see Greene & Naveh-Benjamin, 2022b, 2022c). Specifically, Rabinowitz et al. (1982) used a task in which young and older adult participants generated specific associates of studied words during encoding (e.g., for the word "pigeon," a participant may generate another word associated with "fly" or "wings" or "dove"). The test phase was a cued recall task in which participants were provided with

either the specific associates they had generated earlier (e.g., “wings”) or with a general retrieval cue (e.g., “type of bird”) to aid in recalling the target word (“pigeon”) from the study list. Compared to younger adults, older adults were less capable of using the specific generated cues to recall target words from the list but performed comparably to younger adults when provided with general cues. Importantly, when young adults encoded or retrieved the information under divided attention, the patterns of results were identical to those obtained with older adults, suggesting an attentional demand to encode and/or retrieve specific but not general representations. In their task, Odegard and Lampinen (2005) used a conjoint recognition paradigm (Brainerd et al., 1999), in which young adult participants studied words and were administered recognition tests featuring old words, similar lures (antonyms to studied words), and novel distractors. Compared with full attention young adults, those who studied the words under divided attention were less capable of discriminating studied words from similar lures, which was accompanied by a reduction in specific/verbatim memory parameters of a mathematical model, but were equally capable of discriminating old and similar lures from novel distractors, which was accompanied by no divided attention effect on the gist memory parameters of the model.

More recent evidence from studies using an associative recognition paradigm in which participants studied pictures of faces paired with scenes (Greene & Naveh-Benjamin, 2022b, 2022c) have shown that divided attention disrupts not only the ability to remember a specific pairing (i.e., to remember specifically whether a face had been paired with a particular park scene) but also the gist of the pairing (i.e., to remember in general whether the face had been paired with a park or nature scene as opposed to a

kitchen or indoor scene). These findings contrasted with the earlier findings that showed effects of divided attention on specific but not gist representations (Odegard & Lampinen, 2005; Rabinowitz et al., 1982), which may seem to run counter to fuzzy-trace theory's prediction of differential attentional costs of encoding each type of representation. Nevertheless, in a more recent study, Greene and Naveh-Benjamin (under review) manipulated the difficulty of the concurrent divided attention task across three difficulty levels – low load (1-tone simple reaction time task), intermediate load (2-tone choice reaction time task), and high load (3-tone choice reaction time task) on attention, as the earlier studies relied on only one load of the concurrent task (specifically, the most demanding high load condition in the earlier studies by Greene and Naveh-Benjamin). In this more recent study, the disrupting effects of divided attention at encoding in young adults on specific representations for face-scene pairs emerged under a lighter load (the intermediate divided attention load) compared to the load under which disruptions in general representations for the face-scene pairs emerged (the high divided attention load), reinforcing the assumption, central to fuzzy-trace theory, that the encoding of specific/verbatim representations is more attentionally-demanding than the encoding of gist/general representations.

Overall, then, the findings from a number of studies using divided attention at encoding in young adults has shown a greater attentional cost to encoding specific than general representations and that specific (or verbatim) representations of an episode are more sensitive to degradation due to interference from other events. These findings are relevant to fuzzy-trace theory's predictions pertaining to adult aging. Older adults often fail to inhibit irrelevant information that interferes with task-relevant information (Hasher

& Zacks, 1988), which could complicate their ability to rely on resource-demanding verbatim representations. For example, to maintain the verbatim representations of three lines arranged from left to right in order of increasing length (14cm, 15cm, and 16cm), an individual must remember three specific quantities, which could interfere with each other or with which other, irrelevant quantities (e.g., 17cm) could interfere. Moreover, as this example further demonstrates, retaining the verbatim representations likely requires a greater number of resources – three bits of information to be maintained in this case – compared with those required for holding in mind a gist representation, which could be as few as just one bit of information (e.g., "lines are shorter to the left"). This implicates different demands on the working memory system for encoding and maintaining verbatim compared to gist representations, and it is well known that working memory is severely limited in its encoding capacity (Cowan, 2001) and that this is especially so in older adulthood (Greene et al., 2020; Light & Anderson, 1985; Wingfield et al., 1988).

Hierarchical Representation Theory. Craik's *hierarchical representation theory* was not intended as an alternative to fuzzy-trace theory, but rather as an alternative conceptualization of the "systems" view of memory, which traditionally casts episodic memory and semantic memory as different systems of memory (Tulving & Schacter, 1990). According to Craik's model (Craik, 2002a, 2002b, 2020), episodic and semantic memories exist on a "continuum" of specificity, which can be represented in a hierarchical structure with various access nodes corresponding to retrieval states of low contextual complexity (higher nodes in the model) to high contextual complexity (lower nodes in the model). These nodes are arranged with the more complex and context-rich memories arranged toward the bottom to emphasize a sort of "top-down" organizational

view of episodic and semantic memories, in which semantic features of a memory exist at a "higher order" level because they are oftentimes more schematic in nature, capturing information shared across multiple episodic memories. The extent to which contextual details of the encoded episode are accessible or are retrieved differentiates whether a memory is more "semantic" in nature (e.g., remembering that *Hamlet* is a play by Shakespeare) versus "episodic" in nature (e.g., remembering reading *Hamlet* in an advanced English literature course in high school).

According to Craik's theory, the extent to which context-rich memories can be remembered depends on the *depth of elaboration* with which an individual probes the contents of their memories. To reintegrate a low context memory (such as memory for a general fact, like knowledge that *Hamlet* is a play by Shakespeare), one needs only to retrieve this general knowledge without needing to remember the specific context in which the fact was learned. In contrast, to remember a highly contextual episode, such as memory for a specific time performing the role of Hamlet in a production of the play, the elaboration process requires deeper reflection. This is likely to be a more attentionally-demanding process than remembering a more general representation.

Supporting evidence for this assumption comes from a study by Luo and Craik (2009) in which young adults retrieved items from an earlier-studied list under either full or divided attention (i.e., the locus of divided attention was at retrieval). The items (words) had been studied in one of three specific contexts: (1) alone (the words were presented in isolation), (2) with images of line drawings depicting the concept described by the word (e.g., a line drawing of a bird for the word "bird"), or (3) with photographs of the concept described by the word (e.g., a photograph of a bird for the word "bird"). The

test phase was a recognition test with old and new words tested in lists that placed either high or low demands on remembering specific contextual details associated with the studied words. Specifically, in the high demanding conditions, the old words at test were those that had originally been paired with either a line drawing or a photograph (i.e., none of the old words had been studied in isolation without an image), and participants responded to one of two prompts ("Was this word studied with a line drawing?" or "Was this word studied with a photograph?"). In these conditions, the correct "old" response only applied to old words that had been studied with line drawings (if the prompt asked about line drawings) or photographs (if the prompt asked about photographs), requiring an individual to remember more specific contextual details for each studied word because all of the old words presented at test had been studied originally with some kind of image. In the low demanding conditions, the old words consisted of half that had been studied with an image (either a photograph or a line drawing) and half that been studied in isolation (i.e., with no image), and the prompts asked participants either "Was this word studied with an image?" or "Was this word studied alone/without an image?" Thus, in these conditions, one could perform well even if they remembered only in general whether a word had been studied with or without an image, even if they failed to remember specifically whether the image was of a line drawing or a photograph.

When young adults were tested under divided attention at retrieval, they performed worse, compared to full attention young adults, at discriminating whether an old item that had been studied with an image had been studied with a photograph or a line drawing (the high demanding, or more "specific," condition), but there was no effect of divided attention in the low demanding (more "general") condition involving

discriminating whether a word had been studied with or without an image. These results were comparable to those obtained with older adults who were only tested under full attention conditions. Based on these findings, Luo and Craik (2009) concluded that the retrieval of specific contextual details is more demanding than the retrieval of general details. Older adults, who are less likely to engage in deep elaboration at retrieval (Jacoby et al., 2005), are less likely to remember specific than general details of past episodes.

Trace-Transformation Theory and Hippocampal Pattern Separation Theory. I will review these last two theories more briefly, as their foci on neural mechanisms underlying different levels of memory representation places them somewhat outside of the scope of the present study. Nevertheless, they provide additional convergent insight into the distinctions between specific and general memory representations and reinforce the predictions that older adults' episodic memories are characterized as being more general than specific in nature. Both theories provide complementary insights into the neural processes underlying different levels of memory representation, even as their specific aims are slightly different. Trace-transformation theory (Moscovitch et al., 2016; Robin & Moscovitch, 2017; Winocur & Moscovitch, 2011) identifies neural correlates of different types (i.e., specific versus general) of memory representations. Hippocampal pattern separation theory (Kirwan & Stark, 2007; Stark et al., 2013; Yassa et al., 2011) explains what neural processes are involved in discriminating neural activity patterns corresponding to episodes that share common general but not completely identical features.

Trace-transformation theory originated to explain how the neural basis for episodic memory evolves across time, initially being primarily driven by hippocampal

activity but, following consolidation across days, months, or years, relying instead primarily on the prefrontal cortex, with the hippocampus serving as a "gateway" for re-accessing these older, stored memories (Moscovitch et al., 2016; Winocur & Moscovitch, 2011; Winocur et al., 2007, 2010). Robin and Moscovitch (2017) used trace-transformation theory as a starting point for describing how different types of memory representations depend on unique neural substrates. They differentiated specific, detailed representations (referred to as "peripheral" representations that retain details that are usually not centrally relevant to an episode; cf., Sekeres et al., 2016) from general, central representations of an episode's meaning. Moreover, they also identified a third level of representation – schematic representations – which represent stored knowledge shared across multiple similar episodes. Blood-oxygen-level-dependent (BOLD) signal activity in the posterior hippocampus is correlated with retrieval of detailed/peripheral representations of a specific episode, while BOLD activity in the anterior hippocampus correlates with remembering gist/central representations, and schematic representations are associated with BOLD signal increases in the ventromedial prefrontal cortex. An important aspect of this theory is that it posits that peripheral, central, and schematic representations can all co-exist, but given particular task demands, one type of representation may be retrieved in preference to the others.

Hippocampal pattern separation theory (Kirwan & Stark, 2007; Stark et al., 2013; Yassa et al., 2011) posits that each new experience that is encoded into memory is represented initially by a unique pattern of neuronal activity in the hippocampus, particularly in the posterior regions of the hippocampus referred to as the dentate gyrus (DG) and the third Cornu Ammonis (CA3) subfield. For example, when a participant

studies an image of a red apple in a memory experiment, this image is stored as a unique pattern of hippocampal activity. This pattern of activity can be reintegrated at retrieval from cues that share either complete overlap (e.g., the same red apple presented as a test probe during a recognition experiment) or partial overlap (e.g., an image of a green apple presented as a similar lure during a recognition experiment) with the original, stored pattern of activity. When the retrieval cue provides only a partial match to the originally encoded information, the neural pattern corresponding to the original episode is not likely to be fully reintegrated as it is not a 100% perfect match. Nevertheless, a process dubbed *pattern completion* may still occur if the amount of reintegration of the original pattern associated with the old episode surpasses a threshold set by the individual, which would prompt the individual to equate the new pattern (corresponding to the similar lure) with the old pattern (corresponding to the target), believing the lure to be identical to what they had studied. An opposing process dubbed *pattern separation* occurs when, due to the incomplete match between the new pattern of activity (from the similar lure) and the older pattern of activity (from the target item), the two episodes are orthogonalized or separated into discrete units, leading to detect that the new episode (e.g., the green apple) is not a match with the older episode (e.g., the red apple).

The DG and CA3 subfields of the hippocampus where the pattern separation and pattern completion processes unfold reside primarily within the posterior hippocampus, the region that Robin and Moscovitch (2017) identified as being related to the remembering specific/peripheral details of an episode. Aging is associated with reduced BOLD activity here, which is driven in part by greater rigidity of the DG and CA3 subfields (Yassa et al., 2011), resulting in a more liberal pattern completion rather than

pattern separation process in older compared to younger adults. At the same time, older adults' BOLD signal activity in the anterior hippocampus (corresponding to gist/central representations) and the ventromedial prefrontal cortex (corresponding to schematic representations) is heightened (Rosenbaum et al., 2012; Viard et al., 2012). The take-away from these findings and their broader implications from both *trace-transformation theory* and *hippocampal pattern separation theory* is that, at a neural level, older adults remember information at a more general than specific level.

Adult Age Differences in Specific and General Memory Representations

There is an impressive consensus across the leading theories of episodic memory representation: they all posit that, in older adulthood, episodic memories are representationally less specific in nature than in younger adulthood, but general/gist representations of past experiences are well preserved in old age. To reiterate, fuzzy-trace theory assumes this is so because of its principles that gist traces are more immune to interference and are less attentionally resource-demanding than verbatim traces (Brainerd & Reyna, 1990, 2002, 2015). Hierarchical representation theory proposes that accessing specific, detailed representations of past episodes is an effortful process, requiring attentional resources during retrieval and greater elaboration or probing of the contents of one's memory than the elaboration needed to remember a more general types of representations, such as those that underlie memory for general knowledge (Craik, 2002a, 2002b, 2020). The neuroscientific theories – trace-transformation theory (see Robin & Moscovitch, 2017) and hippocampal pattern separation theory (Kirwan & Stark, 2007; Stark et al., 2013; Yassa et al., 2011) – posit that the neural circuitry underlying specific

memory representations are more rigid and less responsive in older adulthood, whereas the neural processes underlying general representations are highly active in older adults.

Critically, these predictions of leading theories on levels of representation have largely been supported in empirical studies probing age-related differences in the quality of information that is encoded into and retrieved from memory. To take a step back, most of the inferences about age-related differences in episodic memory occur at the level of performance differences on standard tasks of episodic memory (Benjamin, 2010; Greene & Rhodes, 2022; Salthouse, 2000), like item recognition and free recall, in which older adults are more prone to falsely conflating unstudied items as being "old/studied" and recall fewer correct items and make more incorrect recalls (intrusions) than younger adults (for meta-analyses, see Fraundorf et al., 2019; Old & Naveh-Benjamin, 2008a; Rhodes et al., 2019). These types of metrics are certainly informative for assessing age differences in memory, but they do not provide much insight into the representational quality of memories and how these representations may differ between young and older adults. Primarily, standard tests like item recognition or recall require that an individual remember a specific item from the list, but if older adults lack such representations, they will perform worse on these tests than younger adults. However, it is conceivable that an older adult may have access to a more general type of representation (e.g., "I remember having seen a type of bird on the list") that is not typically tested on in these procedures, which require instead that the individual remember specifically whether, for example, a "parrot" or a "pigeon" had appeared on the list.

However, several methods have been developed over the past fifty years to probe age-related differences in the underlying memory representations that contribute to

performance on tests like recall or recognition. A more detailed summary of these methods can be found in a recent review by Greene and Naveh-Benjamin (2023), but here I will concentrate on the main types of findings that have been produced from a diverse set of tasks, before segueing into a task that is especially suitable for measuring age differences in specific and general episodic memory representations.

The earliest types of tasks examining age-related differences in the representational qualities of memories were recognition procedures required discrimination of old words from words that shared a semantic overlap (e.g., synonyms) or from words that shared a perceptual overlap (e.g., rhymes). In these procedures, older adults were more prone to false recognition of both types of lure items, both semantically and perceptually similar lures (Rankin & Kausler, 1979; Smith, 1975), which led to an early consensual view that older adults attempt to encode both the perceptual/specific and conceptual/general features of word stimuli but do so to a less elaborate degree than younger adults (cf., levels of processing; Craik & Lockhart, 1972). That is to say, these early studies suggested that older adults attempt to encode both specific and general types of representations, in contrast to earlier views that they only focused on specific representations (e.g., Eysenck, 1974), but older adults are also more limited in their ability to elaborate upon these representations. These types of results have also been obtained in visual mnemonic discrimination tasks in which participants must discriminate target items (e.g., a yellow rubber duck) from similar lures (e.g., a purple rubber duck), with older adults producing much higher rates of false recognition for similar lures (Koutstaal, 2003; Koutstaal et al., 2003; Pidgeon & Morcom, 2014; Stark et al., 2013;

Trelle et al., 2017) despite no (or very small) age differences in discriminating old items from completely dissimilar distractors (e.g., a shovel).

One of the areas of investigation that has produced some of the most fruitful findings suggesting that older adults retain the gist of what transpired is in the domain of false memory, particularly in studies relying on variants of the Deese-Roediger-McDermott (DRM) paradigm, in which participants study a list of items related to an unpresented lure (e.g., "bed," "pillow," "dream," and "night," all related to the concept of "sleep") and are later administered recall (Deese, 1959) or recognition (Roediger & McDermott, 1995) tests to examine whether participants falsely remember having studied the critical lure. In young adults, these procedures have produced high rates of erroneously endorsing the lure as being studied (Roediger & McDermott, 1995). Among older adults, these rates of false recall and recognition of unpresented lures is far higher and has reinforced the view that older adults' focus preferentially on the gist of what transpired rather than on the specifics (Balota et al., 1999; Dennis et al., 2007; Gallo & Roediger, 2003; Norman & Schacter, 1997; Kensinger & Schacter, 1999; Koutstaal & Schacter, 1997; Tun et al., 1998; for reviews, see Devitt & Schacter, 2016; Gallo, 2006; Schacter et al., 1997). Nevertheless, it is conceivable that what Tun et al. (1998) referred to as a "gist-based processing preference" among older adults reflects not only a preference but, in many cases, a necessity, due to biological/neurological or cognitive limitations that may result in older adults not retaining specific representations of past experiences (cf., Greene & Naveh-Benjamin, in press).

Another topical area in which numerous studies have produced similar findings suggesting that older adults retain general but not specific representations of past

episodes is in reading comprehension. Studies in this domain have concentrated on age-related differences in the ability to remember specifically what was said in a narrative (i.e., the surface-level or verbatim representation of a passage of text) versus the ability to remember the meaning of what a narrative was about (i.e., the situation model or gist representation of a passage of text), with older adults having superior memory than younger adults for the situation model despite much poorer memory for the surface-level representation (Morrow et al., 1992, 1997; Radvansky, 1999; Radvansky et al., 2001, 2003a, 2003b; Reder et al., 1986; Stine & Wingfield, 1988; Stine-Morrow et al., 2002, 2004; for a review, see Radvansky & Dijkstra, 2007).

In studies of autobiographical memory, which ask participants to remember personal experiences from their own lives, older adults are more likely to report memories at a general or categorical level (i.e., reporting on details shared across many experiences, such as "I used to visit my family on summer holidays in Maine") rather than at a more specific level (i.e., reporting on the specific details of a particular episode, such as the last time one visited their family; Cohen, 1998; Beaman et al., 2007; Levine et al., 2002; Piolino et al., 2002). As these studies provide less experimental control than the other procedures reviewed here, it is unclear whether this reflects true age differences in the quality of the accessible memories of one's life or a shift, with age, in how older adults prefer to describe their memories. Nevertheless, these findings are consistent with those of more controlled laboratory experiments in showing that older adults' episodic memories are more general rather than specific in nature.

More recently, studies of visual working memory have probed age-related differences in the quality or precision of reproducing aspects of studied stimuli, such as

the color of an object, its location on a screen, or its angular orientation. These studies have consistently found that older adults are more error-prone than younger adults at reproducing these features of visual stimuli, suggesting that the representations of items held in working memory are less precise in older adulthood (Peich et al., 2013; Pertzov et al., 2015; Souza, 2016). Similar findings have been found in continuous recognition procedures probing the precision of representations in both working and long-term memory (Rhodes et al., 2020).

Collectively, findings from studies in fields as diverse as false memory and reading comprehension, from areas of inquiry as old as early levels of processing studies to recent precision in visual working memory studies, converge with the theoretical positions of fuzzy-trace theory, hierarchical representation theory, trace-transformation theory, and hippocampal pattern separation theory: older adults' episodic memories appear to be representationally more general rather than specific in nature. However, much of this evidence has come from studies examining memory for items (e.g., false recall of critical lures in DRM procedures, or false recognition of synonyms or similar images in mnemonic discrimination procedures, or incorrect recognition of verbatim text probes in studies of reading comprehension), whereas episodic memory is more multifaceted. A core feature of episodic memory is the ability to remember associations among components of an episode (Treisman, 2006; Tulving, 1983; Underwood, 1969; Zimmer & Ecker, 2010; Zimmer et al., 2006). For example, it is one thing to remember that you have seen a person before, but an episodic memory pertains to a specific episode in which you saw that person, including where and when you saw the person. Neglected in most of these earlier studies is whether there are age-related differences in the

representational quality of *associative episodic memory*, or the ability to remember the associations between two or more components of an episode at specific or general levels of representation.

In the ensuing section, I discuss in more detail the typical patterns of results obtained when comparing young and older adults on tests of associative memory, which produce more robust age-related deficits compared to tests of item memory (Old & Naveh-Benjamin, 2008a; Spencer & Raz, 1995). Then, I ask whether these associative memory deficits (cf., Naveh-Benjamin, 2000) are limited to specific or extend to general representations as well. I consider a recent paradigm well-suited to addressing this question and which will serve as the basis for the experimental design of the present study.

Age-Related Deficits in Associative Memory: Limited to Specific Representations Only?

There are a few ways to measure memory for associations between components of an episode. One widely used method involves presenting pairs of items (e.g., pairs of related or unrelated words; pairs of two images presented together, such as a face and a scene; pairs of an image and word, such as a face and a name or a face and an associated occupation) at study and later tasking participants, using recognition procedures, with discriminating intact pairs from recombined pairs, in which the elements of two studied pairs are re-presented in novel test pairs. For instance, if study pairs consist of A-B, C-D, and E-F, where each of the letters denotes a unique item (such as a word), intact pairs at test reinstate the original studied association (e.g., A-B or C-D), whereas recombined pairs feature a repairing of items from different studied pairs (e.g., A-D or C-F).

Importantly, in these procedures, all of the items presented at test (A, D, C, and F in the preceding example) are old, meaning the same degree of familiarity based on prior study exposure should hold across the items at test, as the tests are on associative memory (i.e., whether a participant can remember if two items had been studied together). It is also worth noting that sometimes cued recall procedures rather than recognition procedures are used, in which one element of a pair (e.g., A) is presented, and participants attempt to recall the item associated with that pair (e.g., B).

I will primarily concentrate in the remainder of this section on age-related differences in performance on associative recognition or cued recall tasks, but briefly, other means of measuring associative memory include source recognition designs (Johnson et al., 1993). In these procedures, participants study items that are presented in one of multiple sources. For example, in a procedure by Dodson et al. (1998), participants heard sentences spoken by one of four voices – two females and two males. At test, when participants endorse an item as being "old," they are also asked to indicate from which source the item was studied (e.g., was the sentence spoken by the first or the second female voice?). This provides a metric of associative memory pertaining to the ability to remember the source or context associated with an item. Although there have been fewer studies to apply this method to aging compared with those that rely on associative recognition or cued recall procedures, age-related effects obtained with source recognition tasks are comparable to those obtained with other types of associative memory tasks (Old & Naveh-Benjamin, 2008a; Spencer & Raz, 1995). Specifically, older adults perform disproportionately worse than younger adults at correctly remembering

the source associated with studied items, even as age differences in item recognition are much smaller or negligible in some cases (e.g., Boywitt et al., 2012; Simons et al., 2004).

In the more standard associative recognition procedure, age-related deficits mirror those obtained with source memory tasks. Older adults show, at best, modest impairments in item recognition but quite robust deficits in associative recognition (Castel & Craik, 2003; Chalfonte & Johnson, 1996; Chen & Naveh-Benjamin, 2012; Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2004; Old & Naveh-Benjamin, 2008a). In the classic paradigm involving unrelated word pairs, Naveh-Benjamin (2000) coined the term "associative deficit hypothesis" to account for the finding that older adults' deficits in associative recognition performance were as much as twice as large as their deficits in item recognition, and this finding has translated to more ecologically valid and complex stimuli as well, including for faces paired with scenes (Chen & Naveh-Benjamin, 2012). Thus, age-related impairments in episodic memory are most pronounced for the ability to remember critical associations between components of an episode. This can have dramatic implications in real-world settings, including in misremembering *who* did *what* (Old & Naveh-Benjamin, 2008b), which could lead to false accusations in eyewitness testimony.

Are these age-related deficits in associative memory limited to specific representations, or do they extend also to memory for the gist of the association (i.e., do they extend also to more general representations encapsulating the meaning of an association)? An early study by Castel (2005) provides some insight into this question. In his procedure, young and older adult participants studied images of grocery items along with associated prices that were either realistic (e.g., a carton of eggs priced at $2.50) or

overpriced (e.g., a tub of yogurt priced at $21.45). In the realistic scenario, the price associated with the grocery item is consistent with real-world information (i.e., pre-existing knowledge) that participants can rely upon from their own experiences, providing schematic support to aid in remembering the price associated with the item. In the overpriced scenario, the price associated with the grocery item contrasts with pre-existing knowledge about the real-world price of these items. Although this conflicts with a participant's pre-existing schematic support, this type of major conflict may also help participants remember, at least at a general level, that the item was overpriced, because the price associated with the item was so far off from the typical (real-world) prices associated with that type of item. Castel found that, compared to younger adults, older adults could almost equally remember the specific price associated with an item in the realistic price scenario. In the overpriced scenario, although older adults were not as capable as younger adults of remembering the specific price associated with the items, they were capable of remembering in general the relative price of the item (e.g., that the tub of yogurt was about $20 to $22). These findings suggested that older adults' associative memory deficits, at least for some types of associations, may indeed be limited to more specific representations of novel associations, whereas more general representations of these associations may be preserved in old age. Similar findings have been obtained when older adults could make use of other sources of pre-existing schematic support, such as when pairs of related words rather than unrelated words are presented at study (Naveh-Benjamin et al., 2003b) or when faces are paired with generation-normed names (e.g., older faces paired with names that were common in the 1940s or 1950s; McGillivray & Castel, 2010; Peterson et al., 2017).

Findings like those of Castel (2005) are informative but potentially limited in scope to situations in which participants can make use of pre-existing knowledge (semantic memory) to aid in remembering at least the gist of what they studied in a novel association (e.g., relying on pre-existing knowledge that tubs of yogurt are not usually as expensive as $20-22 to remember that the tub of yogurt presented in the study phase was overpriced). Would similar findings emerge for novel associations for which pre-existing knowledge may provide little or no advantage? Greene and Naveh-Benjamin (2020) set out to address this question by tasking young and older adult participants with studying face-scene pairs (e.g., an image an old man paired with a park scene). Although it is conceivable that participants could rely on pre-existing knowledge (e.g., knowledge of encountering old men in parks) to aid with remembering the specifics or at the least a general representation of the novel association, it is also possible that alternative pre-existing schemas could interfere (e.g., knowledge of encountering young men, young women, or old women in parks as well), such that relying on pre-existing knowledge would be less effective and, potentially, problematic. For instance, reliance on pre-existing knowledge would be problematic if, during test, a participant saw a young woman paired with the park scene and connected this to existing experiences of seeing young women in parks, potentially leading to a higher acceptance of this pair as being "old" or "intact," when in fact it was an old man paired with the park scene.

In Greene and Naveh-Benjamin's (2020) procedure, participants were tasked with discriminating intact pairs (e.g., the old man with the same park scene) from recombined pairs that were similar at very specific (e.g., the old man with a different park scene) or more general levels (e.g., the old man paired with a beach scene, a different type of

nature setting) or from recombined pairs that were dissimilar at specific or general levels (e.g., the old man paired with a bathroom scene, a type of indoor setting categorically unlike the scene with which the old man had originally been paired). Compared with younger adults, older adults could effectively reject the most dissimilar types of recombined pairs (i.e., classify these as "unrelated" or "recombined" rather than "intact") to comparable extents, but age differences in the correct rejection of recombined pairs grew larger as these pairs became increasingly similar to the originally studied pair, that is, from pairs featuring a recombination at a broader level (e.g., the old man paired with the beach) to those featuring a recombination at a very specific level (e.g., the old man paired with a different park scene; Greene & Naveh-Benjamin, 2020, 2022a; Greene et al., 2022). For the latter type of pairs, older adults were oftentimes more likely to endorse these as being "intact" (meaning studied) rather than "related" (meaning similar but not identical to what was studied). These findings suggest that, even for some types of associations for which pre-existing schematic support would offer little aid in remembering specific or general details of the episode, older adults' associative deficits "scale" with how much specific information one needs to remember about the original episode. That is, older adults could remember at a general level whether a face had been paired with an indoor or outdoor scene, but at a more specific level, especially in discriminating whether the face had been paired with one or the other of a very specific exemplar type (e.g., the first or the second park), older adults performed much worse than younger adults.

Reinforcing these findings, Greene and Naveh-Benjamin (2020) applied a type of mathematical model developed in the fuzzy-trace theory literature – conjoint recognition

multinomial-processing-tree (MPT) models (Brainerd et al., 1999; Stahl & Klauer, 2008) – to the data to estimate the contributions of specific and general memory representations, uncontaminated by response bias. The findings of the mathematical model showed that older adults were less likely than younger adults to retrieve specific representations of originally studied face-scene pairs, but there were no age differences in parameters corresponding to the probability of remembering general representations. I will provide more details on the model later, as it will be applied in the present study as well.

In summary, results from studies of associative memory provide additional, convergent insights with those in many other domains, reviewed earlier, in showing that older adults can remember the general but not specific details of associations between components of an episode. Of course, this may be true only of some types of associations, and thus far, the most powerful evidence from the studies by Greene and Naveh-Benjamin (2020, 2022a) have relied on visual associations between faces and scenes, which simulate remembering people in different locations, an important hallmark of episodic memory (Gruppuso et al., 2007). The extent to which their findings would generalize to other types of associations warrants future investigation, but for now, I will rely upon this paradigm in the present study as it provides a powerful method of measuring age differences in specific and general memory representations for a core feature of episodic memory.

Mechanisms Underlying Age-Differences in the Representational Specificity of Episodic Memory

The evidence thus far paints a clear picture about the fate of episodic memory representations in old age. Yet, despite decades of empirical evidence showing that older

adults retain more general rather than specific details of past experiences, we still lack a complete understanding of why this is so. That is, what mechanisms underlying the encoding, maintenance/storage, and/or retrieval of episodic memories contribute to why older adults possess less specific memory representations than younger adults?

Earlier, I reviewed several leading theories of episodic memory representations that were intended to describe and explain the nature of different levels of representation in general (i.e., independent of aging, per se). Although these theories predict that episodic memory representations are less specific in nature in older adulthood, none of these theories provide a truly mechanistic account of different ways in which older, compared to younger adults, encode, store, and retrieve specific versus general memory representations. For instance, although fuzzy-trace theory's principle of differential attentional resource demands to encode verbatim/specific versus gist/general representations (Brainerd & Reyna, 1990) pairs nicely with theories of cognitive aging attributing age-related deficits in episodic memory to depleted attentional resources in older adults (Craik & Byrd, 1982; Craik, 1986), supporting evidence for this position comes from studies with young adults tested under full or divided attention. This shows that there are differential effects of divided attention, in young adults, on specific and general memory representations (Greene & Naveh-Benjamin, under review), but this does not tell us *how* or *why* older adults are contributing more or less of their limited attentional resources to encoding specific versus general representations. As another example, the neuroscientific theories – such as trace-transformation theory (Robin & Moscovitch, 2017) – describe age-related differences in neural activity that underlie remembering detailed versus gist representations, but they do not explain *why* these age-

related differences occur (e.g., what causes a decline in BOLD activity in the posterior hippocampal regions underlying specific memory representations) and whether they are due to different encoding, storage, and/or retrieval processes.

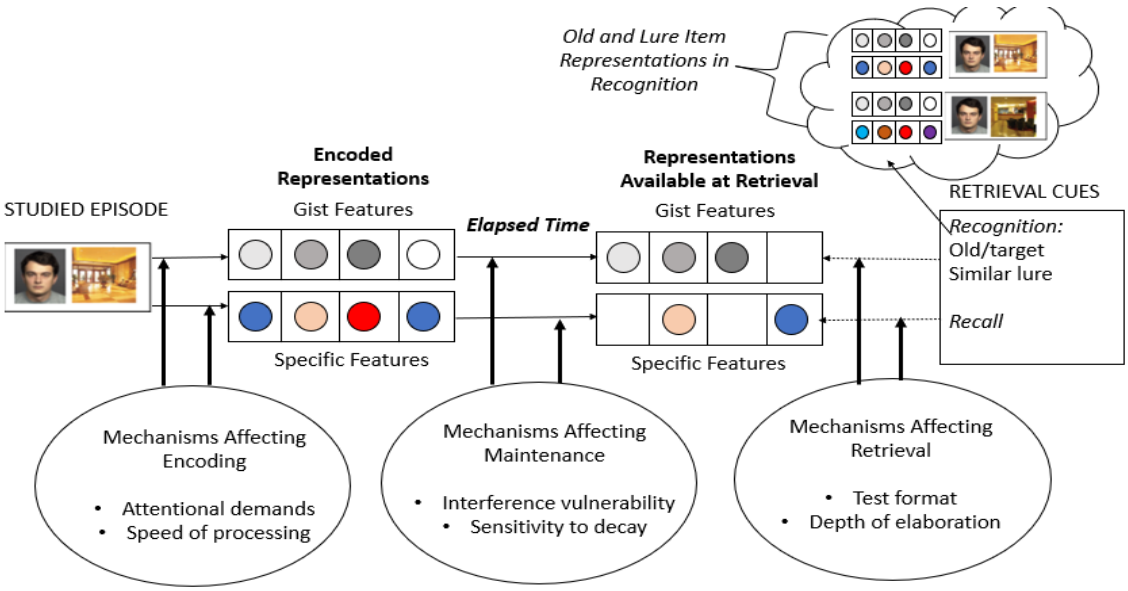
Understanding the mechanisms at the time of encoding, during storage/consolidation into long-term memory, and at retrieval that differ between young and older adults with respect to the ways in which specific and general memory representations are established, consolidated, and accessed is an important area for future research. To this end, Greene and Naveh-Benjamin (2023) have laid the groundwork for a more mechanistic modeling framework, providing a theoretical sketchpad for a more computationally-explicit theory that explains different mechanisms at each of the three stages – encoding, maintenance, and retrieval – that may underscore why older adults retain general but not specific details of past episodes. In the following, I will briefly review this framework, and then I will concentrate on one of the proposed mechanisms pertaining to the rates at which specific versus general representations can be established at encoding, as this forms the basis for the experiments of the present study.

Overview of Greene and Naveh-Benjamin's Theoretical Framework. Borrowing from global matching models of episodic memory (e.g., Cox & Criss, 2020; Cox & Shiffrin, 2017; Gillund & Shiffrin, 1984; Raaijmakers & Shiffrin, 1981; Shiffrin & Steyvers, 1997), Greene and Naveh-Benjamin's (2023) theoretical framework assumes that an episode can be represented as a sum of constituent features, which mathematically can be expressed as a vector of some length consisting of numeric quantities that represent different aspects of an episode that can be encoded into memory (such as the font of a word, its orientation on a computer screen, its semantic meaning, etc.). The

exact nature of the vectors, such as whether the units within the vector are represented on a binary scale (with 1's and 0's denoting whether a feature has or has not been encoded, respectively) or on probabilistic scale (with weight parameters ranging from 0 to 1 denoting the strength with which a feature of an episode has been encoded) and how many units make up a vector (i.e., its length), remains to be determined in a more mathematically explicit treatment of the theoretical framework, but at present, the framework provides a starting point for examining different encoding, maintenance, and retrieval mechanisms that can uniquely disrupt specific but not general representations in older adults.

A schematic of the complete theoretical modeling framework is presented in Figure 2. Two vectors are depicted for an encoded event, one corresponding to specific features of the episode (the perceptual characteristics, such as the color of the face and the scene) and one corresponding to its gist or general features (the meaning of the episode). These vectors store specific and general features of an episode independently, such that there is independent encoding, maintenance, and retrieval of each type of representation. This allows for a more mathematically explicit formulation of a theory of levels of representation because unique parameters capturing, for instance, attentional encoding costs or forgetting rates can be applied to the specific and the general feature vectors, and the values of these parameters can be set to equality across a fit of the model to data from young and older adults (assuming no differences in, for instance, forgetting rates for specific representations with age) or can be allowed to freely vary with age (assuming, for instance, that the forgetting of specific representations is exacerbated in older adulthood).

Figure 2. *Schematic of Theoretical Model for Assessing Age Differences in the Encoding, Maintenance, and Retrieval of Specific and Gist Episodic Memory Representations*



Note. Figure modified from original source to depict theoretical framework of Greene and Naveh-Benjamin (2023). Specific (colored circles) and gist (grayscale circles) features of an episode are encoded in independent vectors. Different mechanisms at encoding, maintenance, and retrieval can have unique effects on gist versus specific representations. For example, the figure depicts a greater forgetting of specific than gist features by the time of retrieval (fewer retained colored circles in the specific feature vector than grayscale circles in the gist feature vector). The cloud insert at retrieval depicts feature vectors for recognition probes that are an exact match at both specific and gist levels (old item) versus recognition probes that are a match at gist but not specific levels (similar lure).

An exhaustive discussion of the different proposed mechanisms and how to model them or test them through empirical means is beyond the scope of the present project.

Instead, I will focus on one proposed mechanism affecting the encoding phase: the speed with which specific and general representations can be laid down at encoding. There has been very little focus on age-related differences in the rate as which specific or general representations are encoded, despite the potential that these age differences could play a significant role in explaining *why* older adults' episodic memory representations are less specific in nature. Moreover, examining age-related differences in the rate at which specific and general representations are established during encoding can be informative for future developments of Greene and Naveh-Benjamin's (2023) modeling framework. That is, if empirical evidence shows that there are indeed differential encoding rates for specific but not general representations based on participant age, then any mathematical model based on the framework sketched in Figure 2 would need to accommodate rate parameters on the encoding of features into the specific and general vectors.

Age Differences in the Rate of Formation of Specific but Not Gist Representations? One of the mechanisms proposed in Greene and Naveh-Benjamin's (2023) theoretical framework that may account for why older adults' episodic memories are representationally less specific in nature than those of younger adults pertains to the rate at which each type of representation (specific versus general) can be encoded into memory. In their theoretical model, different rate parameters, θ_1 and θ_2, can be assigned to the general and specific feature vectors, respectively, allowing for differential rates of encoding each type of representation. It is conceivable that there may be no age-related differences in the value of θ_1, such that young and older adults encode general representations at comparable rates, and that values of θ_1 may be smaller than those of θ_2 among both young and older adults, such that general representations are encoded more

rapidly than specific representations. Moreover, values of θ_2 may be much larger among older than younger adults, such that the rate at which specific representations are encoded into memory is much slower among older than younger adults. Many of these are untested hypotheses that the present study seeks to address.

Among young adults, several studies have shown that general representations are encoded *more rapidly than* or, at the least, as rapidly as specific representations, which runs counter to the earlier-held view that specific representations were extracted from interpreting the gist (e.g., Reder, 1982; van Dijk & Kintsch, 1983). This earlier-held verbatim-gist serial dependency model would predict a slower formation of gist representations than specific representations. Here, I will review evidence from two domains – (1) semantic priming and (2) visual episodic LTM – that provide converging evidence that refutes this verbatim-gist serial dependency model among younger adults.

One early demonstration of rapid semantic/gist encoding that precedes specific/verbatim encoding is from the semantic priming procedure of Draine and Greenwald (1998). In this procedure, young adult participants completed a simple two-choice lexical decision task involving deciding quickly and accurately whether presented names were traditionally male (e.g., "Bob," "David," "Steven") or female (e.g., "Jane," "Ellen," "Mary"). Unbeknownst to the participants, in the brief interstimulus interval between when participants responded to one name and when the next name was presented, a prime was presented for about 30 to 50 milliseconds. The prime consisted of another name that was either semantically congruent or incongruent with the target name. In the congruent condition, the prime belonged to the same gender category as the target (e.g., "Sarah" presented as a prime and "Mary" as the target), whereas in the incongruent

condition, the prime belonged to the opposite gender category as the target (e.g., “Sarah” presented as a prime and “Adam” as the target). Participants responded more quickly and more accurately in classifying the targets in the semantically-congruent versus the semantically-incongruent condition, even as they reported no awareness of the primes. Specifically, the memory discrimination metric (*d'*) for the primes was statistically indistinguishable from 0, indicating that participants did not store a verbatim memory trace of the primes (cf., Balota, 1983). Nevertheless, the primes appeared to have left a semantic (or gist) trace that influenced participants’ responses to names that did or did not share the same semantic category level. Although this evidence only indirectly shows a more rapid deposition of gist than specific representations, it is consistent with the idea that general representations can be laid down more rapidly than specific representations.

Studies of visual LTM have produced additional support for the differential rate of encoding specific versus general representations among young adults. In a study by Ahmad et al. (2017), participants studied pictures of complex scenes under fast (1-second) or slow (4-second) presentation rates and were later tasked in a LTM recognition test with discriminating studied scenes (e.g., a garden) from similar scenes (e.g., a different garden) and from dissimilar scenes (e.g., a bedroom). Compared to the 4-second presentation rate, under the 1-second presentation rate, participants were less capable of discriminating old scenes from similar lures, a discrimination that would require remembering specific representations of the originally studied scene, but there were no differences in discriminating old scenes from dissimilar lures, a discrimination that could be made on the basis of remembering a general representation of the original scene. Thus, Ahmad et al. (2017) concluded that general (or “gist-like”) representations of complex

visual stimuli could be established to comparable extents within 1 versus 4 seconds of encoding time, whereas specific representations of these same stimuli continued to be fleshed out between 1 and 4 seconds (i.e., such representations formed within 1 second were not on par with those formed within 4 seconds).

More recently, in a study that serves as predecessor to the present study, Greene and Naveh-Benjamin (2022d) manipulated the presentation rate (0.75-seconds, 1.5-seconds, or 4-seconds) that young adult participants had to encode face-scene pairs, using the associative specificity paradigm of Greene and Naveh-Benjamin (2020) described earlier, which featured LTM associative recognition tests discriminating studied pairs from distractors that varied in how similar they were to studied pairs. In their first experiment, they found that estimates of the specific memory parameters (corresponding to the probability of remembering specifically which scene had been associated with a given face) continuously increased with increases in the encoding duration (i.e., 0.75-seconds < 1.5-seconds < 4-seconds). However, estimates of the general memory parameters (corresponding to the probability of remembering in general what type of scene had been associated with a given face) initially increased from the 0.75-second to the 1.5-second condition, but there was no further increase from the 1.5-second to the 4-second condition. Thus, in Experiment 1, Greene and Naveh-Benjamin (2022d) showed that general representations of face-scene pairs formed within 1.5 seconds of encoding time were on par with those formed within 4 seconds of encoding time, but specific representations continued to be fleshed out between 1.5 seconds and 4 seconds. This evidence is in line with the position that gist representations can be established *more rapidly* than specific representations.

Importantly, there was a potential confound in Experiment 1 of Greene and Naveh-Benjamin's (2022d) study. Specifically, in each presentation rate condition, which was manipulated between-subject, participants encoded the same number of face-scene pairs per block (12 per block) and completed an interpolated activity task between the encoding and test phases that was of the same length (approximately 60 seconds). This means that the *total block length* from the start of the study/encoding phase to the start of the test phase systematically varied with the length of the presentation rate, being always longer in the 4-second than the 1.5-second and the 1.5-second than the 0.75-second conditions. Although these differences may seem insignificant (with total block lengths prior to the beginning of the test phase, including the presentation rate plus a 0.5 second interstimulus interval and the length of the interpolated activity, of 114, 84, and 75 seconds for the 4-, 1.5-, and 0.75-second conditions, respectively), other studies have shown that some forgetting of specific *and* general representations can unfold with increased time between encoding and retrieval, even on small scales like these (see Greene & Naveh-Benjamin, 2022a, 2022b). The confound then is that, in the 4-second condition, there may have been more pronounced forgetting of specific and/or general representations by the time of test, compared to the 1.5-second condition (or for the 1.5-second compared to the 0.75-second condition), thus masking whether there was any additional increases in general memory representations between the 1.5 seconds and 4 seconds of encoding time. To address this confound, in their Experiment 2, Greene and Naveh-Benjamin (2022d) increased the length of the interpolated activity period in the 1.5-second and 0.75-second conditions to make the total block length prior to the beginning of the test phase equivalent with the 4-second condition. Doing so did not

change the pattern of results with respect to the specific memory parameters, which continued to increase from 0.75 to 1.5 to 4 seconds of encoding time. However, this change did impact the pattern of results regarding the general memory parameters, which showed parallel increases with the specific memory parameters (i.e., 0.75 seconds < 1.5 seconds < 4 seconds). Nevertheless, these findings still show that general representations are not formed at a slower rate than specific representations.

To summarize, several studies with young adults have shown that general representations are established as rapidly, and in some situations *more rapidly* than specific representations. But how do these findings translate to older adults? This is the question that the present study seeks to address. One of the leading theories of cognitive aging that attempts to explain why age deficits in memory and other cognitive processes occur is the processing speed theory of aging (Salthouse, 1996). According to this theory, aging leads to a general cognitive slowing, which leads to performance deficits on tasks of episodic memory because older adults require more time to execute cognitive operations, like encoding information into memory. Age-related cognitive slowing may be manifest in a time-restricted manner (*limited time mechanism*), whereby the slowing of early operations (e.g., the initial sensory or perceptual registration of stimuli to be encoded into memory, and ensuing recognition or categorization of the stimuli based on prior knowledge) restricts time to perform later operations (e.g., employing strategies to encode the memoranda) when the time available to execute multiple sequential processes is limited, as in standard laboratory studies where participants have a limited amount of time to study memoranda. This *limited time mechanism* may be especially important in complex cognitive tasks, like associative memory tasks, in which the quality or accuracy

of performance on the task is affected by the number of operations that can be executed (Salthouse, 1980, 1982, 1985). For example, in an associative memory task, operations may include (1) processing each individual component of the association (e.g., a face and a scene), (2) processing the components as a pair, and (3) employing a strategy to enrich the association of the two components. Under the *limited time mechanism*, older adults' slower processing at an earlier stage (e.g., initially processing the individual items or the pair as a whole) may limit how much time they have to carry out a later stage of processing (e.g., using a strategy to memorize the pairing).

Alternatively, age-related cognitive slowing may be manifest via a *simultaneity-mechanism*, whereby the products of earlier stages of processing may be lost by the time later stages of processing are executed (Salthouse, 1982, 1992, 1996). That is, information lost over time (i.e., forgotten) from earlier stages of processing may limit the ability of an older adult to carry out later stages of processing. For example, a rapid loss (due to decay or displacement/interference) of a sensory/perceptual representation of each individual component of an association that was just presented but is no longer onscreen may slow older adults' ability to form an association of the two components, and this may be especially noticeable in tasks of working memory (Salthouse & Babcock, 1991). Indeed, this mechanism is more likely to be important than the *limited-time mechanism* in accounting for age differences in cognitive performance on tests of working memory, given that there are often simultaneous storage and processing demands of working memory tasks (Rhodes et al., 2019b).

There have been some challenges to this view, including studies using diffusion modeling that show that age-related slowing affects non-mnemonic processes, like motor

control, rather than memory, per se (Ratcliff et al., 2004). Nevertheless, there has been no direct investigation of age differences in the speed with which specific (or general) representations can be encoded, so it remains an open question whether older adults do encode specific representations at a slower rate than younger adults even as there may be no age differences in the rate at which general representations are encoded.

The Present Study

The purpose of the present study is to test a hypothesized mechanism from Greene and Naveh-Benjamin's (2023) theoretical modeling framework: age-related differences in the rate at which specific representations can be encoded into memory may underscore why older adults' episodic memory representations are less specific in nature than those of younger adults. In the standard associative specificity procedure (Greene & Naveh-Benjamin, 2020), participants are given four seconds to encode face-scene pairs. This is the only rate that has previously been used with older adult participants (Greene & Naveh-Benjamin, 2020, 2022a; Greene et al., 2022) and is the same rate of presentation used with younger adults in these studies which compared performance on the task, and underlying qualitative specific and general representations, between older and younger adults. Given long-standing theoretical views that aging is associated with a general slowing of cognitive processes (Salthouse, 1996; but see Ratcliff et al., 2004), it is conceivable that, with longer time to encode the face-scene pairs, older adults may establish specific representations that are on par with those of younger adults. Alternatively, if age-related slowing affects only non-mnemonic processes, as Ratcliff et al. (2004) have shown with more standard recognition tasks (old/new recognition) that do not disentangle the contributions of specific and general representations, then even with

increases in encoding time, older adults' specific representations would still not be commensurate with those that younger adults establish under a shorter presentation duration.

At the same time, age-related differences in general representations are not detected at the standard (4-second) presentation rate, such that older adults appear to establish general representations of complex episodic associations to comparable extents as younger adults under the same encoding duration. In young adults, general representations form more rapidly, or at the least as rapidly, as specific episodic memory representations (e.g., Greene & Naveh-Benjamin, 2022d), and have sometimes been found to be as fleshed out under shorter encoding times as they are under longer encoding times (e.g., Experiment 1 of Greene & Naveh-Benjamin, 2022d; cf., Ahmad et al., 2017). The present study will assess whether this is true for older adults as well by comparing the extent to which older adults can access gist details under speeded compared to slower presentation rates to see whether general representations are established as well at the faster compared to the normal (4-second) presentation rate or if there are continued increases in the extent to which general representations are established with longer encoding times, mirroring what we might see with specific representations. It is also conceivable that, for older adults, general representations capturing the essence or meaning of an episode are encoded as rapidly as they are in younger adults (being on par with the amount of gist that younger adults can access even at faster presentation rates), but that specific representations capturing the details of the episode never fully flesh out to the same degree that they do in younger adults. To address these possibilities, and to

delineate the hypotheses in more specific detail, I turn now to describing the general method to be used in the two experiments of the present study.

CHAPTER 2

GENERAL METHODS

In the following sections, I describe the general methodology of the two experiments of the present study. This includes details about the design of each experiment, the basic experimental procedure, and the planned analyses.

Basic Design

Each experiment compared groups of younger adults (aged 18 to 26) with older adults (aged 65 to 80) across various encoding presentation durations of the associative specificity recognition task (Greene & Naveh-Benjamin, 2020). In this task, participants study pictures of faces paired with pictures of scenes (see more details in the Procedure section), and at test, they discriminate old/intact pairs from similar/related lures and dissimilar/unrelated distractors. All participants in each age group responded to each type of memory probe and encoded the face-scene pairs under each of three presentation rates, which varied from block to block in a random order for each participant. There were three presentation rates per age group, corresponding to a fast, intermediate, and slow rate of presentation. However, the exact lengths of these presentation rates differed for young and older adults, with the fastest rate for young adults being faster than the fastest rate for older adults, and the slowest rate for older adults being slower than the slowest rate for younger adults. Table 1 provides a breakdown of the presentation rates used in each experiment and for young versus older adults. Participants completed nine study-test blocks (described in more detail in the next section), such that one third of the blocks were studied under the fast rate, one third under the intermediate rate, and one third under the slow rate of presentation.

Table 1. *Presentation Rates for Young and Older Adults*

Age Group	Rate of Presentation at Encoding		
	Fast Rate	Intermediate Rate	Slow Rate
Young Adults	1-second (1s)	2-seconds (2s)	4-seconds (4s)
Older Adults	2-seconds (2s)	4-seconds (4s)	6-seconds (6s)

The rates chosen for young adults (1s, 2s, and 4s) differed slightly from those used in Greene and Naveh-Benjamin (2022d), which used rates of 0.75 seconds, 1.5 seconds, and 4 seconds and employed a between-subject design, such that each participant in those experiments encoded all pairs under only one of the three rates of presentation. The rates were slightly adjusted in the present study to make comparison with the older adults more straightforward, given adjustments to the length of the interpolated activity task between encoding and retrieval (see details in Procedure) that were necessary to equate the total block lengths across the various encoding rate conditions. This decision was also made because I planned to compare older adults' data at their fastest rate of encoding to that of younger adults at their intermediate/medium rate of encoding, and using 1.5 seconds as the fastest rate for older adults (37.5% of the standard 4s rate that older adults have typically had to encode pairs in this procedure) would be potentially too rapid of presentation compared with 2 seconds (50% of the standard 4s rate). The move to a within-subject design was for practical reasons, given the large number of participants that would be required for a fully between-subject design

for the rate of presentation, which would require three groups of young and older adults (each with about 40 participants) for each experiment.

The basic design of the quasi-experiment was thus a 2 (Age: Young vs Old) x 3 (Rate of Presentation: Fast vs Intermediate vs Slow) x 3 (Type of Memory Probe: Intact vs Related vs Unrelated) mixed factorial, with age as a between-subject factor and the remaining factors manipulated within-subject.

Materials

The primary stimuli for the task included pictures of faces from the FACES database (Ebner et al., 2010) and pictures of scenes from a categorized scene pool (Konkle et al., 2010). The faces were all White faces in neutral clothing (only the neckline and above is visible), presented on a gray background, such that the faces were uniform with respect to ethnicity, facial expression, and background. Only faces depicting neutral expressions were included (i.e., no happy, angry, sad, disgusted, or shocked faces included in the database were used; see Figure 3 for examples). Faces were divided evenly among young and old and male and female faces. In total, there were 120 faces (30 each per age and sex group), each of which was paired with a unique scene. For the 120 scenes, these came from 60 scene categories, as each category featured two exemplars (e.g., two parks, two kitchens, two bathrooms, two lakes). Faces and scenes were both sized to 312 x 389 pixels.

In addition to the primary face-scene stimuli, participants were also shown arithmetic problems consisting of simple addition or multiplication problems, which were typed and presented visually in Arial size 18 font at the center of the computer screen during periods of interpolated activity between study and test (described in more detail in

the Procedure section). Other stimuli included white boxes and colored red X's for simple and choice reaction time tasks included at the end of the experiment, based on the Deary-Liewald procedure (Deary et al., 2011). Each experiment was programmed in PsyToolkit (Stoet, 2010, 2017) and was administered online using the crowdsourcing platform Prolific (Prolific, n.d.).

Basic Procedure

Both experiments employed the same basic procedure, though there were slight differences that occurred only in the interpolated activity task, which will be described in more detail later when I present the more specific details of the two experiments (see Chapter 3).

Instructions. The procedure began with an instruction phase, in which participants were informed that they would be studying pictures of faces paired with pictures of scenes and would be tasked with remembering which scene had been associated with which face (i.e., participants were given intentional instructions to learn the pairs for forthcoming memory tests). Participants were made aware of the nature of the memory tests, namely that these tests would feature three types of memory probes that included old or intact pairs (the same face appearing with the same scene from the earlier study phase), similar or related pairs (the face appearing with a different, but similar, scene to the scene with which the face had originally been paired), and dissimilar or unrelated pairs (the face appearing with a different and completely dissimilar scene to the scene with which the face had originally been paired). They were also informed that they would study pairs in blocks of 12, and that each block would feature one of three presentation rates during the study phase but that the test phases would be untimed. To

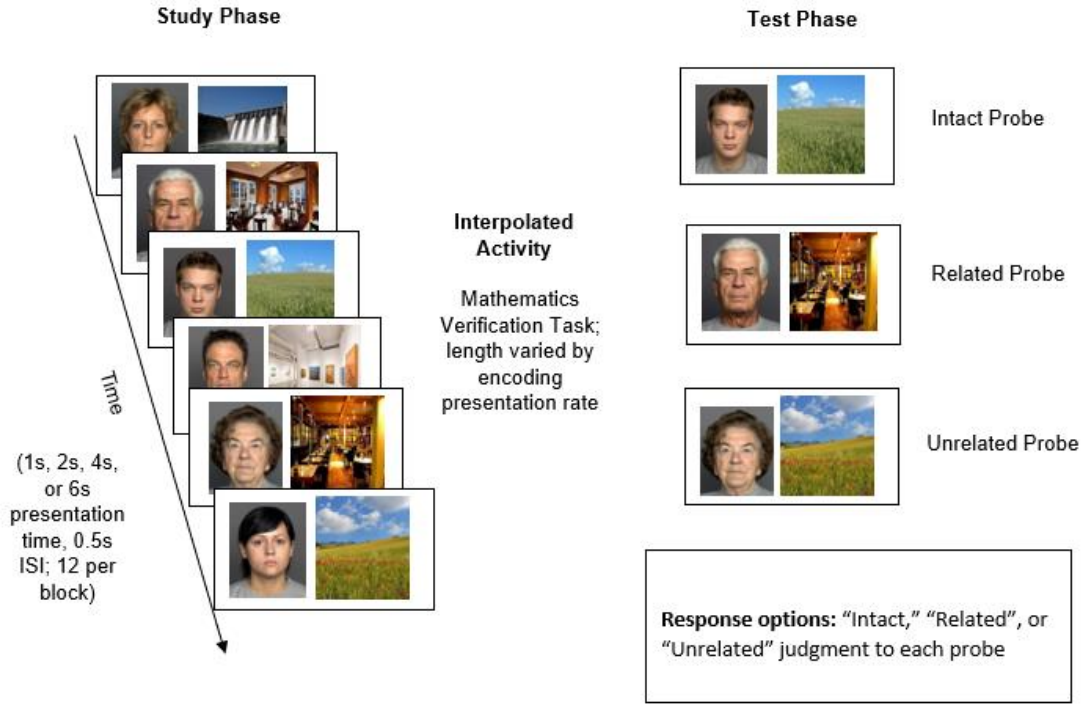
ensure participants read and understood the instructions, there were four attention check questions embedded in the instruction slides, asking about (1) how many rates of presentation would be used (correct answer = 3), and what constitutes (2) an Intact pair (correct answer = same face with same scene), (3) a Related pair (correct answer = face with similar scene), and (4) an Unrelated pair (correct answer = face with completely dissimilar scene). These attention check questions were multiple choice, with three options (one correct and two incorrect) per question, and required participants to press a numbered key between 1 and 3 corresponding to the answer they believed to be correct.

Practice Phase. To familiarize participants with the different presentation rates (fast, intermediate, and slow, differing by age group), participants completed three short practice blocks. Each practice block consisted of four pairs at study, followed by a brief period of interpolated activity (involving verifying whether math problems were solved correctly or incorrectly) for only 20 seconds during the practice phase, and then a test phase with one intact, one related, and one unrelated pair per practice block. In one block, participants studied the pairs under the fast presentation rate (1s for young and 2s for older adults), compared with intermediate presentation rates in another block (2s for young and 4s for older adults), and slow rates in the remaining block (4s for young and 6s for older adults). During the practice test phases, participants were given feedback on their memory responses, informing them whether the test pair was intact, related, or unrelated.

Experimental Phase. The main phase of the experiment consisted of nine study-test blocks. Each block began with a study phase, in which participants studied 12 unique face-scene pairs, one at a time, under one of the three (fast, intermediate, or slow)

presentation rates (see Figure 3). Each pair was separated by a 0.5-second interstimulus interval (ISI), which was constant across the three encoding/presentation rates. Within the study phase and across blocks, no two pairs were identical, but the two exemplars of a given scene category (e.g., the two field scenes depicted in Figure 3) both appeared in the same block, each paired with a unique face.

Figure 3. *Depiction of the Procedure*



Note. Faces depicted in the figure are approved for display purposes by the FACES Platform Release Agreement, Clause 7.

After studying all 12 pairs in a block, participants next completed an interpolated activity task spanning a minimum of 60 seconds between the study and test phases of the block. The interpolated activity task was designed to ensure that the test phase was a

long-term memory (LTM) test. This task presented participants with arithmetic problems involving simple addition or subtraction. The problems were either solved correctly (e.g., "4 x 5 = 20") or incorrectly (e.g., "7 + 6 = 12"), and participants responded by pressing the "1" or "0" key to indicate whether they believed the problem was solved correctly or incorrectly, respectively.

To ensure that the total block length from the beginning of the study phase to the beginning of the test phase was equal across the different presentation rates (as discussed in Chapter 1, and based on findings from Greene & Naveh-Benjamin, 2022a, 2022b regarding effects of forgetting of specific and gist representations under short time scales), the length of this interpolated activity varied based on the presentation rate during the study phase, always being longer for faster presentation rates. Specifically, the minimum length employed was 60 seconds, and this occurred in the 6s presentation rate (the slowest presentation rate used in the study, which corresponded to the slow presentation rate for older adults). As the study phase in this presentation rate was 78 seconds ((6 seconds of presentation time + 0.5 seconds ISI) x 12 pairs = 78 seconds), the total block length prior to the beginning of the test phase in the 6s condition was 138 seconds (78 + 60 = 138). To equate the total pre-test phase block lengths of blocks studied under the 1s, 2s, or 4s rates with the total pre-test phase block length of the 6s condition, the interpolated activity spanned 120 seconds, 108 seconds, and 84 seconds in the 1s, 2s, and 4s conditions, respectively. This ensured that the average amount of time any given face-scene pair would have to be retained in memory before being tested on (and thus, any corresponding specific or general memory representations of the pair) was equal across the 1s, 2s, 4s, and 6s presentation rates.

Following the interpolated activity, participants completed the test phase. The test phase featured 12 pairs per block, and only included tests on pairs from the study phase of that block. There were three types of test probes (Intact, Related, and Unrelated), with four of each per block. All the items (i.e., all the faces and all the scenes) presented at test had been studied, such that there were no new faces or scenes at test, ensuring that all the items would have the same familiarity based on prior exposure. There were no new items at test because the test was on associative (remembering which scene had been paired with which face) rather than item (remembering whether a face or a scene had been studied) memory.

Intact pairs featured a face appearing with the same scene with which the face had been studied (e.g., in Figure 3, the young man appears with the same field scene during the test phase as at study). Related and Unrelated pairs were *recombined pairs* in which the face from one pair was re-paired with the scene from a different pair. Related pairs involved a repairing that retained the general but not specific representation of the original pairing (e.g., in Figure 3, the old man appears with the same type of scene – a restaurant – during the test phase as at study, but the specific exemplar has changed; he is with a different restaurant). Unrelated pairs involved a repairing that was neither consistent with the specific nor the general representation of the original pairing (e.g., in Figure 3, the old woman appears with a field – a type of nature setting – during the test phase but had appeared with a completely different type of scene, a restaurant – a type of indoor setting – during an earlier study trial).

Below each test pair, three clickable response buttons appeared, labeled “Intact,” “Related,” and “Unrelated.” Participants clicked on one of these three responses to each

pair. If participants took longer than 50 seconds to execute a response, the experiment automatically advanced to the next pair. This was done to screen for participants who did not respond to the test pairs within a long response window, as such participants' data would be excluded due to low quality (i.e., such participants likely were not paying attention to the experiment).

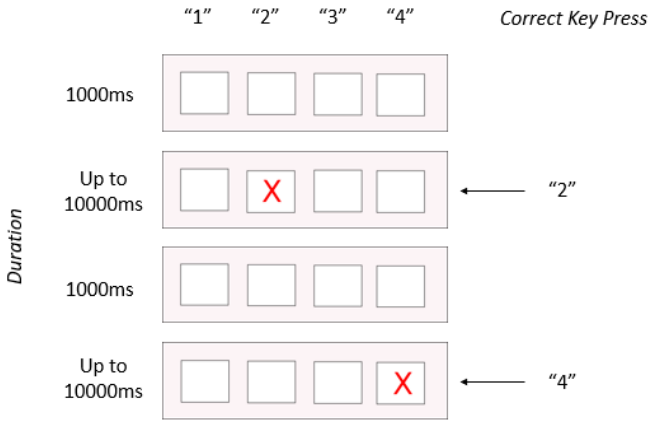
Simple and Choice Reaction Time Tasks. After completing all nine study-test blocks of the main experimental phase, participants completed simple reaction time (SRT) and choice reaction time (CRT) tasks designed to provide independent measures of participants' speed of processing, which could be correlated with their individual-level estimates of specific and general memory representations. The SRT and CRT tasks were based on the validated Deary-Liewald procedure (Deary et al., 2011). Each task employed similar stimuli, in which participants responded by key press to images of red X's appearing in different locations on a screen. Participants first completed the SRT task before completing the CRT task.

In the SRT task, participants responded by pressing the "3" key every time a red X appeared in a white box centered on the screen. Participants were instructed to respond as quickly as possible when the red X appeared. Participants had up to 10 seconds to respond. After responding, the red X disappeared from the white box, which was presented in isolation at the center of the screen for a random delay between 1000ms and 2400ms, after which point another red X appeared in the white box. The delay between trials was varied to ensure that participants would not be able to establish a predictable rhythm of detecting when the red X might appear, as may occur with a single fixed delay.

Participants first completed eight practice trials before proceeding to 20 main SRT trials. Only data from the 20 main SRT trials were included in analyses.

In the CRT task, a grid of four white boxes subtended in a gray background appeared centrally on the computer screen (see Figure 4). After a 1000ms delay, a red X appeared in one of the four boxes. Participants were prompted to respond as quickly and accurately as possible when the red X appeared by indicating with one of the four numbered keys ("1," "2," "3," or "4") corresponding to the number, from left to right, of the box in which the red X appeared. Participants had up to 10 seconds to respond before the experiment automatically advanced to the next trial. Participants completed eight practice and 40 main CRT trials, which featured an even number (10 each) of trials depicting a red X in each of the four-numbered boxes, presented in a random order. Only data from the 40 main CRT trials were included in the analyses.

Figure 4. *Depiction of Deary-Liewald Choice Reaction Time Task*



Post-Test Questionnaire. Finally, after completing the SRT and CRT tasks, participants responded to a multiple-choice question and an open-ended question about

their experience in the experiment. The multiple-choice question asked participants to rate on a 1 (“not at all”) to 5 (“very much”) scale how difficult they found the experiment to be. The open-ended question asked participants to describe any strategies they used to help them commit the face-scene pairs to memory. Data from these post-test questions will not be analyzed in the present study.

Analyses

ANOVA on Proportion Correct. To first get a sense of the behavioral pattern of responses in the data and whether these differed between young and older adults and as a function of presentation duration at encoding, I conducted analysis of variance (ANOVA) on the proportion of correct responses. The outcome was the proportion of correct “intact” responses to Intact probes, “related” responses to Related probes, and “unrelated” responses to Unrelated probes. The ANOVA is a 2 (Age: Young, Old) x 3 (Rate: Fast, Intermediate, Slow) x 3 (Probe: Intact, Related, Unrelated) mixed model with repeated measures on Rate and Probe. These analyses serve simply as a “first pass” to get a quick understanding of performance differences on the task as a function of the three main effects and their interactions. However, none of the primary conclusions of the present study were based on these analyses, as they cannot determine whether performance differences were due to mnemonic (e.g., retrieval of specific or general representations) or non-mnemonic (e.g., guessing/bias) processes. In the ensuing section, I describe a modeling approach suitable to this endeavor. The main reason for first including these more traditional analyses (i.e., ANOVA) is to give readers, most of whom will be familiar with these techniques, an initial glance at performance on the task (what I call the “behavioral data” because these data are simply the observed proportions of

responses to different memory probes) before diving into a more sophisticated modeling approach to these data. This can also help readers appreciate the added benefits that the mathematical modeling (discussed in the next section) provides above and beyond the insights that can be gained from traditional approaches like ANOVA on aggregated proportions of responses.

The ANOVA on proportion correct was conducted under both frequentist and Bayesian statistical approaches. In the Bayesian framework, the strength of evidence for or against each main effect and interaction can be quantified with a Bayes factor (*BF*), where BF_{10} and BF_{01} describes the strength of evidence in favor for or against, respectively, there being an effect. I used the nomenclature of van Doorn et al. (2021) in describing the strength of evidence conveyed by the *BF* with respect to each main effect and interaction. Specifically, I regarded *BF*s between 1 and 3 as weak evidence, *BF*s between 3 and 10 as moderate evidence, and *BF*s > 10 as providing strong evidence. Default prior options based on recommendations from Rouder et al. (2012) were used for the Bayesian ANOVA. The ANOVA models were implemented in JASP (JASP Team, 2020).

Multinomial-Processing-Tree (MPT) Analyses. Standard analyses, like ANOVA on the proportion of correct responses, cannot provide insight into underlying cognitive processes that may differ between young and older adults and as a function of the rate of presentation (see Greene & Rhodes, 2022). Moreover, two participants could have similar performance on a recognition task, like the one used in the present study, but for entirely different reasons. Participant A may remember detailed, specific representations of studied pairs, leading them to respond with high accuracy on the task.

Participant B may lack detailed, specific representations, and perhaps general representations as well, but may have a guessing strategy (or response bias) that leads them to be as accurate as Participant A at classifying some types of memory probes. ANOVA cannot disentangle response bias from mnemonic processes. To gain deeper traction on what underlying cognitive processes contributed to participants' performance on the task, and to assess whether there were any age-related differences in these processes, I next conducted multinomial-processing-tree (MPT) analyses using the MPT model from the simplified conjoint recognition paradigm (Stahl & Klauer, 2008).

An MPT model is a set of mathematical equations that define how participants arrive at their observable responses to different test probes by way of latent parameters representing unobservable cognitive processes, which are connected in branching-like structures (for reviews, see Batchelder & Riefer, 1999; Erdfelder et al., 2009). Each parameter represents the probability that a given cognitive process occurs during the response process. The model equations that define a given MPT model are fit to the data, which are given as the frequencies of responses to different probes, usually aggregated over individuals, though a more suitable approach (detailed below) involves fits at both the group- and individual-level (Klauer, 2010). A given MPT model is designed and validated for the measurement of some processes of interest and is suitable for empirical tasks that provide a data structure compatible with the equations that define the model. For example, an MPT model with parameters corresponding to source memory retrieval would be incompatible with an experiment that lacks any tests of source memory.

The MPT model from the simplified conjoint recognition paradigm (Stahl & Klauer, 2008) has been empirically validated as a measurement tool for estimating the

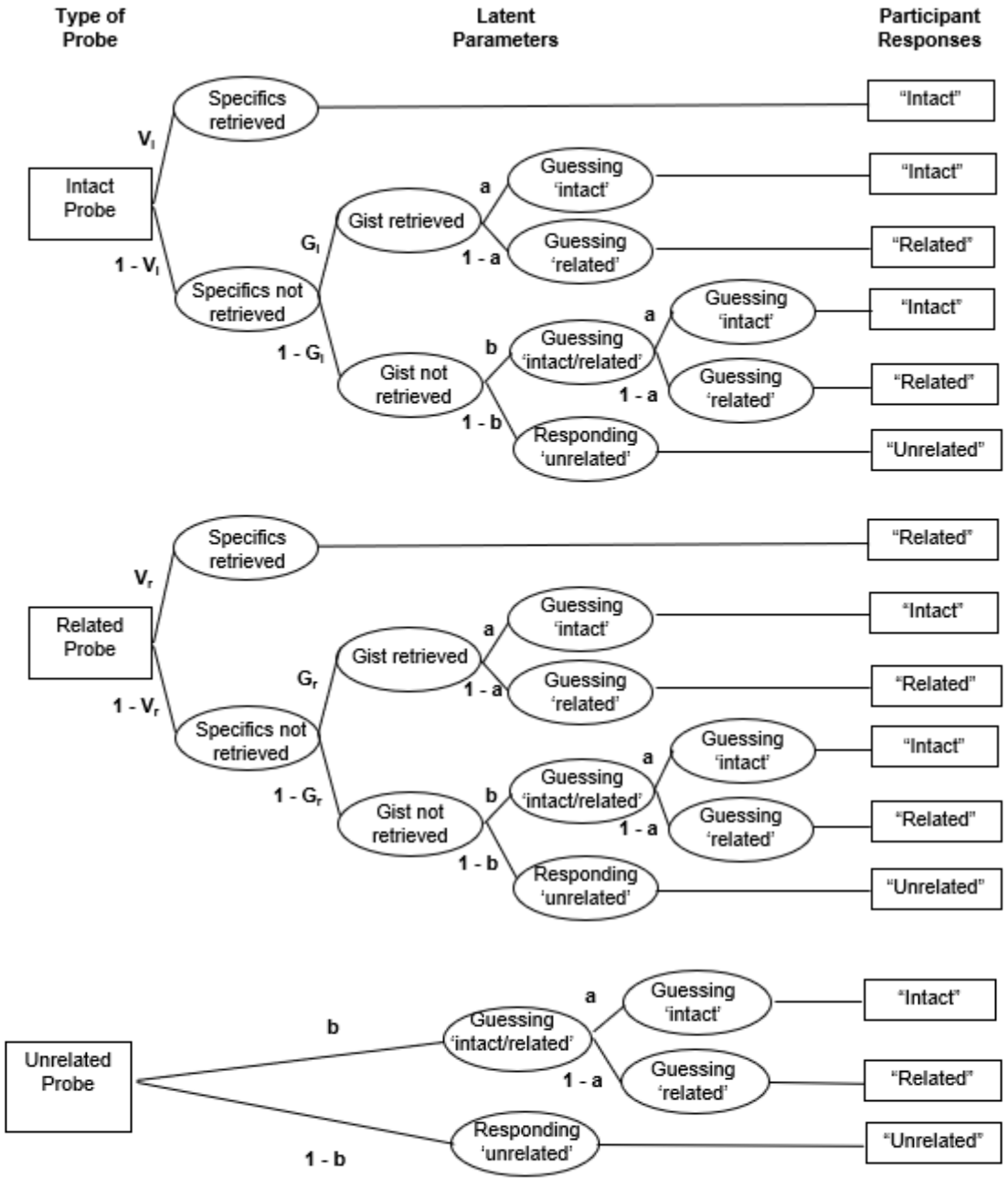
contributions of specific and gist/general memory representations in recognition procedures that use a tripartite judgment ("old/intact," "similar/related," and "new/unrelated") crossed with a minimum of three types of memory probes consisting of old/intact probes, similar/related lures, and new/unrelated distractors, like that used in the present study (see Table 2). Empirical validation of an MPT model entails that the parameters of the model are shown to be selectively responsive to empirical manipulations that should hypothetically impact those parameters (Batchelder & Riefer, 1999). For example, Stahl and Klauer (2008) showed that repetition at study (i.e., providing multiple presentations of each target) enhanced the parameters of specific memory more than those of gist memory, with no observable effects on response bias parameters, which is consistent with the expectation that multiple presentations of a target enhance verbatim traces of that target. The MPT model is depicted in Figure 5.

Table 2. *Data Structure for the Simplified Conjoint Recognition Paradigm*

Probe	Response		
	"Intact"	"Related"	"Unrelated"
Intact	F_{11}	F_{12}	F_{13}
Related	F_{21}	F_{22}	F_{23}
Unrelated	F_{31}	F_{32}	F_{33}

Note. F refers to the frequency in each cell. The frequencies are listed as F_{ij}, where *i* indexes the probe and *j* indexes the response. These F_{ij} are converted to probabilities p_{ij}, to which the model equations are fitted.

Figure 5. *Simplified Conjoint Recognition Multinomial-Processing-Tree (MPT) Model*



Note. Boxes on the left represent memory probes (Intact, Related, or Unrelated probes), which are connected to participants' responses (boxes on the right) by way of different cognitive processes (the branches in the middle, where the ovals describe what each parameter corresponds to). The two *V* parameters correspond to the probability that participants retrieve the

specific/verbatim representation of an association given either an Intact probe (V_i) or a Related probe (V_r). 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. If participants retrieve only a general 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*.

As depicted in Figure 5, participants' responses at test (boxes on the right) are linked to the memory probes (boxes on the left) via parameters reflecting different cognitive processes (circles). The probability of making response *j* to probe *i* is expressed as the sum of the probabilities of the branches terminating in that response. Each parameter measures the probability a given cognitive process will occur and thus takes on a value between 0 and 1. Participants may retrieve specific representations of originally studied face-scene pairs (i.e., remembering specifically which scene had been paired with a given face), which is reflected in parameters V_i and V_r, where "V" denotes that these are *verbatim memory* parameters, based on fuzzy-trace theory. Failing this (i.e., with probabilities $1 - V_i$ or $1 - V_r$), participants may still remember more general representations of studied face-scene pairs, that is, remembering in general what type of scene had been associated with a given face, which is modeled with *gist memory* parameters G_i and G_r. If participants remember general but not specific representations, they then must guess whether a probe is "intact" or "related" with probabilities *a* or 1 – *a*, respectively. There are unique specific and gist parameters for Intact (denoted with the

subscript “i”) and Related (denoted with the subscript “r”) probes because Intact probes are identical to studied pairs and thus serve as more efficient retrieval cues for specific representations of the originally encoded information, whereas Related probes match originally studied pairs only at a gist level of representation and are thus better elicitors of gist than specific representations (see Brainerd et al., 1999, 2019; Brainerd & Reyna, 1990; Stahl & Klauer, 2008; cf., encoding-specificity principle, Tulving & Thomson, 1973).

For Unrelated probes, there are no specific or gist memory parameters, but this is not to say that participants never remember specific or general representations of original pairs when shown an Unrelated probe and use such representations to guide their response. Correct responses to Unrelated probes are modeled to occur through the pathway $1 - b$, where parameter b is a response bias/guessing parameter. This is not to say that all correct “unrelated” responses to Unrelated probes arise through guessing. Rather, a more suitable way to think of parameter b is that it indexes the probability that, even when a participant has not accessed specific or general representations, the participant still elects to guess that the pair could be “intact” or “related” (e.g., “I do not remember this face being paired with this type of scene, *but* perhaps I am wrong”), while the opposite pathway ($1 - b$) corresponds to the state “I do not remember this face being paired with this type of scene, so this is an ‘unrelated’ pair.” As this shows, including specific or gist parameters in the Unrelated probe tree would be redundant with the information already captured in parameter b, because they would lead to an identical state as reflected in pathway $1 - b$ (i.e., acknowledging that the participant does not remember the face being paired with that type of scene). The support for this interpretation of

parameter *b*, and more specifically its complementary pathway, is given by the inclusion of this parameter in the trees for Intact and Related probes. In those trees, parameter *b* (and pathway 1 – *b*) is only reached when specific and gist representations have not been retrieved. Thus, even for Intact or Related probes, pathway 1 – *b* indicates that a participant does not remember the face being paired with that type of scene and thus believes the pair to be "unrelated." At a more technical level, no specific or general representation parameters can be included on the Unrelated probe tree because the model has six free parameters corresponding to six degrees of freedom and is thus saturated. Inclusion of additional parameters would require constraining other parameters in the model to pre-determined values or to equality with another parameter.

To estimate the parameters of the MPT model, the data must be constructed as in Table 2. Then, the ensuing equations are fit to these frequencies, which are converted to probabilities in the estimation process:

[Eqn. 1] $p_{11} = V_i + (1-V_i)*G_i*a + (1-V_i)*(1-G_i)*b*a$

[Eqn. 2] $p_{12} = (1-V_i)*G_i*(1-a) + (1-V_i)*(1-G_i)*b*(1-a)$

[Eqn. 3] $p_{13} = (1-V_i)*(1-G_i)*(1-b)$

[Eqn. 4] $p_{21} = (1-V_r)*G_r*a + (1-V_r)*(1-G_r)*b*a$

[Eqn. 5] $p_{22} = V_r + (1-V_r)*G_r*(1-a) + (1-V_r)*(1-G_r)*b*(1-a)$

[Eqn. 6] $p_{23} = (1-V_r)*(1-G_r)*(1-b)$

[Eqn. 7] $p_{31} = b*a$

[Eqn. 8] $p_{32} = b*(1-a)$

[Eqn. 9] $p_{33} = 1-b$

The equations are closed form, meaning the parameters can be estimated through simple algebra via rearrangement of the preceding equations (see Stahl & Klauer, 2008 for proof of identifiability), by fitting the equations to the data from each individual participant. However, this is not an ideal approach, as it can lead to biased estimates. A more suitable approach involves estimating the parameters through statistical approximation with hierarchical models that simultaneously estimate individual- and group-level estimates of each parameter (Klauer, 2010). A Bayesian estimation technique is thus required.

The MPT model parameters were estimated using a hierarchical Bayesian estimation technique with latent-trait prior specifications, with the TreeBUGS package for R (Heck et al., 2018; R Core Team, 2020). Latent-trait MPT models are highly applicable when parameters in the model are likely to be correlated (Klauer, 2010). The latent-trait specification of a hierarchical Bayesian MPT model captures this assumption by modeling parameters with an inverse normal transformation, such that the parameter vector of participant *j* is transformed as $\Phi^{-1}(\theta_j)$ and follows a multivariate normal distribution with priors on the group-level mean $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{\Sigma}$ specified on the probit scale (Klauer, 2010; Matzke et al., 2015). I retained the program's weakly informative default priors (see Heck et al., 2018 for details). For $\boldsymbol{\Sigma}$, this default prior is a scaled inverse Wishart prior (e.g., Gelman & Hill, 2007), with an identity scale matrix of size S x S with $S + 1$ degrees of freedom, where S describes the number of free parameters in the model (6 in the present implementation). Scaling parameters ξ_s are placed on the standard deviations of each parameter to ensure the inverse Wishart prior is only weakly informative. Each ξ_s had a uniform prior on the interval [0, 10]. For the

group-level means μ_s of each parameter, the prior was a standard normal distribution, which implies a uniform distribution in probability space (Rouder & Lu, 2005). This ensures the prior is only weakly informative as it assigns equal *a priori* probability to all possible values (specifically, those between 0 and 1) that a parameter can assume.

I initially fit the model to the data from young and older adults separately, and within each age group, I modeled the parameters with a within-subject parameterization. This allowed the model to be fitted to the data from each encoding rate condition for a given participant within a given age group simultaneously, with different versions of each parameter in the model for each encoding rate (e.g., a separate V_i for the 1s and 2s rates in fitting the model to younger adults). However, fitting the model in this way resulted in an unstable model whose posterior estimates of the parameters failed convergence diagnostics. That is, the model parameters were estimated from three independent Markov Chain Monte Carlo (MCMC) chains that sampled from the posterior distribution, following an initial adaptation period of 15,000 iterations per chain, a burn-in period of 10,000 iterations, and a sampling period of 55,000 iterations, with thinning set to 10 such that only every tenth iteration was retained (for 16,500 overall), due to limited computing power.

Convergence is monitored by the Gelman-Rubin statistic $\hat{R}$. When $\hat{R}$ approaches 1, the chains have converged on a stable posterior distribution. The standard cut-off for indicating convergence is $\hat{R} < 1.05$. However, in the within-subject parameterization of the model, multiple $\hat{R} > 1.05$, with values as high as $\hat{R} = 1.14$. This indicated that the MCMC chains did not converge on the same posterior distribution for some of the parameters, and the problem persisted even when the adaptation period was doubled.

Moreover, for those parameters with high $\hat{R}$ values, the effective sample size (ESS), which indicates the number of independent draws from the posterior distribution that were effectively retained in the final estimation of each parameter, was low (ESS < 200 out of a possible 16,500 iterations). Although there is no hard guideline for what constitutes a good ESS, especially in the case of an MPT model in which the correlations between model parameters can influence the ESS of any given parameter, in practice, when ESS is low (e.g., ESS < 200), the uncertainty in a given parameter's posterior distribution, captured by the Bayesian credible interval (CI) conveying the range in which, with some probability (e.g., 95%), we can be certain of the "true" value of the parameter within the population, is large. In some cases, when ESS is exceedingly low (ESS < 200 in practice with this model), the 95% CI of a parameter will often cover almost the entire range of the unit [0, 1] interval, meaning we cannot be confident of what the true value of that parameter is as it can assume almost any plausible value. Compounding these issues, the computing time to run one of these models with a within-subject parameterization exceeded one hour in some instances, even with the thinning rate set to 10.

Based on these limitations, I opted instead to fit the model to each encoding rate for a given age group separately, with each model parameter estimated from three independent MCMC chains (adaptation of 15,000 iterations, burn-in of 10,000 iterations, and sampling of 55,000 iterations per chain, with thinning set to 10, such that each model parameter was estimated from 16,500 independent draws from the posterior distribution). Essentially, this approach is equivalent to a within-subject parameterization in which the covariance between different encoding rates for any given parameter is constrained to 0

because it is not estimated. In the present study, covariance between parameters from different encoding rate conditions is not of central interest. Thus, assuming these covariances to be constrained to 0 does not affect the main inferences, which are concentrated on the group-level means of the given parameters and how these means change as a function of encoding rate within a given age group. Importantly, the estimated group-level means of the parameters were nearly identical to those obtained under the within-subject approach, with much improved ESS and $\hat{R}$ (all $\hat{R} < 1.05$ in all models, all ESS > 900, and in most cases, ESS > 2000) and reduced uncertainty in the parameter estimate (i.e., narrower 95% CI). As an added benefit, the computing time was much enhanced, as each model took between seven and twenty minutes to run.

Model fit was assessed with the T_1 and T_2 statistics proposed in Klauer (2010), which measure discrepancies between the observed and predicted mean and covariance of individual frequencies, respectively. The number of samples was computed for which $T_{observed} < T_{predicted}$, yielding a posterior predictive *p* value (PPP). PPP close to 0 indicate insufficient model fit, and general guidelines are that the model fails to provide an accurate fit of the data when PPP < .05. In these instances, an examination of the model-predicted and observed frequencies of responses can often identify where the model is misfitting the data, and adjustments to the model can be made, such as constraining a parameter to 0 if inclusion of that parameter leads to an over- or underestimation of actual response frequencies. I will describe instances where adjustments to the model were required as I present the results of each experiment. These adjustments were guided by past research using this model, so although they may seem "post-hoc," they are in keeping with past results.

Hypothesis Tests Based on MPT Model. There are two different sets of hypotheses that can be assessed with the MPT model. The first set pertains to effects of encoding rate on specific and general memory representations, within a given age group. The second set pertains to between age group effects on specific and general memory representations at different encoding rates. Both types of hypothesis tests can be made using the posterior summaries of the model parameters derived from the fitting of the model to each encoding rate condition within an age group separately, as detailed in the preceding section. No adjustment for multiple comparisons is required, as all hypothesis tests are made with respect to the same posterior distributions, which are unaffected by the number of comparisons made.

For the first set of hypothesis tests, I examined whether there were any increases in specific and general memory representations as a function of increases in the encoding duration. These tests were conducted separately for the young and older adult models, allowing an assessment of whether, within each age group, specific and general representations are established at different rates. Specifically, for the young adults, the hypothesis tests compared each specific and general memory parameter (V_i, V_r, G_i, and G_r) between (1) the 2s (intermediate) and 1s (fast) conditions, (2) the 4s (slow) and 2s (intermediate) conditions, and (3) the 4s (slow) and 1s (fast) conditions. For older adults, these hypothesis tests compared the specific and general memory parameters between (1) the 4s (intermediate) and 2s (fast) conditions, (2) the 6s (slow) and 4s (intermediate) conditions, and (3) the 6s (slow) and 2s (fast) conditions. Thus, the three comparisons concentrated on differences, within each age group, in specific and general memory representations between an intermediate and a fast rate of presentation, between a slow

and an intermediate rate of presentation, and between a slow and a fast rate of presentation.

For each hypothesis test, I subtracted the posterior samples of a model parameter obtained under the faster rate from the posterior samples of the same parameter obtained under the slower rate. For example, in comparing G_r at the 4s and 6s rates for older adults, I subtracted the posterior samples of G_r obtained under the 4s condition from the posterior samples of G_r obtained under the 6s condition. Each hypothesis test yielded a mean difference and 95% Bayesian CI of the difference, with positive difference scores indicating larger estimates of a given parameter at the slower than the faster rate. Along with these difference scores, the proportion of posterior samples of a given parameter that were larger in the slower (e.g., 6s) than the faster (e.g., 4s) conditions was computed. This provides an exact metric of the proportion of times in which a given parameter was estimated to be *larger* in the slower than the faster presentation rate. These proportions are informative in their own right, without hard black-and-white decisions as to whether they indicate the presence or absence of a difference, as is common in frequentist approaches with *p* values. For example, if the proportion of samples of the posterior distribution for parameter V_i that were higher in the 2s than the 1s condition for younger adults was 0.736 this tells us that, 73.6% of the time, V_i is higher in the 2s than the 1s condition.

However, following recommendations of Smith and Batchelder (2010), I used the following decision rule to conclude whether there was *credible* evidence of a difference: if the proportion of posterior samples that differed between the two conditions exceeded 0.95, then there was a credible difference in the given parameter between the two

encoding rates under comparison, with the direction of the difference score indicating whether the parameter was higher in the slower (difference score would be positive) or faster (difference score would be negative) rate of presentation. Otherwise (i.e., if <95% of posterior samples of a given parameter differed between the two encoding rates in the comparison), I remained agnostic as to whether there was a difference. Remaining agnostic is analogous to the frequentist equivalent of obtaining a *p*-value that is greater than .05, when alpha is set to .05. That is to say, remaining agnostic means that I have failed to detect a credible difference in 95% of posterior samples or more, but I also have not detected the *absence* of a difference. The true proportion of samples that differed provides a more continuous metric of differences between encoding rates for a given parameter. The nearer to 0.50 this proportion is, the more similar are the posterior samples of the parameter obtained from the two presentation rates under comparison (i.e., because then 50% of the time, the posterior samples are larger under one presentation rate, whereas the other 50% of the time, the posterior samples of the same parameter are larger under the *other* presentation rate).

The second set of hypothesis tests concerned age-related differences in the specific and general memory representation parameters. In these comparisons, the posterior samples of a given specific or general representation parameter obtained from fitting the model to the data of a given encoding rate condition among *older adults* was subtracted from the posterior samples of the same parameter at a specified encoding rate condition obtained from fitting the model to the data of *younger adults* (i.e., the computed differences were Young – Old). First, I compared estimates of specific and general memory parameters between young and older adults at the 2s rate of presentation,

which corresponded to the intermediate presentation rate for young and the slow presentation rate for older adults. Second, I compared these estimates between young and older adults at the 4s rate of presentation, which corresponded to the slow presentation rate for young and the intermediate rate for older adults. Finally, I compared these estimates between younger adults at the 4s rate and older adults at the 6s rate of presentation, as this corresponded to the slowest presentation rates for both young and older adults. As with the preceding hypothesis tests, the proportion of samples of a given parameter that differed between young and older adults was computed, and I concluded that there was credible evidence for a difference in a given parameter when this proportion exceeded 0.95. Otherwise, I remained agnostic as to whether there was a true age-related difference, but the proportion of posterior samples that differed still provides a continuous metric of how many times a given parameter was higher for younger than older adults.

The first set of hypothesis tests seeks to address whether there are differential rates of formation at encoding of specific compared to general representations for both young and older adults. If there are, with specific representations taking longer to extract than general representations, then I expect to find credible differences (slower > faster) in the specific parameters between at least two adjacent presentation rates that are absent for the gist parameters. Put another way, if gist representations form more rapidly than specific representations, then I would expect that there would be no credible differences in the gist parameters formed within at minimum the intermediate (2s for young, 4s for old) and slow (4s for young, 6s for old) rates of presentation, and possibly between the fast (1s for young, 2s for old) and intermediate (2s for young, 4s for old) rates, whereas

for specific representations, there would be credible differences in these parameters, with larger estimates obtained under the slowest presentation rates. That is to say, if general representations are established more rapidly than specific representations during encoding, then there should be evidence of continued improvements in the specific but not the gist memory parameters with increases in the encoding duration, with general representations being as on par at a faster presentation rate (e.g., the intermediate rate) as they are at the slowest presentation rate, whereas specific representations continue to be fleshed out between the intermediate and slow rates of presentation. If parameters measuring both types of representations are larger at the slowest than the intermediate presentation rates, then this would indicate that both specific and general representations continue to be fleshed out with longer encoding durations.

Regarding the second set of hypotheses, if older adults' deficits in specific representations, compared to younger adults, are attributable to a slower speed of processing such representations, then I expect that age deficits (old < young) on the specific memory parameters should be present at the shared presentation rates (2s and 4s) but would be absent when older adults have *more* time to encode these pairs (6s compared to 4s for younger adults). At the same time, I expect to find no age-related differences in the gist memory parameters, at least at the 4s rate, as this would replicate past research using the 4s rate of presentation (Greene & Naveh-Benjamin, 2020). However, whether there would be any age-related deficits in gist parameters at the 2s rate remains to be determined and would be possible if older adults require more time than younger adults to establish a general representation during encoding.

CHAPTER 3

EXPERIMENT 1 AND EXPERIMENT 2

Introduction

The purpose of the two experiments was to empirically test one of the proposed encoding mechanisms from Greene and Naveh-Benjamin's (2023) theoretical framework that may in part explain why older adults' episodic memory representations are less specific/detailed in nature, compared with those of younger adults, despite no discernible age deficits in general representations for past episodes. Specifically, one possibility that may explain why past empirical results have shown that older adults retain less specific details than younger adults is that there are age-related differences in the rate of formation, during encoding, of specific but not general memory representations. This is compatible with processing speed theories of aging that suggest that older adults' cognitive processes are slowed, which in turn leads to their widespread declines in numerous faculties of cognition, including episodic memory (Salthouse, 1996).

To test this possibility, in two experiments, I manipulated how much time young and older adults had to encode face-scene pairs in the associative specificity task of Greene and Naveh-Benjamin (2020), on which age deficits in specific but not general representations have previously been observed when young and older adults have the same amount of time (4 seconds each) to encode the pairs (Greene & Naveh-Benjamin, 2020, 2022a; Greene et al., 2022). By including various encoding rates of presentation, ranging from fast to slow rates among both young and older adults, the present study sought (1) to map out the time course under which specific and general representations of

complex episodic associations can be established at encoding and (2) to assess whether, with longer time to encode these associations, older adults could establish specific representations that were on par with those that younger adults can form under shorter encoding times.

The two experiments were almost identical in their methods (described in the ensuing section), with one important difference occurring during the interpolated activity task between the encoding and retrieval phases of the experiment. Given their large degree of similarity, I will describe the methodological details and results of each of the two experiments together in this chapter, including a formal test of whether the results differed between the two experiments, before moving to a synthesis that combines across the two experiments to increase the statistical power for tests of the primary hypotheses of the present study.

Method

Participants

The planned sample size was 40 per age group in each experiment, as this sample size has been found to be well-powered by a Bayesian prior sensitivity analysis for estimating a medium sized effect in the associative specificity recognition paradigm in prior work (Greene et al., 2022) and is consistent with the typical sample sizes used in this paradigm. Moreover, with a planned sample size of 40 per age group per experiment, the final combined analysis across the two experiments would include a sample size twice as large as is typically used in the associative specificity recognition paradigm. However, in total, 46 older adults were included in Experiment 1, but all other cells contained 40 participants (see Table 3).

All participants in Experiment 1, all older adults in Experiment 2, and the majority of the younger adults in Experiment 2 (with the exception of 17 young adults who were recruited from SONA at the University of Missouri) were recruited from the crowdsourcing platform Prolific (Prolific, n.d.). Participants on Prolific were eligible to participate if their age, in years, was within the range 18-26 (for young adults) or 65-80 (for older adults); they were fluent in English; they reported no history of mild cognitive impairment or dementia, assessed with a single self-report question; they reported drinking no more than five to nine alcoholic beverages per week; they had an approval rating of >85% based on prior studies completed on the site; their maximum number of prior submissions on Prolific was no more than 300; and their highest level of education obtained was no higher than a Master's degree or equivalent to ensure that the sample would not be too highly educated as to be unrepresentative of the general population, especially among older adults, given that only ~15% of American adults born in the 1960s obtained a college degree or higher (Bialik & Fry, 2019). The 17 young adults in Experiment 2 who completed the study on SONA were undergraduate students at the University of Missouri who participated in exchange for research credits. All participants on Prolific were compensated with between $8.00 and $9.00 US.

Demographic statistics of the two experiments, as well as combined across the two experiments, are given in Table 3. Participant sex was assessed with the question "What is your sex?" Participants responded by selecting "female," "male," "intersex," or "prefer not to say." 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).

Table 3. *Demographic Statistics of Experiment 1 and Experiment 2*

	n	*M* Age (SD)	*M* YoE (SD)	%Female, %Male, %Intersex
Exp 1 (YA)	40	22.55 (2.43)	15.08 (2.00)	57.5%, 42.5%, 0%
Exp 1 (OA)	46	68.39 (3.90)	14.42 (2.70)	54.3%, 46.7%, 0%
Exp 2 (YA)	40	21.10 (2.73)	13.99 (2.18)	65.0%, 35.0%, 0%
Exp 2 (OA)	40	68.88 (3.97)	15.15 (2.80)	65.0%, 35.0%, 0%
All (YA)	80	21.83 (2.67)	14.53 (2.15)	61.3%, 38.7%, 0%
All (OA)	86	68.62 (3.92)	14.76 (2.75)	59.3%, 40.7%, 0%

Note. All indicates the combined samples from Experiment (Exp) 1 and Exp 2. Age is given in years. OA = old adult; YA = young adult; YoE = years of formal education.

As indicated in Table 3, the samples of young and older adults in both experiments were majority female and, at least at the combined level, had similar levels of education. There was no significant difference in the proportion of participants identifying as female within each age group in Experiment 1, $\chi^2(1) = 0.01$, $p = .940$; in Experiment 2, $\chi^2(1) = 0.00$, $p = 1.00$; nor collapsed across the two experiments, $\chi^2(1) = 0.01$, $p = .922$.

There was no significant difference in years of formal education completed between young and older adults in Experiment 1, $t(82.12) = -1.28$, $p = .204$. However, in Experiment 2, the older adults were slightly more highly educated, $t(73.60) = -2.07$, $p = .042$, though the younger adult sample consisted of 17 undergraduate students, many of whom would likely go on to obtain a college degree. Moreover, the average years of completed education was 15.04 among the 23 young adults in Experiment 2 who were

recruited from Prolific, which is on par with the educational attainment of the older adults from Prolific. Combined across the two experiments, there was no significant difference in years of formal education completed between young and older adults, $t(159.38) = -0.60$, $p = .547$. The young adults in Experiment 1 were more highly educated than the young adults in Experiment 2, $t(77.46) = 2.32$, $p = .023$, but this was not the case for older adults, with no significance difference in years of formal education between Experiment 1 and Experiment 2, $t(81.41) = -1.22$, $p = .226$.

Materials, Design, Procedure, and Analyses

The materials were those outlined in the General Method (Chapter 2), and the design of each experiment was a 2 (Age: Young vs Older adult) x 3 (Rate of Encoding Presentation: Fast, Intermediate, Slow) x 3 (Type of Memory Probe: Intact, Related, Unrelated) mixed factorial design, with repeated measures on Rate of Encoding Presentation and Type of Memory Probe (see General Method for more details). The procedure and analysis plan were as outlined in the General Method.

One important note about the procedure, as it differs between Experiment 1 and Experiment 2, is with regards to the nature of the interpolated activity task between the study and test phases of each block. As a reminder, in each block, participants studied 12 face-scene pairs at a rate of 1s, 2s, or 4s (for young adults) or 2s, 4s, or 6s (for older adults), with each pair separated by a 0.5 ISI (see Figure 4). Following the study phase, participants completed a arithmetic verification task as an interpolated activity. During this task, simple addition or multiplication problems appeared on screen at the center of the display in size 18 Arial font. Each problem was either solved correctly (e.g., “3 x 4 = 12”) or incorrectly (e.g., “5 + 7 = 11”), and participants pressed the “1” or “0” key to

indicate whether they believed each problem was solved correctly or incorrectly, respectively.

The interpolated activity task was designed to eliminate any short-term memory for the just-presented face-scene pairs prior to the test phase at the end of the block. This task occurred for 60 seconds in the 6s condition, compared with 84 seconds in the 4s condition, 108 seconds in the 2s condition, and 120 seconds in the 1s condition (see General Method for details). In Experiment 1, participants were able to solve as many problems as possible within the total length of the task. That is, there was no fixed number of arithmetic problems presented from block-to-block and across the different encoding presentation rates. Participants had up to 10 seconds to make a response, or the trial automatically advanced to the next problem. However, responses made within the 10 second window automatically triggered the appearance of the next problem. Thus, while the total amount of time prior to the beginning of the test phase was equal across the different encoding rates (138 seconds from the beginning of the study phase to the beginning of the test phase in each block, regardless of the rate of presentation at encoding), it is conceivable that participants may have attempted to solve more arithmetic problems in the interpolated activity as the length of the interpolated activity task increased. That is, the total amount of non-study-specific interference from the interpolated activity was not constant for the different encoding rates as this potential source of interference systematically increased with decreases in the encoding presentation rate of the study phase. The objective of Experiment 1 with regards to the interpolated activity was to ensure a fixed length of time that any given face-scene pair would have to be retained in memory prior to being tested on, rather than a fixed absolute

amount of interference from the interpolated activity, across the different encoding presentation rates.

In Experiment 2, a constant number of math problems was presented in each period of interpolated activity, regardless of the total length of the interpolated activity task, to ensure that there was an equivalent number of intervening events of the interpolated activity task between the study and test phases at each encoding rate of presentation. Specifically, each arithmetic problem was presented onscreen for up to 3 seconds, during which time participants could execute their response. If participants responded before the 3 seconds were complete, the screen displayed a string of plus signs ("++++") for the remaining duration of the trial. In the 6s encoding rate condition, immediately after the 3 seconds expired, the next arithmetic problem was presented. Because the length of the interpolated activity task spanned 60 seconds in this condition, a total of 20 arithmetic problems were presented. To ensure that only 20 arithmetic problems would be presented in each block studied under the other encoding rates (1s, 2s, or 4s), an ISI was added between subsequent math problems, in which the string of plus signs ("++++") remained onscreen for 1200ms (4s condition), 2400ms (2s condition), or 3000ms (1s condition). Thus, the total durations (including the 3s response time plus the ISI) of each trial during the interpolated activity task in Experiment 2 were 3000ms (6s condition), 4200ms (4s condition), 5400ms (2s condition), or 6000ms (1s condition). Nevertheless, in each condition, participants only had up to 3000ms to respond to the math problem, and the remainder of the time was filled with the ISI. In total, 20 arithmetic problems were presented per interpolated activity period in each block, regardless of the rate of presentation at encoding. Thus, in Experiment 2, not only was

there a constant fixed amount of time that any given pair would have to be retained in memory before being tested on regardless of the presentation rate at encoding, but also, there was a constant number of arithmetic problems presented during the interpolated activity task, ensuring equivalent non-study-specific interference from the interpolated activity across the different encoding rates.

To summarize, the main methodological difference between Experiments 1 and 2 concerned the nature of the interpolated arithmetic verification task between encoding and retrieval. Both experiments attempted to ensure that the average amount of time any given face-scene pair would have to be retained in memory before being tested on would be equivalent across the various rates of encoding. Thus, both experiments adjusted the length of the interpolated activity based on the encoding rate of the primary memory task to control for potential differences in temporal decay between encoding and retrieval. However, Experiment 2, but not Experiment 1, additionally controlled for the amount of non-study-specific interference introduced by the interpolated activity task by equating the number of arithmetic problems presented in the interpolated activity period across the various encoding rates.

Results

Interpolated Activity Task

I concentrate first on data from the interpolated activity arithmetic task, as this is the task on which the primary methodological differences between Experiment 1 and Experiment 2 occurred. Recall that in Experiment 1, participants could solve arithmetic problems at their own pace (with up to a 10 second response window), such that it was possible that they would solve more problems in blocks featuring faster encoding

presentation rates, given that the interpolated activity task spanned a longer length of time (120 seconds, 108 seconds, 84 seconds, or 60 seconds, for the 1s, 2s, 4s, and 6s encoding rates, respectively). Indeed, as shown in Table 4, participants were shown more arithmetic problems with shorter encoding presentation rates in Experiment 1.

Table 4. *Mean (SD) Number of Arithmetic Problems Presented During Interpolated Activity Period Based on Encoding Rate in Experiment 1*

	Encoding Rate of Presentation			
	1s	2s	4s	6s
Young	65.68 (14.33)	54.70 (12.75)	40.78 (8.59)	---
Old	---	53.85 (14.31)	40.35 (11.07)	27.85 (7.46)

For younger adults, there was a significant difference in the number of arithmetic problems presented based on the encoding rate in Experiment 1, $F(2, 78) = 296.44$, $p < .001$, with all post-hoc tests showing significant differences (all $p_{Holm} < .001$), such that younger adults were shown more math problems with decreasing presentation rate at encoding (i.e., 4s < 2s < 1s). Likewise, for older adults, there was a significant difference in the number of arithmetic problems presented based on the encoding rate in Experiment 1, $F(2, 78) = 486.69$, $p < .001$, with all post-hoc tests showing significant differences (all $p_{Holm} < .001$), such that older adults were shown more math problems with decreasing presentation rate at encoding (i.e., 6s < 4s < 2s). It is worth noting that young and older adults were presented with comparable numbers of arithmetic problems at the shared 2s and 4s rates. Also, the data in Table 4 represent the number of arithmetic problems shown

to participants, but participants did not solve all these problems (i.e., there were some missing responses in which no response was recorded). This occurred relatively infrequently, with rates of missing responses of between 1.6% and 2.3% for younger adults and between 1.8% and 2.7% for older adults, with the exception of six older adult participants, who did not complete any of the arithmetic problems. Data from these six older adults were included in analyses of the primary memory task because there was no indication that their performance on the primary task majorly differed from the older adults who did complete most of the arithmetic problems. Note that when participants failed to respond to a arithmetic problem in Experiment 1, it was still presented to them onscreen for up to 10 seconds. Also, in Experiment 1, participants in both age groups were highly accurate in solving the arithmetic problems, with average accuracies of between 94.7% and 97.3%.

In Experiment 2, the same number of arithmetic problems (20 each) were presented during the interpolated activity periods in each block, regardless of the rate of encoding presentation duration. In Experiment 2, five older adults failed to respond to >80% of the math problems within the imposed 3 second response windows. Data from these five older adults on the primary memory task were retained in the analysis as there was no indication that these participants performed better or worse than the remainder of the sample of older adults. The rate of missing responses for the remaining participants ranged between 5.8% and 6.3% for younger adults and between 14.8% and 17.5% for older adults. These rates are higher than in Experiment 1 and may be due to the nature of the fixed response duration of 3000ms. This rate was chosen because, in Experiment 1, on average, younger adults were responding to the arithmetic problems within 1618ms to

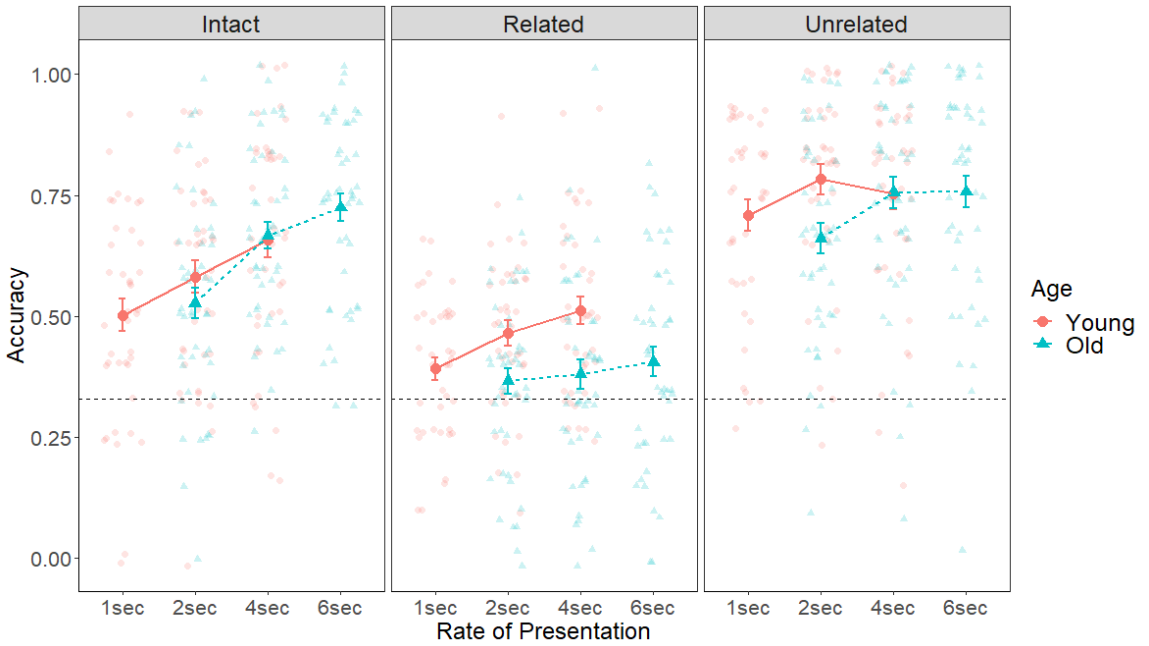
1856ms, while older adults were responding within 1853ms to 2060ms. Nevertheless, it is likely that, on some trials, participants took longer than 3000ms to respond in Experiment 1, and this was evident in Experiment 2, where the response rate was constrained to 3000ms. As in Experiment 1, participants in both age groups in Experiment 2 were highly accurate in identifying the arithmetic problems as being solved correctly or incorrectly, with average accuracies between 94.8% and 97.1%.

In summary, the main methodological differences between Experiments 1 and 2 were with respect to the nature of the interpolated activity task. As is evident from these data, participants were shown many more arithmetic problems in the interpolated activity period in Experiment 1, especially for blocks featuring longer periods of interpolated activity, compared with a fixed number of problems (20 each) in Experiment 2. Given that all other details of the method were identical between the two experiments and that the samples were well matched, any between-experiment differences in the memory task results, described in the ensuing section, would likely be attributable to differences in the interference imposed by the interpolated activity task.

Proportion Correct on the Recognition Task: Between-Experiment Differences?

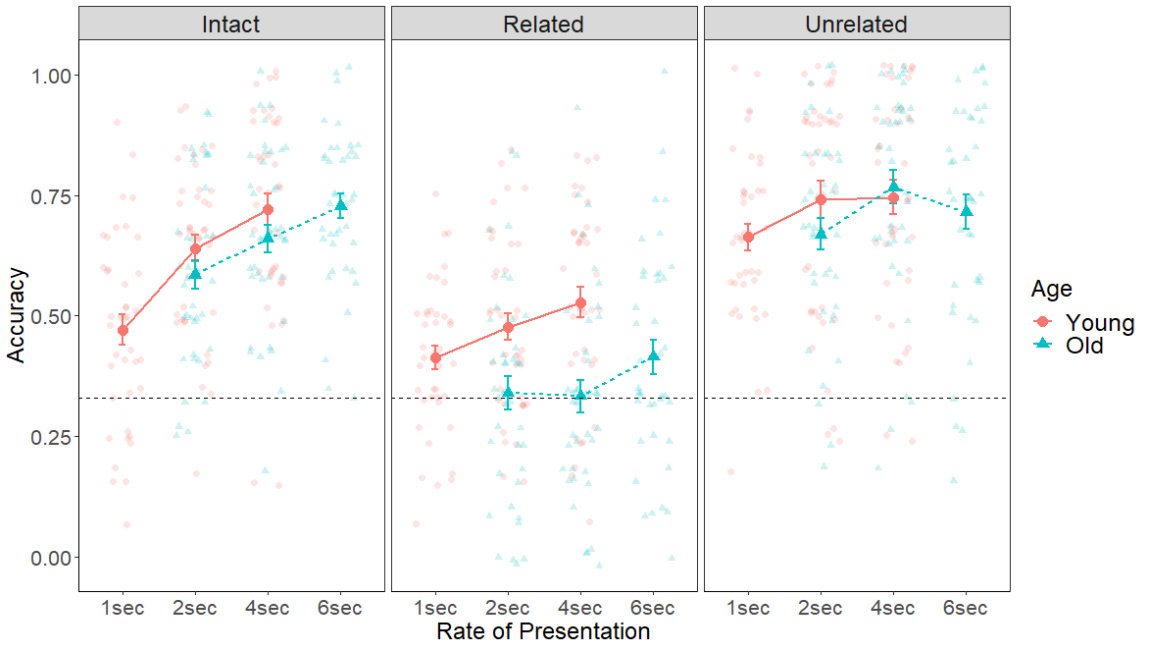
The proportion of correct recognition responses to each type of memory probe under each encoding rate of presentation for young and older adults in Experiment 1 is presented in Figure 6. Figure 7 shows these data for Experiment 2. Notably, the data presented in Figures 6 and 7 are quite comparable, as is evident by combing the two datasets, yielding Figure 8, which closely resembles the data of each individual experiment separately.

Figure 6. *Proportion Correct in Experiment 1*



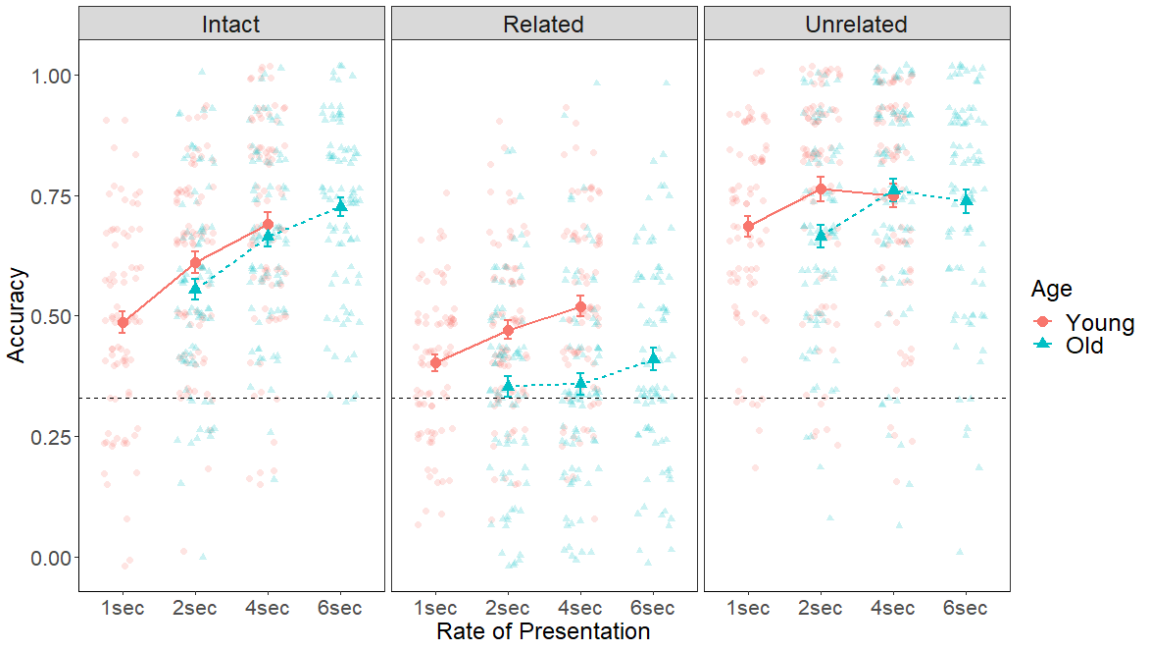
Note. Proportion correct is defined as the proportion of correct "intact" responses to Intact probes, "related" responses to Related probes, and "unrelated" responses to Unrelated probes. Bolded red circles and blue triangles correspond to group averages for young and older adults, respectively. Error bars represent +/- 1 standard error of the mean. Individual participants' data are overlaid as smaller, faded circles and triangles. Lines connecting group means across the Rate of Presentation are intended to show changes at the group level with increases in presentation time at encoding, though the data are measured on a discrete scale. Dashed line at 0.33 on the y-axis corresponds to chance level (33% correct) performance, but performance at or below chance to Intact or Related probes can still be informative in this paradigm.

Figure 7. *Proportion Correct in Experiment 2*



Note. Proportion correct is defined as the proportion of correct "intact" responses to Intact probes, "related" responses to Related probes, and "unrelated" responses to Unrelated probes. Bolded red circles and blue triangles correspond to group averages for young and older adults, respectively. Error bars represent +/- 1 standard error of the mean. Individual participants' data are overlaid as smaller, faded circles and triangles. Lines connecting group means across the Rate of Presentation are intended to show changes at the group level with increases in presentation time at encoding, though the data are measured on a discrete scale. Dashed line at 0.33 on the y-axis corresponds to chance level (33% correct) performance, but performance at or below chance to Intact or Related probes can still be informative in this paradigm.

Figure 8. *Proportion Correct Combined Across Experiments 1 and 2*



Note. Proportion correct is defined as the proportion of correct "intact" responses to Intact probes, "related" responses to Related probes, and "unrelated" responses to Unrelated probes. Bolded red circles and blue triangles correspond to group averages for young and older adults, respectively. Error bars represent +/- 1 standard error of the mean. Individual participants' data are overlaid as smaller, faded circles and triangles. Lines connecting group means across the Rate of Presentation are intended to show changes at the group level with increases in presentation time at encoding, though the data are measured on a discrete scale. Dashed line at 0.33 on the y-axis corresponds to chance level (33% correct) performance, but performance at or below chance to Intact or Related probes can still be informative in this paradigm.

Supporting the visual impression that the accuracy results look comparable between the two experiments, in separate 2 (Experiment) x 3 (Rate of Encoding) x 3 (Type of Memory Probe) mixed ANOVAs, fitted separately to the young and older adult data, there were no significant effects nor interactions of Experiment in either age group.

Specifically, among young adults, there was no significant main effect of Experiment, $F(1, 78) = 0.02$, $p = .878$; no significant two-way interactions between Experiment and Rate of Encoding, $F(2, 156) = 1.26$, $p = .286$, nor between Experiment and Type of Memory Probe, $F(2, 156) = 1.46$, $p = .234$; and no significant three-way Experiment x Rate of Encoding x Type of Memory Probe interaction, $F(4, 312) = 1.30$, $p = .271$. Likewise, among older adults, there was no significant main effect of Experiment, $F(1, 84) = 0.02$, $p = .888$; no significant two-way interactions between Experiment and Rate of Encoding, $F(2, 168) = 0.72$, $p = .487$, nor between Experiment and Type of Memory Probe, $F(2, 168) = 0.35$, $p = .705$; and no significant three-way Experiment x Rate of Encoding x Type of Memory Probe interaction, $F(4, 312) = 1.93$, $p = .106$.

Under the Bayesian model comparison approach, for younger adults, out of all candidate models involving the three main effects, their two-way interactions, and the three-way interaction, the winning model, based on equal prior probabilities of all models and conditioned on the data, did not include any effects or interactions with Experiment and only included the two main effects of Rate of Encoding and Type of Memory Probe, plus their interaction. The probability of this model, given the data, P(M|data) was 0.697, with a Bayes factor in favor of this model (BF_M) = 41.33. Indeed, averaged over all possible models, the BF in favor of retaining the effect of Experiment, analogous to BF_{10} (or the BF for the effects hypothesis) was 0.112, indicating moderate evidence in favor of the null ($BF_{01} = 8.93$). For the Experiment x Rate of Encoding interaction, $BF_{10} = 0.043$, corresponding to a $BF_{01} = 23.26$, or strong evidence for the null. For the Experiment x Type of Memory Probe interaction, $BF_{10} = 0.144$, corresponding to moderate evidence

for the null, $BF_{01} = 6.94$. Finally, for the three-way interaction, the $BF_{10} = 0.004$, corresponding to decisive evidence in favor of the null, $BF_{01} = 250$.

As with younger adults, for older adults, the winning model under the Bayesian approach included the two main effects of Rate of Encoding and Type of Memory Probe plus their interaction, but no effects of or interactions with Experiment, P(M|data) = 0.754, $BF_M = 55.07$. Averaged over all possible models, the BF in favor of retaining the effect of Experiment, analogous to $BF_{10} = 0.071$, indicating strong evidence in favor of the null ($BF_{01} = 14.08$). For the Experiment x Rate of Encoding interaction, $BF_{10} = 0.021$, corresponding to a $BF_{01} = 47.62$, or strong evidence for the null. For the Experiment x Type of Memory Probe interaction, $BF_{10} = 0.015$, corresponding to strong evidence for the null, $BF_{01} = 66.67$. Finally, for the three-way interaction, the $BF_{10} = 3.10 \times 10^{-4}$, corresponding to decisive evidence in favor of the null, $BF_{01} = 3.23 \times 10^{3}$.

Consequently, under both frequentist and Bayesian approaches, the data speak strongly against the possibility that there were any between-experiment differences, among young or older adult participants, in terms of response accuracy on the recognition task. In other words, the between-experiment differences in the interpolated activity task did not materially influence young or older adults' performance on the primary memory recognition task. Therefore, in comparing performance between younger and older adults, in the following, I have combined the data from the two experiments, increasing the statistical power of the tests.

Proportion Correct on the Recognition Task: Effects of Age, Rate of Encoding, and Type of Memory Probe

Because the rates that defined the fast, intermediate, and slow encoding presentation rates differed for young adults (1s, 2s, and 4s, respectively) compared to older adults (2s, 4s, and 6s, respectively), the *a priori* age comparisons focused on the rates in common (2s and 4s) and on the performance of older adults at the 6s rate compared to younger adults at the 4s rate. First, however, I assessed whether, within each age group, there were performance differences in proportion correct recognition using 3 (Rate of Encoding) x 3 (Type of Memory Probe) repeated measures ANOVAs.

Young Adults. For young adults, there were significant main effects of Rate of Encoding, $F(2, 158) = 48.24$, $p < .001$, and Type of Memory Probe, $F(2, 158) = 99.89$, $p < .001$, and a significant Rate of Encoding x Type of Memory Probe interaction, $F(4, 316) = 7.26$, $p < .001$. The main effect of Rate of Encoding was characterized by increases in proportion correct with increases in presentation duration at encoding (1s < 2s < 4s), all post-hoc pairwise comparisons significant with a Holm correction, $p_{Holm} \leq .005$. The main effect of Type of Memory Probe was characterized by highest accuracy to Unrelated probes, intermediate accuracy to Intact probes, and poorest accuracy to Related probes, all pairwise comparisons significant with a Holm correction, $p_{Holm} < .001$. The same credible effects were obtained under the Bayesian model comparison, which indicated that the winningest model, out of all possible models containing the two main effects and the interaction, included both main effects and their two-way interaction, $BF_M = 43.43$, P(M|data) = 0.916. There was decisive evidence for each main effect, with $BF_{10} = 1.54 \times 10^{14}$ for both, and strong evidence for the two-way interaction, $BF_{10} = 43.43$. For the post-hoc comparisons, for the effect of Rate of Encoding, there was strong evidence for improvements in accuracy from the 1s to the 2s to the 4s rates, all $BF_{10} \geq 22.88$; and

for the effect of Type of Memory Probe, there was decisive evidence that accuracy improved from Related to Intact to Unrelated probes, all $BF_{10} \geq 1.11 \times 10^{14}$.

To make sense of the significant two-way interaction, I conducted separate one-way ANOVAs to assess effects of Rate of Encoding on accuracy to each type of memory probe. For Intact probes, the main effect of Rate of Encoding held, $F(2, 158) = 47.48$, $p < .001$, $BF_{10} = 7.04 \times 10^{13}$, with all pairwise comparisons yielding significant differences, all $p_{Holm} < .001$, all $BF_{10} \geq 151.33$. For Related probes, the main effect of Rate of Encoding held, $F(2, 158) = 18.71$, $p < .001$, $BF_{10} = 2.42 \times 10^{5}$, with all pairwise comparisons yielding significant differences, all $p_{Holm} \leq .012$, all $BF_{10} \geq 2.46$. Finally, for Unrelated probes, the main effect of Rate of Encoding held, $F(2, 158) = 7.51$, $p < .001$, $BF_{10} = 29.26$, but the pairwise comparisons revealed that there was no significant improvement in accuracy from the intermediate (2s) to the slow (4s) rate of presentation, $t(79) = 0.59$, $p_{Holm} = .559$, $BF_{10} = 0.16$ (or $BF_{01} = 6.25$).

To summarize, for younger adults, there were in general improvements in accuracy from the fastest (1s) to the intermediate (2s) to the slowest (4s) rate of presentation at encoding. The only exception was for Unrelated probes, those probes that maintain neither a specific nor a general representation of the originally studied pairs, as accuracy to Unrelated probes was on par at the 2s and 4s rates, which may indicate that general representations formed within 2 seconds of encoding time were on par with those formed within 4 seconds of encoding time, though the MPT results will be needed to assess this possibility. Young adults' performance was lowest for those probes for which individuals would need to retrieve the most specific details in order to classify them (Related probes, which provide no exact match at a specific level but which do match the

originally studied pairs at a general level) but improved for Intact probes, which provide a match to the studied information at both specific and general levels of representation, and was highest for Unrelated probes, which were opposed to specific and general representations of originally studied pairs.

Old Adults. As with the younger adults, among older adults, the winning model under the Bayesian model comparison included both main effects and their interaction, $BF_M = 41.97$, P(M|data) = 0.913. Indeed, there were significant main effects of Rate of Encoding, $F(2, 170) = 35.24$, $p < .001$, $BF_{10} = 1.68 \times 10^8$, and Type of Memory Probe, $F(2, 170) = 116.72$, $p < .001$, $BF_{10} = \infty$, and a significant Rate of Encoding x Type of Memory Probe interaction, $F(4, 340) = 10.42$, $p < .001$, $BF_{10} = 41.97$. The main effect of Rate of Encoding was characterized by increases in proportion correct with increases in presentation duration at encoding (2s < 4s < 6s), all post-hoc pairwise comparisons significant with a Holm correction, $p_{Holm} \leq .015$, all $BF_{10} \geq 2.00$. Notably, the Bayes factor for the difference in accuracy between the 4s and 6s rates ($BF_{10} = 2.00$) is only considered weak by conventional standards, though the BF_{10} for both contrasts involving the 4s and the 6s rates with the 2s rate were decisive, both $BF_{10} \geq 3.71 \times 10^7$. The main effect of Type of Memory Probe was characterized by highest accuracy to Unrelated probes, intermediate accuracy to Intact probes, and poorest accuracy to Related probes, all pairwise comparisons significant with a Holm correction, $p_{Holm} \leq .003$, all $BF_{10} \geq 1.48 \times 10^3$.

To make sense of the significant two-way interaction, I conducted separate one-way ANOVAs to assess effects of Rate of Encoding on accuracy to each type of memory probe. For Intact probes, the main effect of Rate of Encoding held, $F(2, 170) = 41.07$, $p <$

.001, $BF_{10} = 2.05 \times 10^{12}$, with all pairwise comparisons yielding significant differences, all $p_{Holm} \leq .001$, all $BF_{10} \geq 13.14$. For Related probes, the main effect of Rate of Encoding held, $F(2, 170) = 5.58$, $p = .004$, $BF_{10} = 5.55$. The post-hoc pairwise comparisons revealed that there was no significant difference in accuracy to Related probes at the 2s and 4s rates, $t(170) = -0.26$, $p_{Holm} = .795$, $BF_{10} = 0.12$ (or $BF_{01} = 8.33$), but performance was higher at the 6s rate than at both the 2s and 4s rates, both $p_{Holm} \leq .013$, $BF_{10} \geq 3.44$. Finally, for Unrelated probes, the main effect of Rate of Encoding held, $F(2, 170) = 15.27$, $p < .001$, $BF_{10} = 1.75 \times 10^4$, but the pairwise comparisons revealed that there was no significant improvement in accuracy from the intermediate (4s) to the slow (6s) rate of presentation, $t(170) = 1.28$, $p_{Holm} = .201$, $BF_{10} = 0.23$ (or $BF_{01} = 4.35$), whereas accuracy to Unrelated probes was higher at both the 4s and 6s rates compared to the 2s rate, both $p_{Holm} < .001$, $BF_{10} \geq 228.29$.

To summarize, for older adults, as for younger adults, accuracy generally improved with increases in the presentation rate at encoding from the fastest (2s) to the intermediate (4s) to the slowest (6s) rate, with a couple of exceptions. To Related probes, older adults' accuracy did not differ at the 2s and 4s rates, which may suggest that there were no improvements in *specific* representations unfolding over this presentation duration, given that such representations would be needed to correctly classify these pairs. To Unrelated probes, older adults' accuracy did not differ between the 4s and 6s rates, which may suggest that there were no improvements in *general* representations unfolding beyond 4s presentation duration at encoding, given that such representations would be sufficient for rejecting these pairs. The MPT results will be needed to see if these assumptions are supported by a mathematical model that can decompose the

behavioral data into each type of memory representation and separate these representations from response biases. Finally, as with younger adults, among older adults, accuracy was poorest for Related probes, intermediate for Intact probes, and highest for Unrelated probes, which is in accord with the idea that older adults' errors on the task were greatest when the most specific information would need to be retrieved in situations in which the retrieval cue provided a match only at a general but not specific level of representation (Related probes).

Age-Related Comparisons. To compare performance between young and older adults, I conducted three separate 2 (Age) x 3 (Type of Memory Probe) ANOVAs, one comparing performance at the shared 2s rate of encoding presentation, one at the shared 4s rate of encoding presentation, and one at the 6s rate for older adults compared to the 4s rate for younger adults.

At the 2s rate of presentation, there was a significant main effect of Age, $F(1, 164) = 17.28$, $p < .001$, $BF_{10} = 232.45$, with younger adults outperforming older adults on the recognition task. There was also a significant main effect of Type of Memory Probe, $F(2, 328) = 123.47$, $p < .001$, $BF_{10} = \infty$, which was characterized by highest accuracy to Unrelated probes, intermediate accuracy to Intact probes, and lowest accuracy to Related probes, all pairwise comparisons significant, $p_{Holm} < .001$, all $BF_{10} \geq 1.53 \times 10^7$. However, there was no significant Age x Type of Memory Probe interaction, $F(2, 328) = 1.31$, $p = .270$, $BF_{10} = 0.56$. Indeed, under the Bayesian model comparison, the winning model contained just the two main effects and no interaction, $P(M|data) = 0.87$, $BF_M = 27.69$.

At the 4s rate of presentation, there was a significant main effect of Age, $F(1, 164) = 6.05$, $p = .015$, $BF_{10} = 2.86 \times 10^3$, with younger adults outperforming older adults on the recognition task. There was also a significant main effect of Type of Memory Probe, $F(2, 328) = 157.74$, $p < .001$, $BF_{10} = 1.05 \times 10^{14}$, which was characterized by highest accuracy to Unrelated probes, intermediate accuracy to Intact probes, and lowest accuracy to Related probes, all pairwise comparisons significant, $p_{Holm} < .001$, all $BF_{10} \geq 956.84$. There was also a significant Age x Type of Memory Probe interaction, $F(2, 328) = 11.94$, $p < .001$, $BF_{10} = 5.00 \times 10^3$. Indeed, under the Bayesian model comparison, the winning model contained both main effects and their interaction, $P(M|data) = 0.999$, $BF_M = 5.00 \times 10^3$. To follow-up on the interaction, I conducted separate independent samples *t*-tests on each proportion correct to each memory probe. The only significant age difference at the 4s rate of encoding presentation was to Related probes, $t(164) = -5.21$, $p < .001$, $BF_{10} = 2.37 \times 10^4$, whereas there were no significant age differences to Intact probes, $t(164) = -0.83$, $p = .410$, $BF_{10} = 0.23$, or Unrelated probes, $t(164) = 0.31$, $p = .754$, $BF_{10} = 0.18$. Thus, age differences at the 4s rate were only present on those probes for which individuals would need to retrieve the most specific information without much environmental support, as the Related probes match originally studied representations only at a general but not specific level of representation.

Finally, comparing the slowest rates of encoding (older adults at the 6s rate compared with younger adults at the 4s rate), there was no significant main effect of Age, $F(1, 164) = 1.34$, $p = .249$, though the Bayesian analysis suggested there was strong evidence of an Age difference, $BF_{10} = 19.90$, with younger adults outperforming older adults. However, this main effect is qualified by the significant interaction noted below.

There was a significant main effect of Type of Memory Probe, $F(2, 328) = 144.75$, $p < .001$, $BF_{10} = \infty$, which was characterized by highest accuracy to Unrelated probes, intermediate accuracy to Intact probes, and lowest accuracy to Related probes, all pairwise comparisons significant, $p_{Holm} \leq .044$, though the Bayesian post-hoc tests revealed no credible difference in accuracy to Intact or Unrelated probes $BF_{10} = 0.61$, with the remaining contrasts yielding $BF_{10} \geq 3.34 \times 10^{23}$. There was also a significant Age x Type of Memory Probe interaction, $F(2, 328) = 8.70$, $p < .001$, $BF_{10} = 90.41$. Indeed, under the Bayesian model comparison, the winning model contained both main effects and their interaction, $P(M|data) = 0.96$, $BF_M = 90.41$. To follow-up on the interaction, I conducted separate independent samples *t*-tests on each proportion correct to each memory probe. The only significant age difference at the slowest rates (6s and 4s) of encoding presentation was to Related probes, $t(164) = -3.50$, $p < .001$, $BF_{10} = 42.02$, whereas there were no significant age differences to Intact probes, $t(164) = 1.17$, $p = .243$, $BF_{10} = 0.32$, or Unrelated probes, $t(164) = -0.37$, $p = .715$, $BF_{10} = 0.18$. Thus, even when older adults had more time to encode face-scene pairs than younger adults, age differences remained on those probes (Related probes) for which individuals would need to retrieve the most specific information without much environmental support.

To summarize the age comparisons on proportion correct, when young and older adults had only two seconds to encode face-scene pairs, age-related differences in proportion correct were present across all memory probes, including those pairs that matched originally studied pairs at neither a specific nor a general level of representation (Unrelated probes), which may suggest there were age deficits in general representations at the 2s rate that are not usually present with four seconds of encoding time. The MPT

analyses will be needed to verify if this is so. With four seconds to encode face-scene pairs, older adults showed typical deficits on Related probes, those probes which matched originally studied pairs only at a general but not specific level of representation and thus require an individual to retrieve specific representations with little environmental support from the memory probe. These age deficits in Related probes persisted even when older adults had more time to encode face-scene pairs (six compared to four seconds for younger adults). This may suggest that increases in encoding time among older adults may do little to offset their diminished specific representations for past episodes, or at any rate, the effects of encoding time may interact with retrieval processes, as detailed in the MPT analyses to follow.

Multinomial-Processing-Tree (MPT) Parameter Estimates in Experiments 1 and 2

Before diving into the MPT results, I first present in Tables 5 through 8 the average proportion of responses to each type of memory probe for young adults (Table 5 for Experiment 1, Table 6 for Experiment 2) and older adults (Table 7 for Experiment 1, Table 8 for Experiment 2) that were obtained under the different encoding rates, as the MPT model attempts to explain how participants arrived at these response proportions. Although the data in these table reflect group averages, as a reminder, the MPT model was fitted to the data at the group- and individual-level simultaneously under a hierarchical Bayesian estimation routine.

Table 5. *Average Proportion of "Intact," "Related," and "Unrelated" Responses to Each Memory Probe under Each Encoding Rate among Young Adults in Experiment 1*

Proportion	1s Rate	2s Rate	4s Rate
p ("Intact" | Intact) *	0.50 (0.03)	0.58 (0.03)	0.66 (0.04)
p ("Related" | Intact)	0.24 (0.02)	0.20 (0.03)	0.16 (0.02)
p ("Unrelated" | Intact)	0.26 (0.03)	0.22 (0.02)	0.18 (0.02)
p ("Intact" | Related)	0.33 (0.03)	0.30 (0.02)	0.23 (0.02)
p ("Related" | Related) *	0.39 (0.02)	0.47 (0.03)	0.51 (0.03)
p ("Unrelated" | Related)	0.28 (0.02)	0.24 (0.02)	0.26 (0.03)
p ("Intact" | Unrelated)	0.09 (0.02)	0.08 (0.01)	0.08 (0.02)
p ("Related" | Unrelated)	0.20 (0.02)	0.14 (0.02)	0.17 (0.03)
p ("Unrelated" | Unrelated) *	0.71 (0.03)	0.78 (0.03)	0.75 (0.03)

Note. Proportions are given as proportion (*p*) of a given response (in quotations) conditional on a given probe. Values are mean and standard error (in parentheses). * denotes the correct response to a given probe.

Table 6. *Average Proportion of "Intact," "Related," and "Unrelated" Responses to Each Memory Probe under Each Encoding Rate among Young Adults in Experiment 2*

Proportion	1s Rate	2s Rate	4s Rate
p ("Intact" | Intact) *	0.47 (0.03)	0.64 (0.03)	0.72 (0.03)
p ("Related" | Intact)	0.24 (0.02)	0.17 (0.02)	0.15 (0.02)
p ("Unrelated" | Intact)	0.29 (0.03)	0.19 (0.02)	0.13 (0.02)
p ("Intact" | Related)	0.31 (0.02)	0.29 (0.03)	0.28 (0.03)
p ("Related" | Related) *	0.41 (0.02)	0.48 (0.03)	0.53 (0.03)
p ("Unrelated" | Related)	0.27 (0.03)	0.23 (0.02)	0.20 (0.02)
p ("Intact" | Unrelated)	0.14 (0.03)	0.10 (0.02)	0.11 (0.03)
p ("Related" | Unrelated)	0.20 (0.02)	0.16 (0.02)	0.14 (0.02)
p ("Unrelated" | Unrelated) *	0.66 (0.03)	0.74 (0.04)	0.75 (0.04)

Note. Proportions are given as proportion (*p*) of a given response (in quotations) conditional on a given probe. Values are mean and standard error (in parentheses). * denotes the correct response to a given probe.

Table 7. *Average Proportion of "Intact," "Related," and "Unrelated" Responses to Each Memory Probe under Each Encoding Rate among Older Adults in Experiment 1*

Proportion	2s Rate	4s Rate	6s Rate
p ("Intact" | Intact) *	0.53 (0.03)	0.67 (0.03)	0.72 (0.03)
p ("Related" | Intact)	0.24 (0.02)	0.13 (0.02)	0.14 (0.02)
p ("Unrelated" | Intact)	0.24 (0.03)	0.20 (0.02)	0.14 (0.02)
p ("Intact" | Related)	0.42 (0.03)	0.43 (0.04)	0.37 (0.04)
p ("Related" | Related) *	0.37 (0.03)	0.38 (0.03)	0.41 (0.03)
p ("Unrelated" | Related)	0.22 (0.02)	0.19 (0.02)	0.22 (0.02)
p ("Intact" | Unrelated)	0.16 (0.03)	0.12 (0.03)	0.12 (0.03)
p ("Related" | Unrelated)	0.18 (0.03)	0.13 (0.02)	0.13 (0.02)
p ("Unrelated" | Unrelated) *	0.66 (0.03)	0.76 (0.03)	0.76 (0.04)

Note. Proportions are given as proportion (*p*) of a given response (in quotations) conditional on a given probe. Values are mean and standard error (in parentheses). * denotes the correct response to a given probe.

Table 8. *Average Proportion of "Intact," "Related," and "Unrelated" Responses to Each Memory Probe under Each Encoding Rate among Older Adults in Experiment 2*

Proportion	2s Rate	4s Rate	6s Rate
p ("Intact" | Intact) *	0.59 (0.03)	0.66 (0.03)	0.73 (0.03)
p ("Related" | Intact)	0.22 (0.02)	0.15 (0.02)	0.15 (0.02)
p ("Unrelated" | Intact)	0.19 (0.02)	0.19 (0.02)	0.12 (0.01)
p ("Intact" | Related)	0.44 (0.03)	0.45 (0.03)	0.37 (0.03)
p ("Related" | Related) *	0.34 (0.03)	0.33 (0.03)	0.42 (0.04)
p ("Unrelated" | Related)	0.22 (0.03)	0.22 (0.02)	0.21 (0.02)
p ("Intact" | Unrelated)	0.14 (0.02)	0.09 (0.02)	0.12 (0.02)
p ("Related" | Unrelated)	0.19 (0.02)	0.15 (0.03)	0.17 (0.02)
p ("Unrelated" | Unrelated) *	0.67 (0.03)	0.77 (0.03)	0.71 (0.03)

Note. Proportions are given as proportion (*p*) of a given response (in quotations) conditional on a given probe. Values are mean and standard error (in parentheses). * denotes the correct response to a given probe.

Young Adults. The MPT model from the simplified conjoint recognition paradigm (Stahl & Klauer, 2008) satisfactorily fit the data from the younger adults in both experiments, as indicated by good correspondence between the observed frequencies of responses in the data and those predicted by 1,000 posterior-predictive generated datasets (see Appendix A, Figure A1 and Figure A2). In Experiment 1, the posterior-predictive *p* (PPP) values for the T_1 statistics (indicating the convergence between the observed and predicted mean frequencies) and the T_2 statistics (indicating the convergence between the observed and predicted covariances) were all above the .05

criterion, ranging from a low of .052 (for the T_1 statistic obtained from the fit of the model to the 1s encoding rate) to .434 (for the T_2 statistic obtained from the fit of the model to the 4s encoding rate). Notably, the lower PPP value for T_1 at the 1s rate, which was just above the criterion of .05, was probably attributable to a slight, but not credible, overestimation of "related" responses to Related probes at the 1s rate, which can often occur when the observed proportion of "related" responses to Related probes is near chance (33% correct) because in this situation, the model-predicted estimate of the specific representation parameter V_r leads to a slightly higher prediction of "related" responses than may be observed in the data, as parameter V_r results in a correct "related" response. At both the 2s and 4s encoding rates, the PPP value for the T_1 statistic was much higher (PPP $\geq$ .323). In Experiment 2, all PPP $\geq$ .229, indicating satisfactory model fit in each encoding rate condition when fitted to the younger adults' data.

Population-level parameter estimates of the MPT model when fitted to the data of the younger adults are listed in Table 9. There was a striking similarity for each parameter obtained when fitted to the younger adult data from Experiment 1 (top panel of Table 9) and Experiment 2 (bottom panel of Table 9). To test whether there were any credible differences in the young adults' parameter estimates obtained from Experiment 1 and Experiment 2, for each parameter in each encoding rate condition, I subtracted the posterior samples of that parameter from the model fitted to the young adult data in Experiment 2 from the same parameter in the same encoding rate condition fitted to the young adult data in Experiment 1. Difference scores are listed in Table 10.

Table 9. *Young Adults' Population-Level Parameter Estimates of the MPT Model in Experiments 1 and 2*

Experiment 1			
Parameter	1s Rate	2s Rate	4s Rate
V_i	0.30 [0.19, 0.40]	0.43 [0.30, 0.55]	0.58 [0.45, 0.70]
V_r	0.02 [0.00, 0.08]	0.05 [0.00, 0.15]	0.07 [0.00, 0.21]
G_i	0.42 [0.24, 0.58]	0.46 [0.33, 0.58]	0.41 [0.22, 0.56]
G_r	0.57 [0.46, 0.67]	0.67 [0.58, 0.74]	0.61 [0.48, 0.72]
a	0.42 [0.36, 0.48]	0.42 [0.35, 0.51]	0.35 [0.27, 0.45]
b	0.28 [0.21, 0.34]	0.19 [0.13, 0.25]	0.21 [0.15, 0.28]
Experiment 2			
Parameter	1s Rate	2s Rate	4s Rate
V_i	0.25 [0.13, 0.35]	0.51 [0.41, 0.60]	0.60 [0.44, 0.73]
V_r	0.04 [0.00, 0.12]	0.04 [0.00, 0.14]	0.08 [0.00, 0.23]
G_i	0.37 [0.20, 0.52]	0.44 [0.30, 0.55]	0.58 [0.40, 0.73]
G_r	0.56 [0.44, 0.67]	0.64 [0.52, 0.74]	0.69 [0.56, 0.79]
a	0.44 [0.37, 0.50]	0.38 [0.31, 0.46]	0.39 [0.30, 0.49]
b	0.33 [0.27, 0.39]	0.21 [0.14, 0.29]	0.21 [0.14, 0.29]

Note. Estimates represent the group-level (i.e., "population-level") posterior mean [lower 2.5th percentile, upper 97.5th percentile] of each parameter. V_i = probability of remembering a specific representation when shown an Intact probe. V_r = probability of remembering a specific representation when shown a Related probe. G_i = probability of remembering a gist/general representation when shown an Intact probe. G_r = probability of remembering a gist/general

representation when shown a Related probe. *a* = probability of guessing "intact." *b* = probability of guessing either "intact" or "related"

Table 10. *Difference Scores (Experiment 1 minus Experiment 2) of Each Parameter under Each Encoding Rate among Young Adults*

Parameter	1s Rate	2s Rate	4s Rate
V_i	0.05 [-0.11, 0.20]	-0.08 [-0.23, 0.07]	-0.02 [-0.20, 0.18]
V_r	-0.02 [-0.11, 0.05]	0.01 [-0.11, 0.13]	-0.01 [-0.19, 0.16]
G_i	-0.05 [-0.18, 0.27]	0.03 [-0.15, 0.21]	-0.17 [-0.41, 0.06]
G_r	0.01 [-0.14, 0.17]	0.03 [-0.11, 0.17]	-0.08 [-0.25, 0.08]
a	-0.01 [-0.11, 0.08]	0.04 [-0.07, 0.15]	-0.04 [-0.17, 0.09]
b	-0.06 [-0.14, 0.03]	-0.02 [-0.13, 0.07]	0.00 [-0.10, 0.10]

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 obtained from fitting the model to the data in Experiment 2 from the posterior samples of the same parameter obtained from fitting the model to the data in Experiment 1. 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. V_r = probability of remembering a specific representation when shown a Related probe. G_i = probability of remembering a gist/general representation when shown an Intact probe. G_r = probability of remembering a gist/general representation when shown a Related probe. *a* = probability of guessing "intact." *b* = probability of guessing either "intact" or "related"

As listed in Table 10, none of the parameters credibly differed (difference detectable in >95% of posterior samples) between Experiments 1 and 2 among young

adults. Indeed, the mean difference scores were almost always near 0, with relatively equal mass in the 95% CI above and below 0, and in most cases, the proportion of posterior samples that were higher in Experiment 1 than in Experiment 2 was near 50%, indicating that about half of the time, a parameter was estimated to be higher in Experiment 1, whereas for the other approximately half of posterior samples, that parameter was estimated to be higher in Experiment 2. The one notable exception was for parameter G_i at the 4s rate, which was estimated to be higher among younger adults in Experiment 2 than in Experiment 1 in 93% of posterior samples, though this difference falls short of the criterion for concluding the presence of a credible difference, and the 95% CI's of the parameter overlap in both experiments, as listed in Table 9. Nevertheless, the overall pattern apparent in Table 10 is that, across the two experiments, similar estimates of each MPT parameter were obtained when the model was fitted to the data from younger adults.

Old Adults. In Experiment 1, PPP values for the T_1 and the T_2 statistics were all above the .05 criterion, all PPP $\geq$ .103. Indeed, as depicted in Figure A3 in Appendix A, there was close correspondence between the observed and posterior-predicted mean response frequencies.

In Experiment 2, at the 6s encoding rate, the model satisfactorily fit the data, with PPP = .140 for the T_1 statistic and PPP = .327 for the T_2 statistic. However, at both the 2s and 4s encoding rates, the model provided a poor fit to the mean response frequencies, with PPP = .014 and PPP = .000 for the T_1 statistic at the 2s and 4s encoding rates, respectively. As depicted in Figure A4 in Appendix A, the model overestimated the proportion of correct "related" responses to Related probes and underestimated the

proportion of erroneous "intact" responses to Related probes. A plausible reason for this is that the model assumes some non-zero probability that older adults at the 2s and 4s encoding rates relied upon specific representations (indexed by parameter V_r), leading them to correctly endorse Related probes as "related." Even though the estimate of this parameter was low and concentrated near 0 in the 2s (V_r = .015 [.00, .062]) and 4s (V_r = .016 [.00, .063]) conditions, the inclusion of this parameter in the model resulted in an overestimation of "related" responses. We have previously identified that this occurs when the observed proportion of "related" responses to Related probes is at or below chance (33% correct), and one solution is to constrain V_r to 0 (Greene & Naveh-Benjamin, 2022a, 2022b, 2022c, 2022d).

An undesirable aspect of constraining V_r to 0 is that it results in there being only one parameter that governs correct "related" responses to Related probes, specifically the complement of the guessing parameter a (i.e., the pathway $1 - a$ results in "related" responses). However, by constraining V_r to 0, the number of parameters to be estimated (five free parameters) is now less than the degrees of freedom imposed by the data (six degrees of freedom), which allows us to model additional processes that cannot be incorporated in the saturated (six parameter) structure of the model. Specifically, we can incorporate a different guessing tendency to endorse a probe as being "intact" rather than "related" in states in the model in which participants retrieve a gist/general representation versus in states in which participants fail to retrieve these representations or in situations in which the test probe does not match the gist of the originally studied information. That is, rather than assuming that participants adopt a uniform "guessing 'intact'" tendency (and, thus, a uniform "guessing 'related'" tendency), we can instead model a possible

situation in which, when participants respond on the basis of gist but not specific memory, they have a potentially stronger tendency to guess "intact" (rather than "related"), but when participants respond on the basis of neither gist nor specific memory, they are somewhat more uncertain and may have a stronger tendency to guess "related" rather than "intact." Thus, two separate guessing parameters for responding "intact" can be incorporated into the model. Parameter *a* is retained in all gist pathways, whereas parameter a_b is introduced into pathways where participants enter cognitive state *b* in the model. That is, a_b controls the guessing "intact" tendency when participants reach the state in the model that captures the possibility of "I do not remember this face being paired with this type of scene, but perhaps I am wrong." Essentially, we assume that $a = a_b$ in most instances, as we are not able to estimate separate parameters in the saturated model, but by constraining a parameter in the saturated model (as in setting V_r to 0), we can freely estimate both *a* and a_b.

When I constrained V_r to 0 and incorporated the a_b parameter in pathways involving parameter *b*, this modified model satisfactorily fit the older adult data in Experiment 2 at the 2s and 4s rates, with PPP $\geq$ .277. Indeed, as depicted in Figure A5 in Appendix A, the modified model performed much better at capturing the observed mean response frequencies in the data. Consequently, in the ensuing, the MPT estimates listed for the 2s and 4s encoding rates in Experiment 2 were obtained by fitting the modified model with V_r constrained to 0 and parameter a_b introduced.

Population-level parameter estimates of the MPT model when fitted to the data of the older adults are listed in Table 11. Difference scores between experiments are listed in Table 12. No between-experiment differences in parameter *a* at the 2s or 4s rates were

computed because there was a uniform *a* parameter in Experiment 1 at these rates but separate *a* parameters in Experiment 2 at these rates.

Table 11. *Old Adults' Population-Level Parameter Estimates of the MPT Model in Experiments 1 and 2*

Experiment 1			
Parameter	2s Rate	4s Rate	6s Rate
V_i	0.23 [0.10, 0.34]	0.49 [0.37, 0.59]	0.56 [0.42, 0.72]
V_r	0.02 [0.00, 0.08]	0.02 [0.00, 0.08]	0.02 [0.00, 0.08]
G_i	0.52 [0.40, 0.63]	0.44 [0.31, 0.55]	0.58 [0.42, 0.72]
G_r	0.66 [0.56, 0.75]	0.74 [0.68, 0.81]	0.68 [0.60, 0.75]
a	0.53 [0.45, 0.61]	0.55 [0.45, 0.66]	0.47 [0.38, 0.56]
b	0.32 [0.25, 0.39]	0.18 [0.12, 0.25]	0.20 [0.13, 0.28]
Experiment 2			
Parameter	2s Rate	4s Rate	6s Rate
V_i	0.28 [0.10, 0.44]	0.45 [0.29, 0.58]	0.57 [0.46, 0.68]
V_r	Constrained to 0	Constrained to 0	0.03 [0.00, 0.10]
G_i	0.53 [0.26, 0.70]	0.48 [0.32, 0.62]	0.59 [0.44, 0.72]
G_r	0.66 [0.56, 0.75]	0.70 [0.62, 0.77]	0.67 [0.57, 0.76]
a	0.62 [0.51, 0.74]	0.66 [0.55, 0.78]	0.50 [0.40, 0.60]
a_b	0.43 [0.33, 0.54]	0.37 [0.20, 0.55]	---
b	0.32 [0.25, 0.39]	0.20 [0.13, 0.27]	0.25 [0.17, 0.33]

Note. Estimates represent the group-level (i.e., "population-level") posterior mean [lower 2.5th percentile, upper 97.5th percentile] of each parameter. V_i = probability of remembering a specific representation when shown an Intact probe. V_r = probability of remembering a specific representation when shown a Related probe. G_i = probability of remembering a gist/general representation when shown an Intact probe. G_r = probability of remembering a gist/general representation when shown a Related probe. a = probability of guessing "intact" when gist is retrieved. a_b = probability of guessing "intact" in state b, in which gist has not been retrieved. b = probability of guessing either "intact" or "related"

Table 12. *Difference Scores (Experiment 1 minus Experiment 2) of Each Parameter under Each Encoding Rate among Older Adults*

Parameter	2s Rate	4s Rate	6s Rate
V_i	-0.05 [-0.25, 0.16]	0.04 [-0.14, 0.23]	-0.02 [-0.19, 0.15]
V_r	----	----	-0.01 [-0.09, 0.07]
G_i	-0.01 [-0.22, 0.28]	-0.05 [-0.23, 0.15]	-0.01 [-0.21, 0.20]
G_r	0.00 [-0.13, 0.13]	0.04 [-0.06, 0.14]	0.01 [-0.12, 0.13]
a	----	----	-0.03 [-0.17, 0.11]
b	0.00 [-0.10, 0.10]	-0.02 [-0.12, 0.08]	-0.05 [-0.15, 0.07]

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 obtained from fitting the model to the data in Experiment 2 from the posterior samples of the same parameter obtained from fitting the model to the data in Experiment 1. 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. V_r = probability of remembering a specific representation when shown a Related probe. G_i =

probability of remembering a gist/general representation when shown an Intact probe. G_r = probability of remembering a gist/general representation when shown a Related probe. a = probability of guessing "intact." b = probability of guessing either "intact" or "related"

As listed in Table 12, none of the parameters credibly differed (difference detectable in >95% of posterior samples) between Experiments 1 and 2 among older adults. Mean difference scores were almost always near 0 with relatively equal mass in the 95% CI above and below 0, and the proportion of posterior samples that were higher in Experiment 1 than in Experiment 2 were usually near 50% but never higher than 78% and well below the criterion of 95%. Thus, as with the younger adults, for the older adults, comparable estimates of the MPT parameters were obtained in Experiments 1 and 2. As a result, in the ensuing, I have combined the data from the two experiments such that the sample size that factors into the estimation of each parameter is doubled, leading to more precision in the estimation of each parameter (i.e., reduction in the width of the 95% CI).

MPT Results: Effects of Rate of Encoding among Young and Older Adults

Given the comparability in the MPT estimates obtained from Experiment 1 and 2 within each age group, I combined the data from both experiments and estimated the parameters of the model under each encoding rate separately using the combined data from 80 young and 86 older adults to increase the precision of the parameter estimates. In the young adult sample, the original simplified conjoint recognition model satisfactorily fit the data in each encoding rate condition, all PPP ≥ .071 (see Figure A6 in Appendix A). However, among older adults, the original model failed to capture the observed proportions of "related" and "intact" responses to Related probes under each encoding

rate (see Figure A7 in Appendix A), with all PPP ≤ .045 for the T_1 statistic. Therefore, I fit the modified model with V_r constrained to 0 and incorporating parameter a_b as a separate tendency to guess "intact" in cognitive state *b*. This modified model satisfactorily fit the older adult data in each encoding rate (see Figure A8 in Appendix A), all PPP ≥ .358. Table 13 lists the population-level parameter estimates for the combined datasets of younger adults (top panel) and older adults (bottom panel) under each encoding rate.

Young Adults. For young adults, I tested whether each of the memory parameters differed between the 1s and 2s rates (2s minus 1s), between the 2s and 4s rates (4s minus 2s), and between the 1s and 4s rates (4s minus 1s), to measure changes in specific or general memory representations with increases in encoding time. Difference scores are listed in Table 14, and Figure 9 provides a visual depiction. For the specific representation parameter V_i, there were credible increases in the estimate of this parameter with increases in the encoding duration, all difference scores indicated a higher estimate of V_i under the slower than the faster encoding rate in >95% of posterior samples. However, increases in the specific representation parameter V_r were not credibly observed with increases in the encoding rate, as the percentage of posterior samples that were larger in the slower than faster rate of encoding were only 63.8% (2s > 1s), 72.6% (4s > 2s), and 82.8% (4s > 1s). Although each difference score indicated a higher percentage of posterior samples were larger under the slower than faster rate of presentation at encoding, as shown in Figure 9, estimates of V_r were largely concentrated at 0 under each rate of encoding, though under the 4s rate, more than 99.9% of posterior samples exceeded 0.

Table 13. *Young and Older Adults' Population-Level MPT Parameter Estimates under Each Encoding Rate Combined Across Experiments 1 and 2*

Young Adults				
Parameter	1s Rate	2s Rate	4s Rate	6s Rate
V_i	0.28 [0.21, 0.36]	0.48 [0.40, 0.55]	0.60 [0.51, 0.68]	-----
V_r	0.01 [0.00, 0.05]	0.03 [0.00, 0.09]	0.06 [0.002, 0.16]	-----
G_i	0.40 [0.28, 0.50]	0.45 [0.37, 0.53]	0.49 [0.37, 0.60]	-----
G_r	0.58 [0.50, 0.64]	0.67 [0.60, 0.73]	0.66 [0.57, 0.74]	-----
a	0.42 [0.38, 0.46]	0.38 [0.34, 0.44]	0.35 [0.29, 0.42]	-----
b	0.30 [0.26, 0.34]	0.20 [0.15, 0.24]	0.21 [0.12, 0.25]	-----
Old Adults				
Parameter	1s Rate	2s Rate	4s Rate	6s Rate
V_i	-----	0.23 [0.11, 0.33]	0.48 [0.38, 0.56]	0.56 [0.46, 0.65]
V_r	-----	Constrained to 0	Constrained to 0	Constrained to 0
G_i	-----	0.54 [0.44, 0.62]	0.47 [0.37, 0.55]	0.59 [0.48, 0.69]
G_r	-----	0.66 [0.59, 0.72]	0.73 [0.68, 0.77]	0.68 [0.62, 0.74]
a	-----	0.60 [0.53, 0.67]	0.60 [0.53, 0.68]	0.51 [0.44, 0.60]
a_b	-----	0.44 [0.35, 0.53]	0.39 [0.27, 0.52]	0.34 [0.24, 0.44]
b	-----	0.32 [0.27, 0.37]	0.19 [0.14, 0.24]	0.22 [0.17, 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. V_i = probability of remembering a specific representation when shown an Intact probe. V_r = probability of remembering a specific representation when shown a Related probe. G_i = probability of remembering a gist/general representation when shown an Intact probe. G_r = probability of remembering a gist/general

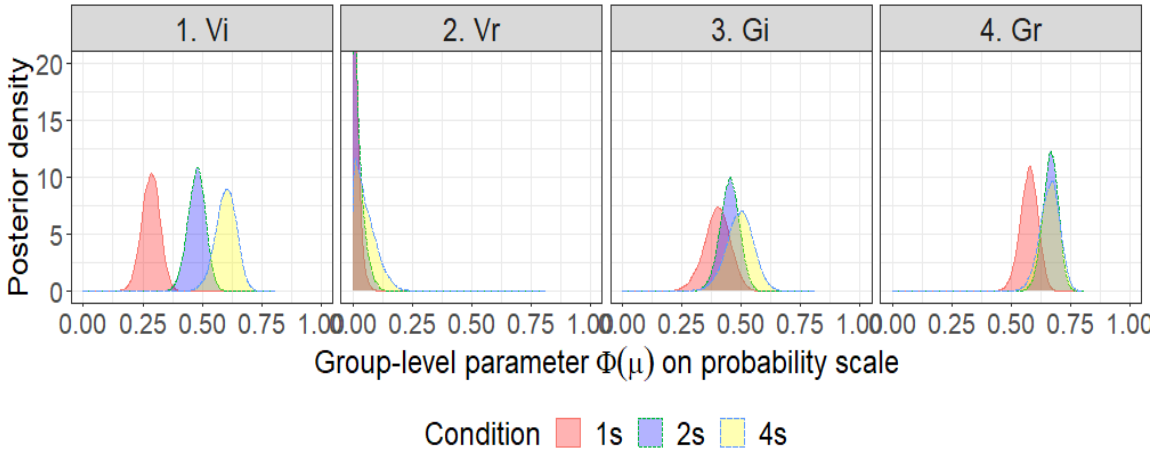
representation when shown a Related probe. a = probability of guessing "intact" when gist is retrieved. a_b = probability of guessing "intact" in state b, in which gist has not been retrieved. b = probability of guessing either "intact" or "related"

Table 14. *Difference Scores in the Specific and Gist Memory Parameters Across the Encoding Rates Among Young Adults*

Parameter	Differences Between Encoding Rates		
	2s – 1s	4s – 2s	4s – 1s
V_i	**0.19 [0.09, 0.30]**	**0.12 [0.01, 0.24]**	**0.32 [0.20, 0.43]**
V_r	0.01 [-0.04, 0.08]	0.03 [-0.06, 0.15]	0.04 [-0.03, 0.15]
G_i	0.07 [-0.08, 0.19]	0.04 [-0.10, 0.18]	0.10 [-0.06, 0.26]
G_r	**0.09 [-0.01, 0.19]**	-0.00 [-0.11, 0.10]	0.09 [-0.02, 0.20]*

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 obtained under a faster presentation rate of encoding from the posterior samples of that parameter obtained under a slower encoding rate. 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. V_r = probability of remembering a specific representation when shown a Related probe. G_i = probability of remembering a gist/general representation when shown an Intact probe. G_r = probability of remembering a gist/general representation when shown a Related probe. *93.7% of posterior samples were higher under the 4s than 1s rate for parameter G_r.

Figure 9. *Posterior Densities of Specific and General Memory Parameters as a Function of Rate of Encoding Among Young Adults*



Note. 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. Each parameter has been transformed from a latent probit scale to a natural probability scale, such that the x-axis for each parameter ranges from 0 to 1. Condition describes the rate of encoding in seconds (s). Vi = probability of remembering a specific representation when shown an Intact probe. Vr = probability of remembering a specific representation when a shown a Related probe. Gi = probability of remembering a general representation when shown an Intact probe. Gr = probability of remembering a general representation when shown a Related probe.

For the two general representation parameters (G_i and G_r), there were no credible improvements (in >95% of posterior samples) in G_i with increases in the encoding duration among younger adults, with the proportion of posterior samples that were larger under the slower than the faster rate in each comparison falling short of the 0.95 criterion: 0.776 (2s > 1s), 0.729 (4s > 2s), and 0.885 (4s > 1s). Notably, the comparison of the 4s to the 1s rates falls just short of the "hard black-and-white" decision metric of 95%

separation in the posterior distributions. As depicted in Figure 9, the posterior densities of G_i substantially overlapped under each encoding rate, though there appears to be a slight shift toward higher estimates of G_i at the 4s compared to the 1s rate, which is apparent in that 88.5% of posterior samples of G_i were higher at the 4s rate than the 1s rate. For parameter G_r, a somewhat clearer picture emerges: this parameter was credibly larger in 96.7% of posterior samples under the 2s than the 1s rate, but it was about equivalent between the 2s and 4s rates (48.1% of samples were larger under the 4s than the 2s rate). Comparing the 4s to the 1s rates, 93.7% of posterior samples of G_r were larger under the 4s rate, which is just shy of the 95% criterion recommended by Smith and Batchelder (2010). Nevertheless, the visual depiction in Figure 9 clearly shows that the distributions of G_r practically overlaid each other at the 2s and 4s rates and in both instances were higher than the distribution of this parameter obtained at the 1s rate.

To summarize, among young adults, there were consistent increases in one specific representation parameter (V_i) with increases in the encoding time, such that specific representations continue to be fleshed out with more time to encode the face-scene pairs. Although this was not maintained for the other specific representation parameter (V_r), estimates of that parameter were low under each encoding rate. For the general representation parameters, there were clearly no credible differences between the intermediate (2s) and slow (4s) rates of encoding, such that the gist of an episode established within two seconds of encoding time was comparable to that established within four seconds of encoding time. However, the gist established within one second of encoding time was less than that available at longer encoding times, though the magnitude of these differences depended in part on the nature of the memory probe

(Intact versus Related pairs), as estimates of G_i (gist for Intact probes) were more comparable between the 1s and 2s rates than between the 1s and 4s rates, whereas estimates of G_r (gist for Related probes) were lower at the 1s than at either the 2s or 4s rates.

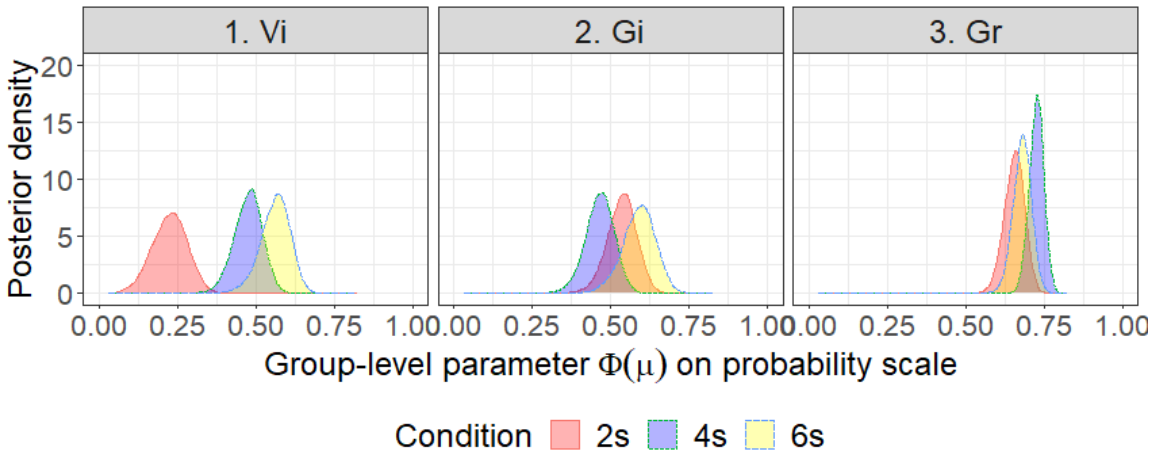
Old Adults. Difference scores for each memory parameter (excluding V_r as it was constrained to 0 under each encoding rate) for (1) the 4s minus the 2s rate, (2) the 6s minus the 4s rate, and (3) the 6s minus the 2s rate among older adults are listed in Table 15. Figure 10 provides a visual depiction.

Table 15. *Difference Scores in the Specific and Gist Memory Parameters Across the Encoding Rates Among Older Adults*

Parameter	Differences Between Encoding Rates		
	4s – 2s	6s – 4s	6s – 2s
V_i	**0.25 [0.11, 0.39]**	0.09 [-0.05, 0.21]	**0.34 [0.19, 0.48]**
G_i	-0.07 [-0.20, 0.06]	**0.12 [-0.01, 0.26]**	0.05 [-0.09, 0.19]
G_r	**0.07 [-0.01, 0.15]**	-0.05 [-0.12, 0.03]	0.03 [-0.06, 0.11]

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 obtained under a faster presentation rate of encoding from the posterior samples of that parameter obtained under a slower encoding rate. 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. G_i = probability of remembering a gist/general representation when shown an Intact probe. G_r = probability of remembering a gist/general representation when shown a Related probe.

Figure 10. *Posterior Densities of Specific and General Memory Parameters as a Function of Rate of Encoding Among Older Adults*



Note. 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. Each parameter has been transformed from a latent probit scale to a natural probability scale, such that the x-axis for each parameter ranges from 0 to 1. Condition describes the rate of encoding in seconds (s). Vi = probability of remembering a specific representation when shown an Intact probe. Gi = probability of remembering a general representation when shown an Intact probe. Gr = probability of remembering a general representation when shown a Related probe.

There was a credible improvement in the specific representation parameter V_i from the fast (2s) to the intermediate (4s) encoding rate of presentation, and between the 2s and slow (6s) encoding rates, with both difference scores indicating higher estimates of V_i under the slower rate in >95% of posterior samples. The difference between the 4s and 6s rates fell short of the 95% criterion but was still present in 90.7% of posterior

samples being larger under the 6s than the 4s rate. Thus, increases in the encoding duration resulted in improvements in specific representations among older adults.

Differences in the general representation parameters with increases in encoding duration for older adults did not have a consistent pattern. Specifically, for parameter G_i, this parameter was unintuitively estimated to be slightly lower at the intermediate (4s) rate than the fast (2s) rate, with 85.8% of posterior samples of G_i being larger in the 2s than the 4s rate. Although this difference falls short of the 95% criterion, it does complicate any interpretation of the credible difference in G_i between the 6s and 4s rates, as G_i was estimated to be higher at the 6s rate in 96.0% of posterior samples. That is, although there appeared to be an improvement in gist memory indexed by parameter G_i between four and six seconds of encoding time, this likely reflected some randomness in the data from rate-to-rate, given that the difference between the 6s and the 2s rates was only present in 78.5% of posterior samples. For parameter G_r, it was also unclear whether increases in this parameter with encoding duration reflected reliable improvements with longer time to encode the face-scene pairs or were attributable to random variation in response accuracy among older adults under the different encoding rates. That is, G_r was found to be credibly larger under the 4s than the 2s rate of encoding in 96.5% of posterior samples, but was also unexpectedly larger under the 4s than the 6s rate of encoding in 89.4% of posterior samples. Framed another way, there was an initial increase in the gist memory parameter G_r from two to four seconds of encoding time, but a slight drop in the estimate of this parameter from four to six seconds of encoding time. As a result, there was no credible difference in G_r between the 6s and the 2s rates, with only 71.9% of posterior samples being larger under the 6s rate.

To summarize, among older adults, there were increases in the specific representation parameter (V_i) with increases in the encoding time, though the increase from the intermediate (4s) to the slow (6s) rates fell just shy of the criterion to conclude the presence of a credible difference. Nevertheless, these data indicate that longer time to encode the face-scene pairs resulted in older adults encoding more well-fleshed out specific representations, especially as the estimate of V_i was higher under both the 4s and 6s rates than the 2s rate. For the general representation parameters, there were fluctuations based on rate of encoding, which do not fall naturally out of any theoretical model, in that gist representations were sometimes more well-established under shorter than longer encoding rates. These abnormal patterns were primarily driven by either unexpectedly smaller values of a gist parameter at the intermediate than the fast rate or by unexpectedly larger values of a gist parameter at the intermediate than the slow rate of encoding. However, concentrating on the extreme ends (the 2s and 6s rates), there were no credible increases in gist representations formed within two and six seconds of encoding time.

MPT Results: Age Differences in Specific and Gist Representations

Three sets of comparisons were conducted on the parameters V_i, G_i, and G_r (V_r was excluded as it was constrained to 0 among older adults, though it is worth noting that the percentage of posterior samples of V_r among young adults that were estimated to be larger than 0 was found to be >99% at both the 2s and 4s rates of encoding). I compared the estimates of each parameter (young minus older adults) at the shared 2s and 4s rates of encoding and for older adults at the 6s rate compared with younger adults at the 4s

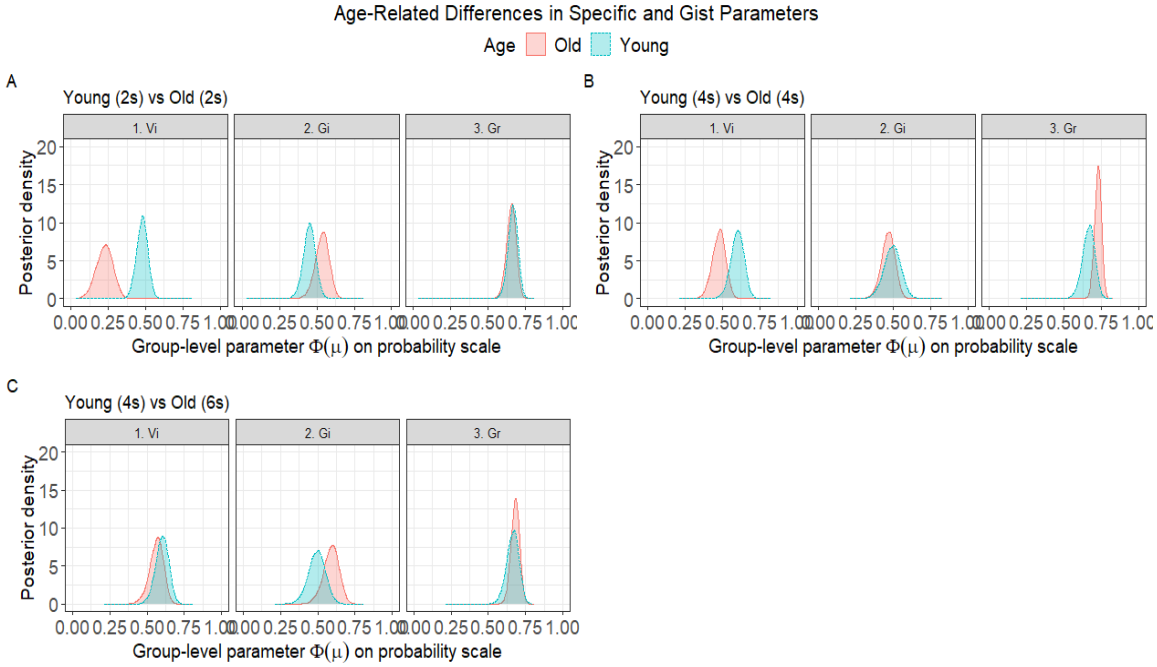
rate. The difference scores are listed in Table 16, and Figure 11 provides a visual depiction.

Table 16. *Age-Related Differences Scores in the Specific and Gist Memory Parameters under Different Encoding Rates*

Parameter	Young 2s – Old 2s	Young 4s – Old 4s	Young 4s – Old 6s
V_i	**0.25 [0.12, 0.38]**	**0.12 [-0.00, 0.25]**	0.04 [-0.09, 0.17]
G_i	-0.09 [-0.21,0.04]	0.03 [-0.12, 0.17]	-0.10 [-0.25, 0.06]
G_r	0.01 [-0.09, 0.10]	-0.06 [-0.16, 0.03]	-0.02 [-0.13, 0.08]

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 obtained among older adults at a specified encoding rate (2s, 4s, or 6s) from those of younger adults obtained at either the 2s or 4s encoding rate. 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. G_i = probability of remembering a gist/general representation when shown an Intact probe. G_r = probability of remembering a gist/general representation when shown a Related probe.

Figure 11. *Posterior Densities of Specific and General Memory Parameters for Young and Older Adults under Different Encoding Rates*



Note. 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. Each parameter has been transformed from a latent probit scale to a natural probability scale, such that the x-axis for each parameter ranges from 0 to 1. Condition describes the rate of encoding in seconds (s). Vi = probability of remembering a specific representation when shown an Intact probe. Gi = probability of remembering a general representation when shown an Intact probe. Gr = probability of remembering a general representation when shown a Related probe.

As indicated in Table 16, the only credible age-related differences were in parameter V_i, which were obtained at the 2s and 4s encoding rates, but not at the 6s vs 4s encoding rate for old and young adults, respectively. Estimates of V_i were higher among young than older adults in 100% and 97.3% of posterior samples at the 2s and 4s rates,

respectively, but only in 72.0% of posterior samples at the slowest rates (4s for young and 6s for older adults). There were no credible age-related differences (difference detectable in >95% of posterior samples) in either of the gist parameters under any of the rate comparisons, though there were a couple instances where the gist parameter for *older adults* appeared to be marginally larger than the estimate of the same parameter for younger adults (see Figure 11). Specifically, at the 2s rate, estimates of G_i were higher among older than younger adults in 91.2% of posterior samples; at the 4s rate, estimates of G_r were higher among older than younger adults in 91.3% of posterior samples; and at the 6s versus the 4s rate, estimates of G_i were higher among older than younger adults in 89.0% of posterior samples. Nevertheless, in no instances were there credible age-related *deficits* in the gist memory parameters, with younger adults having credibly higher estimates of these parameters than older adults.

To summarize, the age-related deficit in the specific representation parameter V_i obtained at the 4s rate replicates what has traditionally been found in this paradigm (Greene & Naveh-Benjamin, 2020, 2022a) and was also found to be present at the 2s rate. However, this age-related deficit was no longer credible when older adults had more time to encode face-scene pairs (six compared to four seconds for younger adults). Although this may suggest that increases in encoding time result in older adults having as well fleshed out of specific representations as younger adults, the picture is clearly more nuanced, as I will discuss in the next chapter, as estimates of the other specific representation parameter V_r were so low that they had to be constrained to 0 among older adults even at the 6s rate, whereas for younger adults, >99% of posterior samples of V_r exceeded 0 at the 2s and 4s rates. Finally, older adults' general representations were at

least on par with, and perhaps slightly better than, those of younger adults, replicating the past studies that have shown no age-related deficit in general representations (e.g., Greene & Naveh-Benjamin, 2020).

Correlations Between RT Tasks and Individual Estimates of Specific and Gist Memory

Finally, I conducted correlational analyses to test whether participants' RT on the Deary-Liewald SRT and CRT tasks, and their accuracy on the CRT task, correlated with their individual-level posterior means of the specific and general memory parameters. To do so, I extracted for each individual, their central estimate (posterior mean) of parameters V_i, V_r (for young adults only), G_i, and G_r from the hierarchical Bayesian MPT model under each encoding rate. Table 17 lists the average RT on the SRT and CRT tasks and the average proportion correct in the four-choice discrimination CRT task for young and older adults.

Table 17. *Descriptive Statistics for Simple and Choice Reaction Time Tasks*

Age Group	SRT RT	CRT RT	CRT % Correct
Young Adults	284.82 (42.02)	458.35 (94.60)	95.5% (4.3%)
Older Adults	357.47 (206.91)	732.49 (403.48)	97.2% (3.5%)

Note. Values are mean (SD). For the RT, values are listed in milliseconds. RT = reaction time. SRT = Simple reaction time. CRT = Choice reaction time. The CRT task was a four-choice discrimination task. % Correct denotes the proportion of correct discriminations on the CRT task.

As indicated in Table 17, younger adults responded more rapidly than older adults on both tasks, which is not surprising. A formal statistical comparison using Welch's *t*-

tests to correct for the violation of unequal error variances for young and older adults supported this claim, with significant age-related differences in RT on both the SRT, $t(91.34) = 3.17$, $p = .002$, and the CRT, $t(94.99) = 6.12$, $p < .001$. However, older adults were slightly more accurate on the CRT task, $t(152.34) = 2.80$, $p = .006$.

Table 18 lists all pairwise Pearson's *r* correlations between the three Deary-Liewald RT measures and the specific and general memory parameters obtained under each encoding rate (1s, 2s, and 4s) for younger adults. Table 19 lists these correlations for older adults at the 2s, 4s, and 6s encoding rates. Among young adults, all listed correlations were negative, and there were numerous statistically significant correlations. In particular, at the 1s rate of encoding, longer RT on both the SRT and CRT was generally associated with lower estimates of each specific and gist memory parameter. However, at the 2s rate, the only significant relationship was between RT on the SRT task and parameter G_i, and at the 4s rate, longer RTs on the SRT but not the CRT were associated with lower estimates of all memory parameters. In general, among younger adults, RT on the SRT task was most highly correlated with estimates of specific and gist memory, with longer RTs being associated with lower estimates of specific and gist memory. That is, for younger adults, slower processing speed was associated with lower estimates of specific and gist memory.

Table 18. *Pearson Correlations Between RT Tasks and Specific and Gist Memory Parameters among Young Adults*

Parameter (Rate)	SRT_RT	CRT_RT	CRT_% Correct
V_i (1s)	-0.28*	-0.28*	-0.12
V_r (1s)	-0.19	-0.25*	-0.20
G_i (1s)	-0.26*	-0.24*	-0.10
G_r (1s)	-0.27*	-0.24*	-0.10
V_i (2s)	-0.21	-0.21	-0.11
V_r (2s)	-0.11	-0.05	-0.15
G_i (2s)	-0.24*	-0.21	-0.09
G_r (2s)	-0.20	-0.19	-0.01
V_i (4s)	-0.32**	-0.21	-0.08
V_r (4s)	-0.35**	-0.23*	-0.04
G_i (4s)	-0.33**	-0.20	-0.03
G_r (4s)	-0.32**	-0.22	-0.02

Note. * = $p < .05$; ** = $p < .01$. SRT _RT= simple reaction time (RT) in milliseconds. CRT_RT = choice reaction time (RT) in milliseconds. CRT_% Correct = proportion correct on CRT task. V_i = probability of remembering a specific representation when shown an Intact probe. V_r = probability of remembering a specific representation when shown a Related probe. G_i = probability of remembering a general representation when shown an Intact probe. G_r = probability of remembering a general representation when shown a Related probe.

Table 19. *Pearson Correlations Between RT Tasks and Specific and Gist Memory Parameters among Older Adults*

Parameter (Rate)	SRT_RT	CRT_RT	CRT_% Correct
V_i (2s)	-0.09	-0.04	0.18
G_i (2s)	-0.09	-0.08	0.16
G_r (2s)	-0.18	-0.10	0.12
V_i (4s)	-0.04	0.01	0.04
G_i (4s)	-0.15	-0.09	-0.00
G_r (4s)	-0.22*	-0.16	0.02
V_i (6s)	-0.13	-0.12	0.04
G_i (6s)	-0.20	-0.19	0.06
G_r (6s)	-0.18	-0.20	0.00

Note. * = $p < .05$; ** = $p < .01$. SRT _RT= simple reaction time (RT) in milliseconds. CRT_RT = choice reaction time (RT) in milliseconds. CRT_% Correct = proportion correct on CRT task. V_i = probability of remembering a specific representation when shown an Intact probeG_i = probability of remembering a general representation when shown an Intact probe. G_r = probability of remembering a general representation when shown a Related probe.

However, among older adults, there was only one significant correlation, occurring between RT on the SRT task and the estimate of G_r obtained at the 4s rate of encoding. Thus, whereas there were generally negative relationships between young adults' RT on the SRT task and their estimates of specific and gist memory, and some negative relationships with their RT on the CRT task as well, among older adults, RT on these tasks was usually not significantly related to their estimates of specific and gist

memory. In other words, individual differences in processing speed among older adults were not majorly related to individual differences in specific and gist memory.

CHAPTER 4

GENERAL DISCUSSION

The primary aim of the present study was to map out the time course under which both young and older adults can establish specific and general representations of complex associations during encoding, thus enabling an assessment of whether speed of processing differences at encoding may explain, at least in part, why older adults' episodic memory representations are less specific in detail than those of younger adults. Specifically, building on the recent theoretical framework of Greene and Naveh-Benjamin (2023), and inspired by processing speed theories of aging that attribute age-related deficits in numerous faculties of cognition, including episodic memory, to slower cognitive processing speeds (Salthouse, 1996; but see Ratcliff et al., 2004), I manipulated how much time young and older adult participants had to encode face-scene pairs in the associative specificity recognition task on which age deficits in specific but not general representations have been documented in the past (Greene & Naveh-Benjamin, 2020, 2022a; Greene et al., 2022). In these previous studies, older adults had the same amount of time to encode face-scene pairs – four seconds per pair – as younger adults, which may not be enough time for older adults to establish a specific representation of the associations as well as younger adults.

In the present study, across two experiments, I included three rates of presentation at encoding for young and for older adults, including a speeded rate of presentation, an intermediate rate of presentation, and a slow rate of presentation. For younger adults, these rates corresponded to one-, two-, or four-seconds of encoding time, whereas for older adults, these rates corresponded to two-, four-, or six-seconds of encoding time.

Thus, at the slowest rate, older adults had *more time* to encode the face-scene pairs than their younger counterparts, allowing me to assess whether, at this longer encoding duration, older adults could encode specific representations that would be on par, by the time of long-term memory (LTM) testing, as those formed by younger adults under shorter (i.e., four seconds) encoding durations. Moreover, by including fast, intermediate, and slow rates of presentation at encoding for both young and older adults, the present study was able to measure, within each age group, whether specific and/or general representations formed under shorter encoding rates were already on par with those formed under longer encoding rates and if there were any differences in the rates at which each type of representation form. Indeed, leading theories of episodic memory representations like fuzzy-trace theory (Brainerd & Reyna, 1990, 2004) predict more rapid formation of gist/general than specific representations, but no prior studies have assessed whether this is so for older adults as it may be for younger adults.

To test these aims, during the retrieval phase, I employed conjoint recognition tests (see Brainerd et al., 1999; Stahl & Klauer, 2008), in which participants discriminated intact/old face-scene pairs from related lure pairs (which retained the gist but not specific representation of the original pair) and from unrelated pairs (which retained neither the specific nor the gist representation of the original pair). By crossing three types of memory probes with three types of recognition responses, I was able to mathematically estimate the contributions of specific and general memory representations, independent of response biases, and to compare estimates of these representations (1) across the different encoding rates within a given age group, and (2) between young and older adults at various rates of encoding by relying on empirically-

validated multinomial-processing-tree (MPT) models of specific and gist memory (Stahl & Klauer, 2008).

Principal Findings

Differential Rates of Encoding Specific and Gist Representations. Among younger adults, there were clear and consistent increases in specific representations (remembering specifically which scene was associated with a particular face) with increases in the encoding duration, though these increases were also dependent in part on the type of memory probe provided during the LTM test, a point I will elaborate on in the ensuing discussion. At the same time, increases in gist/general representations (remembering in general what type of scene – e.g., whether it was a park scene or another type of scene, but not remembering specifically which park scene – had been associated with a given face) with increases in the encoding duration were modestly observed from one- to two-seconds or one- to four-seconds of encoding time, with no further improvements from two- to four-seconds of encoding time among younger adults. As with the specific representations, these encoding rate effects on general representations were influenced by the type of LTM test probe, but the picture for younger adults clearly shows differential rates of formation at encoding of specific and general representations of visual episodic associations. General representations are laid down more rapidly, in that there is no further observable increase in the probability of later accessing these representations in the LTM tests between two- and four-seconds of encoding time, whereas increases in the probability of later accessing specific representations in the LTM tests do occur with increases from two- to four-seconds of encoding time.

Among older adults, as with younger adults, there were generally increases in specific representations with increases in encoding time, which were observable in that the probability of later accessing specific representations in the LTM tests increased from two- to four-second of encoding time and from two- to six-seconds of encoding time, though the difference between the four- and six-seconds was more modest and not statistically credible by the standards set by Smith and Batchelder (2010). There was still an indication of a positive increase in the majority of posterior samples of the specific representation parameter V_i from the fitted MPT model from four- to six-seconds of encoding time. However, the increase in specific representations with increases in encoding time was influenced by the nature of the memory probe in the LTM tests. For general representations, the picture with older adults is a bit hazy, as there were some fluctuations in the probability of later accessing these representations across the different encoding rates. Specifically, estimates of gist memory parameters of the MPT model were sometimes unexpectedly lower at the intermediate (four-second) rate than at the fast (two-second rate) or unexpectedly higher at the four-second than the six-second rate. Nevertheless, there were no credible differences between the two- and six-second rates, which suggests that there were no consistently maintained increases in general representations with increases in encoding time among older adults. Thus, the overall pattern for older adults is strikingly on par with that for younger adults, in that specific representations form at a more protracted rate than that under which general representations of complex visual episodic associations are formed during encoding.

Age-Related Deficits in Specific Representations May in Part Be Due to Slower Processing Speed. Concerning age-related differences in specific and general

memory representations, replicating the previous studies that largely motivated the present study (Greene & Naveh-Benjamin, 2020, 2022a), there were no credible age-related deficits in the gist memory parameters of the MPT model. That is, older adults' estimates of gist/general memory were on par with those of younger adults not only at the standard four-second encoding rate used in the previous studies, but also at the faster two-second encoding rate. In fact, rather than an age-related *deficit* in general representations, the data speak more to the possibility that older adults may have had more well-established general representations than those of younger adults.

But what of specific representations? As in previous studies, at the encoding rates that were common to both young and older adults, namely the two- and four-second rates, there was the typical age-related deficit in the probability of remembering specific details of face-scene pairs. However, when older adults had *more time* to encode these pairs, up to six seconds compared with four seconds for younger adults, these age-related deficits disappeared, suggesting that speed of processing differences may play a major contributing role in accounting for age-related differences in specific episodic memory representations.

As with most of science, however, the picture is much more nuanced. That is, we must also factor in the nature of the memory probe itself. Specifically, we must consider how much environmental support is provided in the retrieval cue to aid in older adults' ability to access specific representations as well as younger adults. In the present study, the nature of the memory probe itself played an important role, not yet discussed, in influencing whether there were encoding rate increases in specific (or general) memory representations and whether older adults could access specific representations as well as

younger adults. When participants were shown Intact test pairs, which were an exact reproduction of originally studied pairs (i.e., the same face paired with the same scene from an earlier study trial), there were increases in the probability of accessing specific representations at retrieval with increases in the encoding duration for both young and older adults. By six seconds of encoding time for older adults compared with four seconds for younger adults, age-related differences in the probability of accessing specific representations were no longer statistically credible. Intact probes are quite effective retrieval cues for an episode's specific representation because they provide a "lock-and-key" match with such representations in that they are an exact match (Brainerd et al., 1999, 2019; see encoding-specificity principle; Tulving & Thomson, 1973).

When participants were shown Related pairs, which match an original pair only at a general but not at a specific level of representation (e.g., a young man's face was studied with a lake scene but was tested with a different lake scene), the probability of accessing specific representations of the originally studied pair (e.g., "the young man was paired with the *other* lake scene, not this one") was low for both young and older adults. This is perhaps not too surprising given that Related probes are stronger elicitors of gist than specific memory representations (Brainerd et al., 2019; Stahl & Klauer, 2008) and estimates of the specific representation parameter for Related probes is often found to be quite low, ranging from near 0 to ~0.15 on the proportion scale (Brainerd et al., 2022a; Stahl & Klauer, 2008). However, for older adults, estimates of the probability of accessing specific representations in this situation, in which the test pair was a Related probe, were so highly concentrated at 0 that including a specific representation parameter in the MPT model resulted in a misfit to the older adults' data. Consequently, I

constrained the estimate of this specific representation parameter (V_r for the probability of remembering a specific/verbatim representation when shown a Related probe) to 0 in fitting the model to the older adults' data. Importantly, this constraint was required at each encoding rate, even up to six seconds of encoding time, such that, even with longer time to encode the face-scene pairs, when the test cue was only a *partial match* to the originally studied pair, older adults were still highly unlikely to access specific representations of the original pair. For younger adults, estimates of the V_r parameter were also quite low, but by two- and four-seconds of encoding time, more than 99% of posterior samples of this parameter exceeded 0. Thus, even though younger adults were not responding often to Related probes on the basis of remembering a specific representation of the original pair, they were clearly doing so more often than older adults. These findings have theoretical implications, to be discussed at length in the ensuing section.

Additional Findings of the Present Study. The type of memory probe also influenced the presence of rate of encoding effects on the general representation parameters. As a reminder, the rate effects on the general representation parameters were most noticeable for younger adults, in that there were improvements from the fastest (one-second) to the slowest (four-seconds) presentation rate at encoding, whereas for older adults, there were no improvements from the fastest (two-seconds) to the slowest (six-seconds) encoding rates. Among younger adults, these rate of encoding effects were most noticeable on estimates of the general representation parameter (G_r) for responding to Related probes. The probability of accessing general representations when the test pair was a Related probe was lower at the one-second than the two- and four-second rates.

When the test probe was an Intact pair, there were positive increases in the probability of accessing general representations (parameter G_i from the MPT model) with increases in the encoding rate, though none of the differences were credible in >95% of posterior samples. In other words, the rate effects on gist representations were most noticeable for Related probes, which are strong elicitors of gist but not specific memory representations (Brainerd et al., 2019), while the rate effects on specific memory representations were most noticeable for Intact probes, which are strong elicitors of specific more than gist memory representations (Brainerd et al., 2019).

Another finding of the present study was that differences in the nature of the interpolated activity task between the encoding and retrieval phases of the primary memory task did not materially influence participants' recognition accuracy nor their underlying memory representations. In both experiments of the present study, the interpolated activity task involved verifying whether simple addition or multiplication arithmetic problems were solved correctly or incorrectly. The length of this task varied based on the rate of encoding during the primary memory task to ensure that the average amount of time any given face-scene pair would have to be maintained in memory before being tested on would be equal across the various encoding rates (cf. Greene & Naveh-Benjamin, 2022d). In Experiment 1, participants could respond to as many arithmetic problems as possible within the designated length of the interpolated activity, which was always longer in blocks featuring shorter encoding rates (i.e., in the 1s rate for younger adults, the interpolated activity task spanned 120 seconds, compared with 108 seconds, 84 seconds, and 60 seconds at the 2s, 4s, and 6s encoding rates). As a result, participants were exposed to more arithmetic problems during the retention interval between

encoding and retrieval in blocks featuring faster encoding rates, which may have introduced more non-study-specific interference (i.e., interference from intervening events that are not directly related to the studied material involving the face-scene pairs) in these blocks. This also entails that, when comparing older adults at the six second encoding rate to younger adults at the four second encoding rate, there were potential age-related differences in the amount of non-study-specific interference, which would have been higher among younger adults in this comparison and thus lead to an *underestimation* of the magnitude of an age difference. In Experiment 2, a fixed number of arithmetic problems (20 per block) was presented per block by adjusting the response window to three seconds per problem and adding blank ISIs between problems with lengths that varied based on the encoding rate for the primary memory task of a given block. Despite this change, which ensured the amount of non-study-specific interference would be constant regardless of the rate of encoding and for both young and older adults, participants' performance on the primary recognition task did not differ statistically between Experiment 1 and 2, and there were no credible between-experiment differences in the MPT parameter estimates of specific and general memory representations. Thus, variations in the amount of non-study-specific interference from the interpolated activity task did not unduly influence participants' ability to remember specific or general representations of the face-scene pairs, as there were no credible differences in these underlying representations at a given rate of encoding (e.g., the 1s rate) based on whether a fixed or random number of arithmetic problems were presented in the retention interval.

The preceding is not to say that interference plays no role in forgetting, as there is some role of interference in forgetting (Oberauer & Lin, 2017; Wixted, 2004). Rather, the

point of the preceding was that, regardless of the amount of non-study-specific interference from the interpolated activity task at a given encoding rate (e.g., 1s, or 2s), which was *larger* in Experiment 1 than in Experiment 2, the same estimates of specific and general representations for the face-scene pairs were obtained at that specified encoding rate (e.g., there was no difference in the estimates of the specific and general memory parameters between the 2s rate in Experiment 1 and the 2s rate in Experiment 2, despite more non-study-specific interference from the interpolated activity task in Experiment 1).

A final additional finding of the present study was that participants' reaction time (RT) on a different task sometimes correlated with and sometimes did not correlate significantly with their estimates of specific and gist memory on the primary task. Specifically, participants completed Deary-Liewald RT tasks at the end of the experiment, which involved both simple RT (SRT) and 4-choice RT (CRT) tasks designed to provide an independent metric of participants' processing speed on more simple cognitive tasks (Deary et al., 2011). In the SRT task, participants responded as quickly as possible every time a red X appeared in a centrally located white box subtended in a gray background on the computer screen. In the CRT task, participants responded as quickly and as accurately as possible by indicating in which of four numbered boxes the red X appeared on the screen. Thus, the CRT task is more demanding as it requires a discrimination among four options. Indeed, RTs on the CRT task were generally slower than those of the SRT task, and there were expected age-related differences in these RTs, with older adults exhibiting slower processing speed on these tasks. However, performance on the CRT task did not significantly correlate with

older adults' estimates of specific and gist memory representations. Indeed, only one memory parameter (parameter G_i at the 4s encoding rate) significantly correlated with any of the RTs from the Deary-Liewald task among older adults; this parameter was negatively correlated with RTs on the SRT task. Thus, among older adults, the speed of processing on these SRT and CRT tasks was not generally related to their estimates of specific or general memory representations of the face-scene obtained under various rates of encoding.

For younger adults, there were many significant and negative correlations between their RT on the SRT task and their estimates of specific and general memory representations for face-scene pairs obtained under the various encoding rates, as well as negative correlations between their RT on the CRT task and their estimates of the specific and general memory representations obtained primarily under the most speeded rate of encoding (the 1s condition). Combined with those findings obtained from the older adults, these results may indicate that individual differences in processing speed are a more important factor in determining the extent of encoding specific or general memory representations for *younger* but not older adults. In particular, younger adults with slower cognitive processing speeds (and/or possibly slower motor or attentional speeds, as the SRT task is not particularly cognitively-demanding but was found to be most consistently associated with the specific and gist memory parameters) encode weaker specific or general memory representations (indexed by lower estimates of the specific and gist memory parameters) under various encoding rates, but perhaps especially so under highly speeded encoding rates, such as one second. Among older adults, individual differences in processing speed appear to play a smaller role in the encoding of specific or general

representations, but group level differences (compared to younger adults) appear to be a significant contributing factor in the encoding of specific representations.

Theoretical Implications

Results of the present study are informative to our understanding of mechanisms underlying adult age-related differences in the representational quality of episodic memories. Numerous studies have shown that older adults' episodic memories are representationally less specific than those of younger adults (for a detailed review, see Greene & Naveh-Benjamin, 2023), including studies of mnemonic discrimination of words (Rankin & Klauser, 1979) or visual images (Koutstaal, 2003), false recall or recognition in DRM procedures (Koutstaal & Schacter, 1997; Tun et al., 1998), reproduction of qualitative aspects of stimuli like color or location in precision paradigms (Peich et al., 2013), studies of autobiographical recall (Levine et al., 2002), and studies of reading comprehension (Radvansky et al., 2001; Radvansky & Dijkstra, 2007). These findings are in accord with the predictions of several leading mainstream theories of memory representation, like fuzzy-trace theory (Brainerd & Reyna, 1990, 2015), hierarchical representation theory (Craik 2002a, 2002b, 2020), hippocampal pattern separation theory (Yassa et al., 2011), and trace-transformation theory (Robin & Moscovitch, 2017), all of which predict that older adults' episodic memories are more general/gist-like rather than specific in nature. The present set of results adds to this existing literature but also provides insight into a mechanism during encoding that may in part explain why these age-related differences occur.

Recently, Greene and Naveh-Benjamin (2023) sketched a graphical representation of a theoretical model to inspire future development of a more computationally-explicit

theory of the encoding, maintenance, and retrieval of specific and general episodic memory representations, which can help identify mechanisms that differentiate young and older adults during each of these critical stages of memory formation. One proposed mechanism pertained to the rates under which each type of representation can be initially encoded into memory.

This hypothetical mechanism was in part inspired by evidence in younger adults of more rapid deposition of gist than specific traces, from studies of semantic priming showing that young adults are rapidly influenced by the semantic content of primes even as they lack verbatim awareness of those primes (Draine & Greenwald, 1998) and studies of visual LTM of scenes showing that, under shorter presentation rates of one second, young adults appear to form gist-like representations that are on par with those formed in four seconds of encoding time (Ahmad et al., 2017). More recently, Greene and Naveh-Benjamin (2022d) manipulated the amount of time that young adults had to encode face-scene pairs across three levels: 0.75 seconds, 1.5 seconds, or four seconds. In their experiments, specific representations of face-scene pairs, measured using the simplified conjoint recognition MPT model (Stahl & Klauer, 2008) also used in the present study, continued to improve with increases in encoding time, whereas gist representations formed within 1.5 seconds of encoding time were sometimes on par with those formed within four seconds (Experiment 1). However, there were some further improvements in gist representations between the 1.5s and 4s conditions when the length of the interpolated activity task was adjusted to be longer in the 1.5s than 4s condition (Experiment 2) to equate the amount of time any given pair would have to be maintained in memory, as was also done in the present study.

This evidence from young adults is consistent with the position of theories like fuzzy-trace theory (Brainerd & Reyna, 1990) that assume independent, and in some cases more rapid, formation of gist than specific representations and is opposed to an earlier-held model that posited that gist representations formed more slowly as they would only be formed after a specific trace was laid down and its contents interpreted (van Dijk & Kintsch, 1983). Notably, evidence from the present study involving young adults is more strongly in line with the more rapid gist formation view, and the results from older adults in the present study extend to show that gist representations are laid down at encoding more rapidly than specific representations are even among older adults.

Greene and Naveh-Benjamin (2023) proposed that, at encoding, different rate parameters may govern how rapidly specific and gist features of an episode are encoded into memory, and in particular, for older adults, the rate at which specific features are encoded may be especially slow. This is in line with processing speed theories of aging (Salthouse, 1996) that posit that older adults' deficits in numerous aspects of cognition are attributable to a slower speed of executing cognitive processes like the encoding of information into memory. These processing speed differences may be attributable either to a *limited time mechanism* (in which age-related slowing of earlier stages of processing constrain the amount of time older adults have to engage in later stages of processing when the total amount of time is limited, as in the present study which featured fixed encoding rates) or to a *simultaneity mechanism* (in which losses due to decay or interference in earlier stages of processing result in slowing of later processing stages). In tasks like associative recognition, the *limited time mechanism* may be especially important in accounting for age-related differences in performance (cf., Salthouse, 1980,

1982, 1985), given that such tasks (like the one used in the present study) likely involve numerous sequential processes during encoding. However, in traditional old/new recognition tasks, slower processing speed among older adults may have more to do with non-mnemonic processes, like motor coordination, than memory process, as Ratcliff et al. (2004) demonstrated with a diffusion modeling analysis of a two-choice discrimination tasks. Importantly, typical old/new discrimination tasks are not sensitive to separating the representational bases of participants' responses into those that are attributable to specific, detailed representations and those that are attributable to gist/general representations. The conjoint recognition task (Brainerd et al., 2019; Stahl & Klauer, 2008) used in the present study provides a powerful empirical method of separating these types of representations because it requires individuals to discriminate old items (or pairs, in our case) from distractors that vary in how representationally similar they are to originally studied pairs. Because the earlier studies using diffusion modeling to measure age differences in the rate of cognitive and non-cognitive processes only relied on standard two-choice discrimination tasks, their conclusions regarding whether there are age differences in cognitive processes are limited in scope and cannot ascertain whether there are age differences in the rate of encoding of specific versus general memory representations.

The present study thus provided a powerful empirical test of the age-related cognitive slowing theory (Salthouse, 1996) as it pertains to underlying memory representations. By manipulating the amount of time young and older adults had to encode face-scene pairs, and in particular creating a condition in which older adults had more time to encode these pairs (six compared to four seconds for younger adults), and

using conjoint recognition tests, the present study provided the clearest evidence to date that there are age-related differences in the rate at which specific, but not general, representations of episodic memories can be encoded. That is, the rate at which specific representations are encoded into memory appears to be slower for older adults, as is evident by the finding from the present study that, when older adults had two or four seconds to encode face-scene pairs, there were age-related deficits in specific representations, but when older adults had six seconds to encode the face-scene pairs, their ability to later access specific representations in some conditions (depending on the nature of the test probe) was on par with the ability of younger adults under shorter (four seconds) encoding duration.

Importantly, the finding that specific representations only improved with increases in the encoding duration if the test probe provided an exact match to the studied pairs indicates that speed of encoding alone cannot account for age-related deficits in specific memory representations. If speed of encoding alone accounted for these deficits, we should have observed commensurate increases in specific representations when the test probes were only partial matches to originally studied pairs (i.e., when the test probes were Related, representing the original pair at a general but not specific level of representation). The finding from the present study that increases in encoding time did not influence the specific representation parameter for Related probes, and in particular that, for older adults, estimates of this parameter were so highly concentrated at 0 as that it had to be constrained to 0 even at the six second encoding rate, indicate that mechanisms beyond the rate of encoding also need to be considered when attempting to explain why older adults' episodic memories are representationally less specific in nature.

In Greene and Naveh-Benjamin's (2023) theoretical framework, mechanisms at retrieval are also theorized to play a role. The results of the present study provide powerful support for this assumption, in showing that a single mechanism affecting encoding is not sufficient to cover the full swathe of age-related differences in specific representations, especially as prior studies have often found age-related deficits in the V_r parameter (Greene & Naveh-Benjamin, 2020, 2022a). Even in the present study, there was some indication that estimates of this parameter were probably higher among younger adults at the two- and four-second encoding rates, though a formal test of this is not possible because the parameter had to be held to 0 among older adults. That is, among younger adults, >99% of posterior samples of parameter V_r exceeded 0 at the 2s and 4s encoding rates. Because increases in the encoding rate did not improve older adults' ability to access specific representations when the test pairs were Related but not identical, this suggests that another mechanism at play may operate during the retrieval phase.

In particular, the amount of environmental support provided in the retrieval cue may influence whether older adults access specific representations even when they have equivalent encoding of such representations as younger adults. As Intact probes are an exact reproduction of studied information, they provide an exact match to any encoded specific representations of original pairs, and thus the ability to reintegrate the specific representation of the original pair is likely to be much less effortful (Brainerd et al., 2019). Related probes match studied information only at a general but not at a specific level of representation. Thus, for a Related probe, more effort would be required to reintegrate the specific representation of the original information, requiring deeper

elaboration on the contents of one's memory, and older adults are especially less likely to deeply elaborate on their memories (Jacoby et al., 2005).

It is important to keep in mind that estimates of the specific representation parameter V_r were low among not only older but also young adults, and this is typically so. Indeed, in a meta-analysis by Brainerd et al. (2022a), across 400 conjoint recognition studies (all involving younger adults), the mean estimate of V_r was around 0.13. When individuals are shown Related probes, they appear to be far more likely to respond on the basis of the retrieved gist/general representation (as indicated by high estimates of *Gr*, which are typically found to be >0.60; Brainerd et al., 2022a) than by reintegrating a specific representation of the original episode and using that specific representation to *reject* the Related probe (cf., Brainerd et al., 2019). This may be because retrieval of specific representations is more effortful, as indicated by studies of divided attention in young adults showing that, under conditions of divided attention at retrieval, there are deficits in specific but not general representations of previously studied item-context associations (Dodson et al., 1998; Luo & Craik, 2009). Nevertheless, although the rates of retrieval of specific representations when shown Related pairs is also low among younger adults, it is still evident that these rates appear to be *even lower* among older adults (Greene & Naveh-Benjamin, 2020).

Limitations

The present study is certainly not without its limitations. A first set of limitations pertains to the generality of the samples. I primarily recruited participants from an online crowdsourcing platform (Prolific, n.d.). There are many unanswered questions about what kinds of older adults are participating in online studies and whether they are

representative of the larger population of older adults (Greene & Naveh-Benjamin, 2022e). Indeed, in the present study, the overall education level of older adults was almost commensurate with a college degree, which may make these older adults somewhat unrepresentative of the general population, given that, at least in the United States, only ~15% of individuals born in the 1960s obtained a Bachelor's degree or higher (Bialik & Fry, 2019). Moreover, the older adults who did participate were clearly literate enough in the use of computers to be able to take part in the present study. It is conceivable that this may make these older adults somewhat unrepresentative of older adults in general, given that older adults often hold more negative views toward technology (Lee et al., 2019) and that older adults who are most likely to use technology tend to be more highly educated (Anderson & Perrin, 2017).

Relatedly, I aimed to include only older adults with no history of mild cognitive impairment (MCI) or dementia, to ensure the conclusions of the present study would be with respect to natural aging independent of pathological complications like those due to the dementia. However, the presence or absence of MCI was only assessed with a single self-report question to which participants responded on the site, and any participant who indicated they did have a diagnosis of MCI or dementia was not eligible to participate. The validity of this single self-report question remains to be determined, as by including additional screeners, such as online diagnostic measures like the electronic Montreal Cognitive Assessment (eMOCA; Berg et al., 2018) that would provide a more reliable screening for dementia.

The generality of the samples is also important to consider with regards to the younger adults, which included a mix of (primarily) young adults from Prolific and a few

introductory psychology students at the University of Missouri. As with the older adults, these younger adults may be more highly educated than the general population of individuals aged 18 to 26, as even the students who participated had not yet completed their formal education. Even beyond educational attainment, the samples of both young and older adults were majority-White. Indeed, among older adults, 95.3% of participants identified as White, and among younger adults, 75% of participants identified as White. Clearly, the samples are not racially diverse, and especially so for the older adults. It remains to be determined how feasible it is to recruit non-White older adult participants, especially given that the present study was conducted online and still resulted in >95% of participants in the older adult group identifying as being White.

A second potential limitation pertains to the type of modeling employed in the present study. The present study relied upon a mathematical model, an MPT model, that separates the contributions of specific and general memory representations and provides independent estimates of these mnemonic processes uncontaminated by response biases, as these are represented in separate parameters (see Stahl & Klauer, 2008; for reviews of MPT models, see Batchelder & Riefer, 1999; Erdfelder et al., 2009). MPT models typically imply a discrete-state assumption, which entails that, upon entering a memory state, the probability of accepting a probe as old proceeds on an all-or-none basis. It is worth noting that the simplified conjoint recognition model may only be discrete-state with respect to its specific representation parameters, as the entry into the gist memory states triggers a response selection process rather than an all-or-none response. Nevertheless, the discrete-state assumption underlying MPT models has been the subject of some controversy (Batchelder & Alexander, 2013; Dube & Rotello, 2012; Pazzaglia et

al., 2013; Province & Rouder, 2012; Klauer & Kellen, 2011a, 2011b), with Pazzaglia et al. (2013) criticizing their use all together as being woefully insufficient in accounting for the form of empirical receiver-operating-characteristic (ROC) curves in item recognition tasks.

However, in my view, this debate is far too limited in its scope to lead to a complete refutation of the simplified conjoint recognition model. Specifically, the debate has hinged almost entirely on the suitability of only *one* MPT model, the two-high-threshold (2HTM) model of item recognition, and whether it can reproduce ROCs as well as an unequal variance signal detection model. The picture Pazzaglia et al. (2013) paint of insufficiencies in the 2HTM model is somewhat overstated, given that (1) the model can reproduce the form of empirical ROCs (e.g., Kellen & Klauer, 2011a, 2011a), (2) ROCs represent merely one aspect of the data and can themselves be prone to limitations in arbitrating between model classes (Batchelder & Alexander, 2013), and (3) the 2HTM model represents only one class of MPT models, so generalizing to an entire class is inappropriate, especially as the 2HTM is itself a derivative of the more general theoretical modeling class that encompasses the unequal variance signal detection model. More to the point, the debate has not been extended to the conjoint recognition model, and it is highly conceivable that specific representations would trigger an "all-or-none" type of response inherent in the discrete-state view (see Brainerd et al., 2014). Moreover, the controversy surrounding MPT models has been restricted to studies of item rather than associative recognition; in the latter case, MPT models may offer a better account of the data (Rotello, 2017; Yonelinas, 1997). Also, the use of cognitive models in cognitive aging research has been scarce (see Greene & Rhodes, 2022). My use of an MPT model

to estimate the contributions of specific and gist memory in the present study provides more meaningful information about these memory states than would be possible with standard analyses like ANOVA on proportion correct, as such analyses cannot isolate age-related differences in unobservable, underlying cognitive processes (Salthouse, 2000).

A third set of limitations pertains to the choice of stimuli. The present study used face-scene pairs as stimuli to simulate the ability to remember people in different locations (Gruppuso et al., 2007), an important hallmark of episodic memory (Tulving, 1983). However, the extent to which findings from the present study would generalize to other types of stimuli, such as verbal stimuli, cannot be directly ascertained. Moreover, there may be inherent differences in the way participants process facial stimuli compared with other types of stimuli, such as words (or word-pairs), which are among the most commonly encountered types of stimuli in memory experiments. This is not to say that facial stimuli are inherent inappropriately for memory studies or that verbal stimuli are superior, as verbal stimuli are certainly susceptible to their own host of confounds (Brainerd et al., 2022b). Nevertheless, the facial stimuli in the present study all depicted White faces. These stimuli were chosen as they were accessible from a validated database of faces (Ebner et al., 2010) and were homogenous with respect to the racial profile of the faces and other background characteristics. That is, all faces expressed neutral emotions and were presented from the neckline up on a gray background. Whether results of the present study would replicate with a more diverse set of facial stimuli depicting faces from more racially diverse background remains to be determined.

Also, the face was presented in equal size to the scene, with both stimuli sized to 312 x 389 pixels. This was done to ensure that participants could devote equal processing to both stimuli, but this may limit the ecological validity of the use of face-scene pairs. A more realistic presentation may involve presenting the face embedded within the scene. Such a format may create a more "unitized" association between the face and the scene, but it may also limit participants', especially older adults, ability to encode the facial stimuli, given that they would be presented in a much smaller size than the scene stimuli.

Future Directions

Despite these limitations, there are many exciting future directions to build on the results of the present study. One promising avenue would be to attempt to replicate these findings with non-visual stimuli and in non-associative recognition paradigms or in different types of associative memory paradigms. For example, Simons et al. (2004) used a source memory task in which young and older adult participants listened to sentences spoken by one of four voices (two males and two females), previously used by Dodson et al. (1998) to measure effects of divided attention in young adults on specific and partial source memory. The found that older adults observed deficits, relative to younger adults, not only in their ability to remember specifically which voice spoke a given sentence ("was it the first or the second male voice?") but in general what type of voice spoke the sentence ("was it a male or female voice?"). These findings suggest that the age-related representational deficit in source memory may be more pervasive than what we have traditionally found in associative recognition, extending beyond specific but to general representations as well. There are a number of differences between their paradigm and ours, including the modality with which participants learn the information (auditorily

versus visually). In a future study, it would be potentially useful to examine how variations in the rate of encoding spoken sentences or other non-visual types of associations (e.g., word pairs or other verbal stimuli, like passages of text, even if these are presented visually) influences the presence or absence of age-related differences in specific and general representations.

The present study, and indeed most studies examining age-related differences in the representational quality of episodic memories, relied exclusively on older adults who self-reported to be in good cognitive health, with no history of complications due to mild cognitive impairment or other forms of dementia. Future studies could consider the effects of encoding time on the ability of older individuals with dementia to remember specific or general representations. This may be an especially important avenue of future research given that declines in the ability to remember *gist* representations in old age have been shown to be a potentially more accurate predictor of the onset of Alzheimer's dementia than standard genetic biomarkers like the presence of the APOE-4 allele that contributes to the accumulation of neurofibrillary plaques and tangles (Brainerd & Reyna, 2015; cf., Brainerd et al., 2009). Finding ways to offset memory loss among older adults with dementia will be an important avenue for future research given the tremendous burden not only to individuals with dementia but to society more broadly, especially given the rising population rates of individuals over the age of 65 in many developed countries, like the United States (U.S. Census Bureau, 2018). This is not to say that all older adults over the age of 65 will develop dementia, but age remains the most significant predictor of dementia (Barnes et al., 2009).

Another exciting future direction would be to examine methods to increase the probability that participants, young or especially older adults, would rely upon specific representations of past episodes, assuming they have been able to sufficiently establish such representations, at retrieval when the test probes are Related/similar but not identical to the studied pairs. It is likely much easier to respond to Related probes based on gist rather than specific memory because these probes match originally studied episodes at general but not specific levels of representation (cf., Brainerd et al., 2019) and as such, an individual would need to put in more effort to retrieve the specific representation of the original episode. In the future, a manipulation that can increase participants' tendency to rely on specific rather than gist representations in responding to similar/Related probes would be useful for testing whether age-related deficits in this specific representation parameter can be offset by increases in encoding duration. One possibility may be to manipulate the reward incentives on a trial-by-trial basis, encouraging participants to respond more accurately to Related/similar lures with higher possible financial payouts.

Finally, future studies should consider other mechanisms that may explain why older adults have deficits in specific but not general representations, including tests of some of the proposed mechanisms impacting not only encoding but also retrieval from Greene and Naveh-Benjamin's (2023) theoretical modeling framework. Moreover, future studies should consider how different potential mechanisms, such as the speed of encoding and the attentional demands to encode or retrieve specific versus general representations, interact to influence young and older adults' abilities to encode, maintain, and retrieve specific and general memory representations.

Conclusions

To conclude, the present study examined whether speed of encoding differences between young and older adults could account for why older adults exhibit deficits in specific but not gist/general episodic memory representations. Converging results combined across two comparable experiments showed that increases in encoding time did offset some of the age-related deficits in specific representations in tests of long-term memory. Specifically, when older adults had more time to encode face-scene pairs than younger adults (six compared to four seconds), age-related deficits in specific representations in tests of long-term memory disappeared, but only when the test probe provided an exact match to originally studied information. When the test probe provided a match at a general but not specific level, increases in the encoding duration did not benefit older adults' abilities to rely upon specific representations at retrieval, though there were also no benefits of increases in encoding duration for younger adults' ability to access specific representations in this situation. The picture that emerges is complex and suggests that multiple interactive processes not only at encoding but also during retrieval may underscore why older adults observe deficiencies in specific memory representations.

The present study also provided a powerful test of fuzzy-trace theory's (Brainerd & Reyna, 1990) assumption of independent, and more rapid, formation of general/gist than specific/verbatim representations. Specifically, among both young and older adults, general memory representations were laid down more rapidly at encoding than were specific representations, as increases in the encoding time led to consistent improvements only in the specific but not in the gist memory parameters of the multinomial-processing-tree model. These results do indicate differential rates of formation of specific and

general memory representations, with gist/general representations being established more rapidly than specific representations, in keeping with fuzzy-trace theory's predictions.

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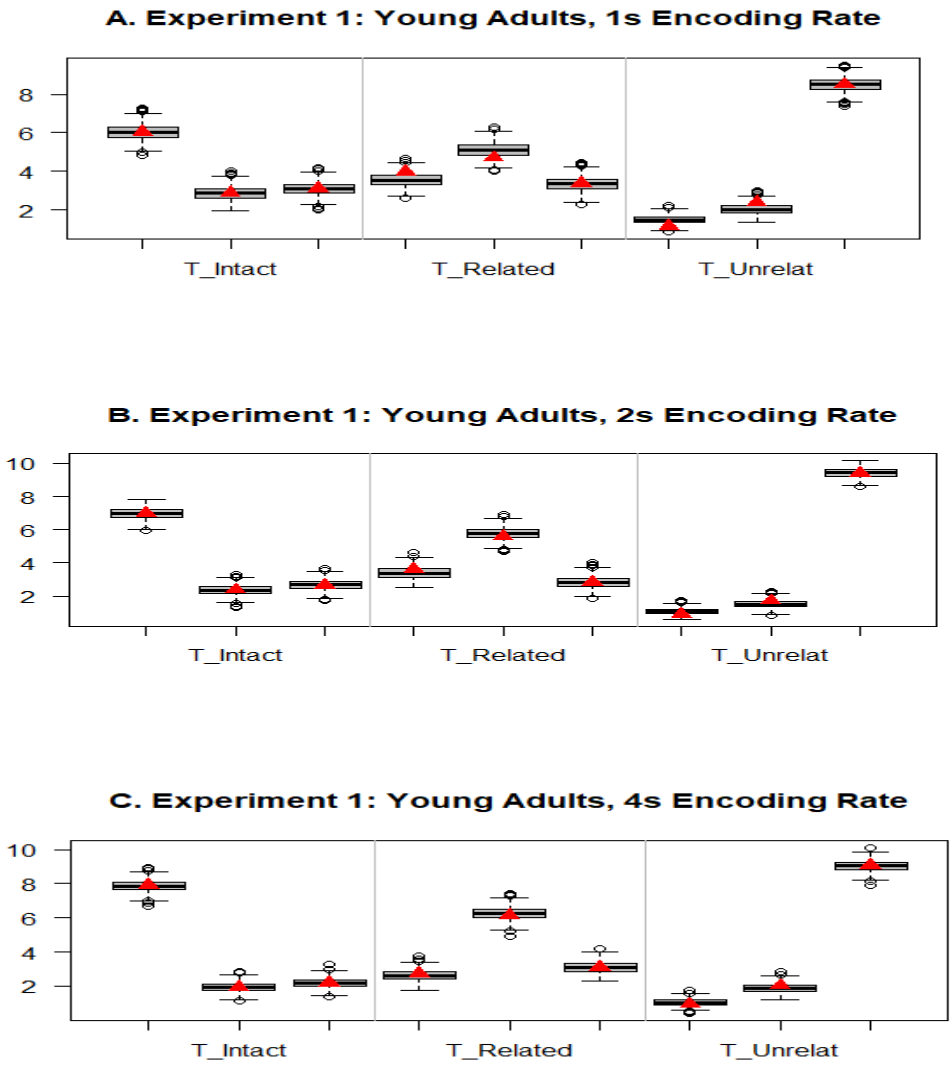
Appendix

Appendix A

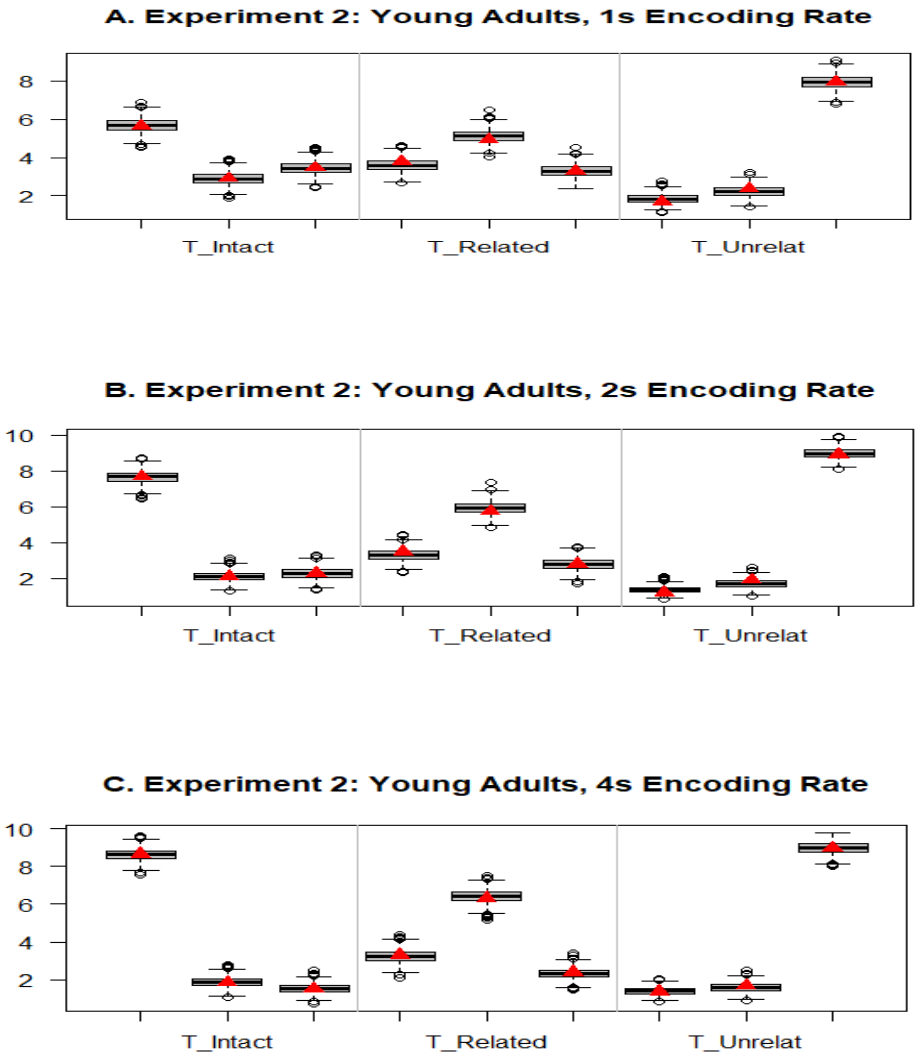
Appendix A contains model fit plots for the multinomial-processing-tree (MPT) models reported in the main text. All plots depict the observed posterior frequencies of responses in the data, which appear as boxplots, against the means of 1000 samples drawn from the posterior distribution (i.e., posterior predictive distribution), which appear as red triangles.

Figure A1. *Comparison of Observed and Posterior-Predicted Mean Response Frequencies for Young Adults in Experiment 1*



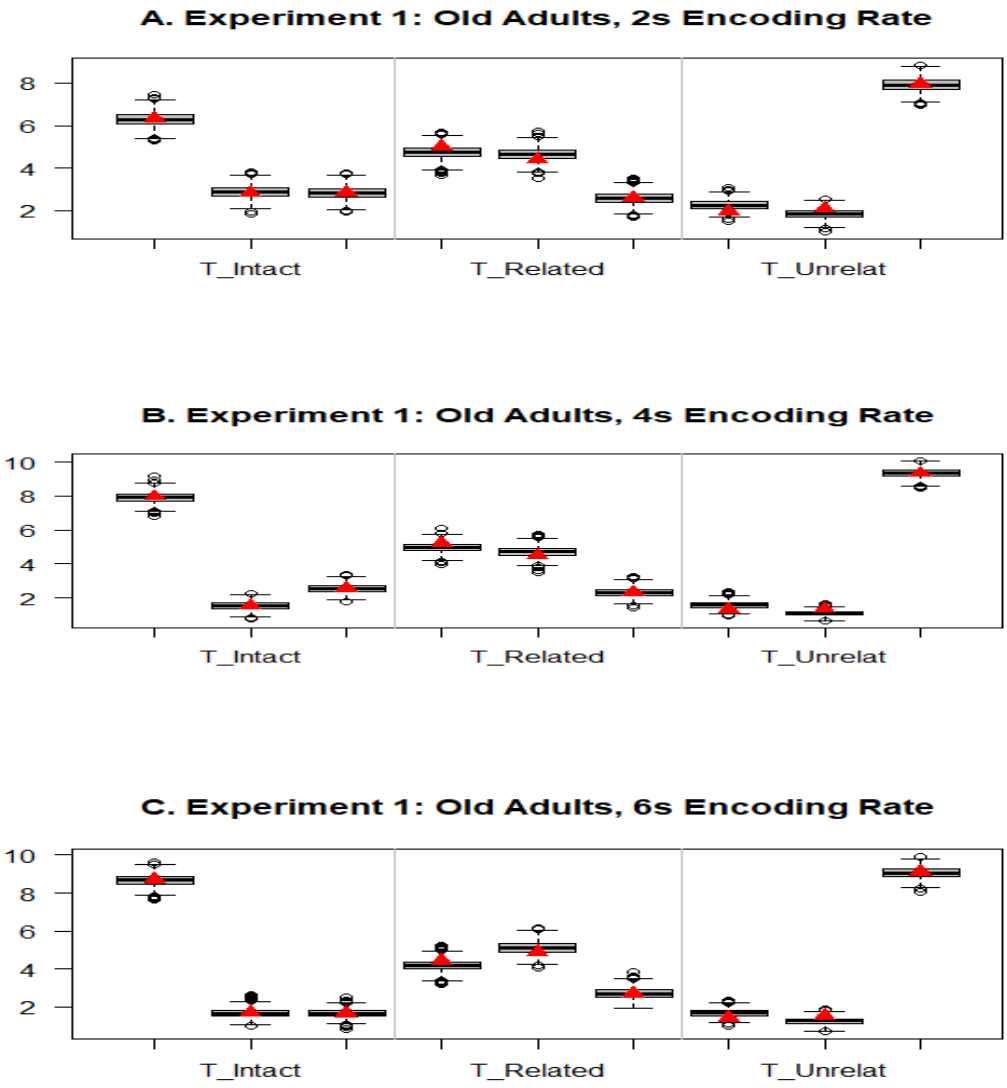
Note. Model fit for MPT model to young adult data in Experiment 1 at the 1s (A), 2s (B), and 4s (C) encoding rates. The y-axis gives the frequencies of "intact" (first tick on x-axis in each tree), "related" (second tick on x-axis in each tree), and "unrelated" (third tick on x-axis in each tree) responses to each probe, modeled in different MPT trees (T_Intact, T_Related, T_Unrelated). Red triangles are posterior-predicted mean frequencies from 1,000 samples drawn from the posterior distribution. Boxplots are the observed frequencies in the data.

Figure A2. *Comparison of Observed and Posterior-Predicted Mean Response Frequencies for Young Adults in Experiment 2*



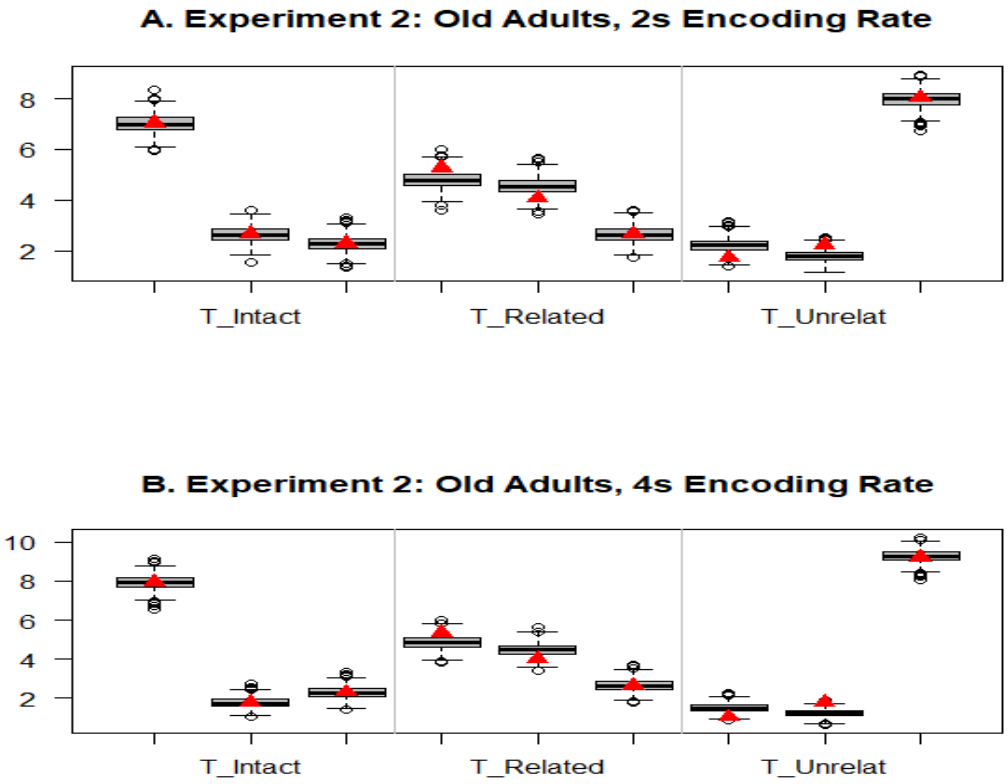
Note. Model fit for MPT model to young adult data in Experiment 2 at the 1s (A), 2s (B), and 4s (C) encoding rates. The y-axis gives the frequencies of "intact" (first tick on x-axis in each tree), "related" (second tick on x-axis in each tree), and "unrelated" (third tick on x-axis in each tree) responses to each probe, modeled in different MPT trees (T_Intact, T_Related, T_Unrelated). Red triangles are posterior-predicted mean frequencies from 1,000 samples drawn from the posterior distribution. Boxplots are the observed frequencies in the data.

Figure A3. *Comparison of Observed and Posterior-Predicted Mean Response Frequencies for Older Adults in Experiment 1*



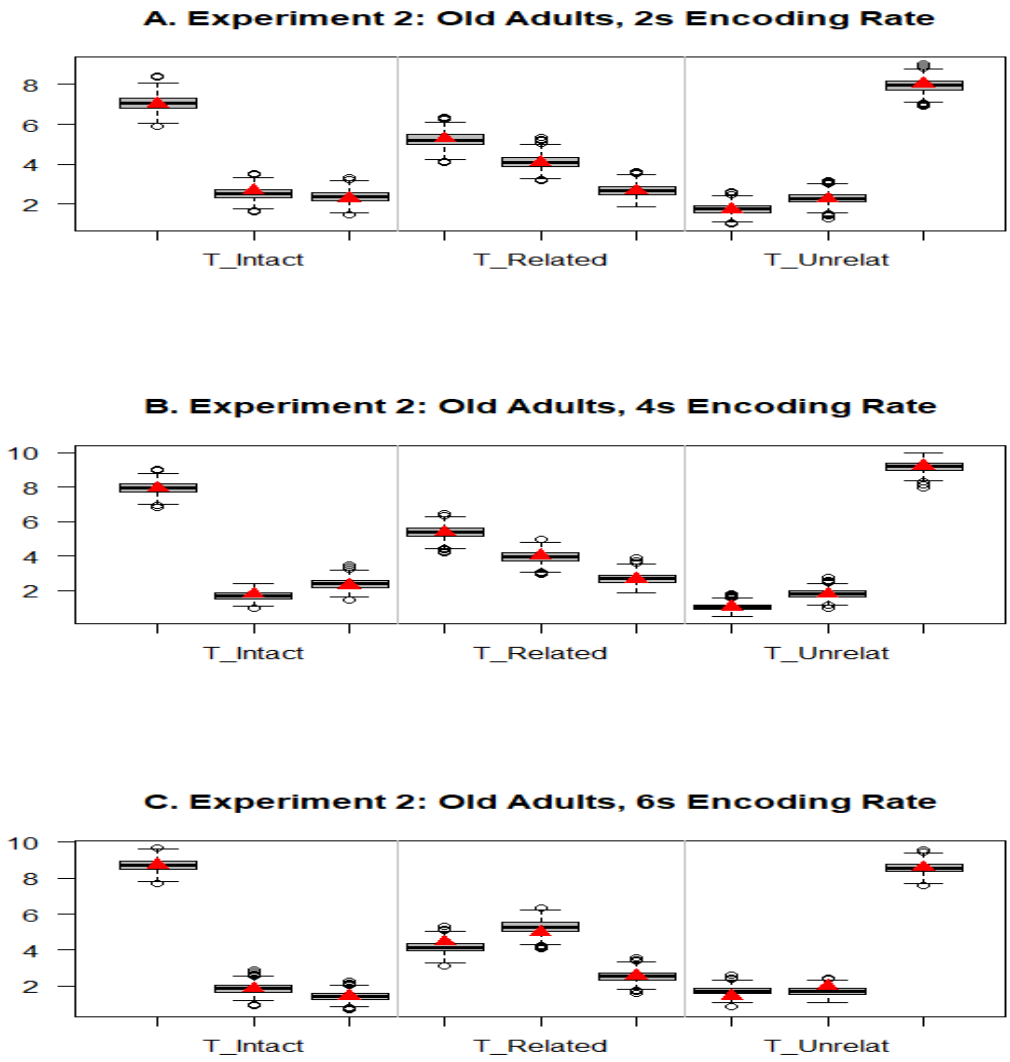
Note. Model fit for MPT model to older adult data in Experiment 1 at the 2s (A), 4s (B), and 6s (C) encoding rates. The y-axis gives the frequencies of "intact" (first tick on x-axis in each tree), "related" (second tick on x-axis in each tree), and "unrelated" (third tick on x-axis in each tree) responses to each probe, modeled in different MPT trees (T_Intact, T_Related, T_Unrelated). Red triangles are posterior-predicted mean frequencies from 1,000 samples drawn from the posterior distribution. Boxplots are the observed frequencies in the data.

Figure A4. *Comparison of Observed and Posterior-Predicted Mean Response Frequencies for Older Adults in Experiment 2 at the 2s and 4s Rates When V_r Was Not Constrained to 0*



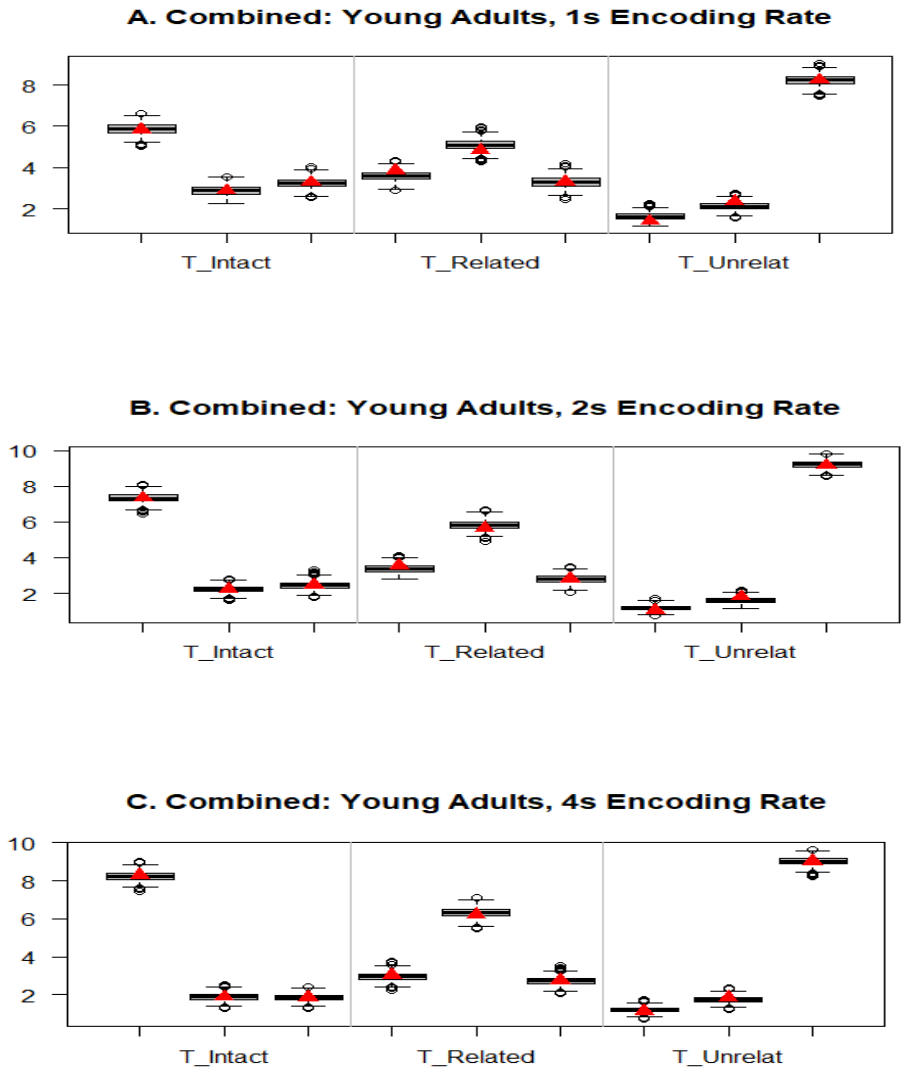
Note. Model fit for MPT model to older adult data in Experiment 2 at the 2s (A) and 4s (B) encoding rates in the initial fit of the model in which V_r was not constrained to 0. The y-axis gives the frequencies of "intact" (first tick on x-axis in each tree), "related" (second tick on x-axis in each tree), and "unrelated" (third tick on x-axis in each tree) responses to each probe, modeled in different MPT trees (T_Intact, T_Related, T_Unrelated). Red triangles are posterior-predicted mean frequencies from 1,000 samples drawn from the posterior distribution. Boxplots are the observed frequencies in the data.

Figure A5. *Comparison of Observed and Posterior-Predicted Mean Response Frequencies for Older Adults in Experiment 2 with Modified Model*



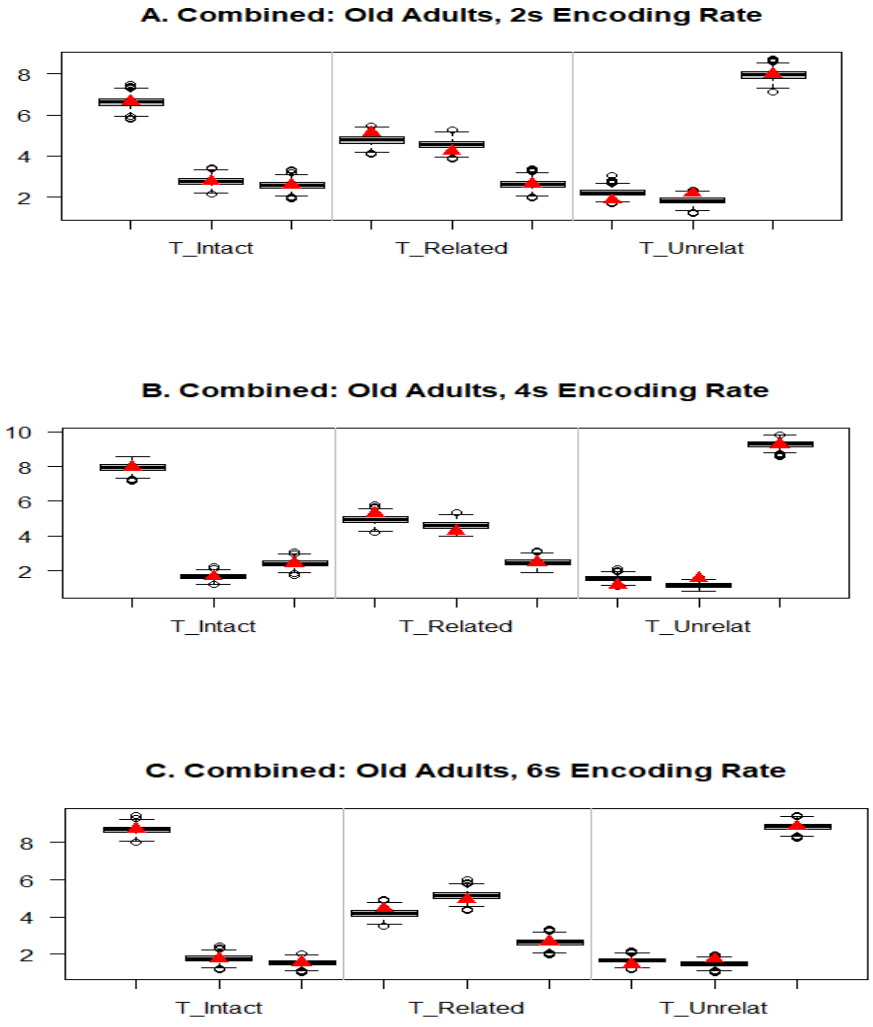
Note. Model fit for modified MPT model to older adult data in Experiment 2 at the 2s (A), 4s (B), and 6s (C) encoding rates. The y-axis gives the frequencies of "intact" (first tick on x-axis in each tree), "related" (second tick on x-axis in each tree), and "unrelated" (third tick on x-axis in each tree) responses to each probe, modeled in different MPT trees (T_Intact, T_Related, T_Unrelated). Red triangles are posterior-predicted mean frequencies from 1,000 samples drawn from the posterior distribution. Boxplots are the observed frequencies in the data.

Figure A6. *Comparison of Observed and Posterior-Predicted Mean Response Frequencies for Young Adults Combined Across Experiments 1 and 2*



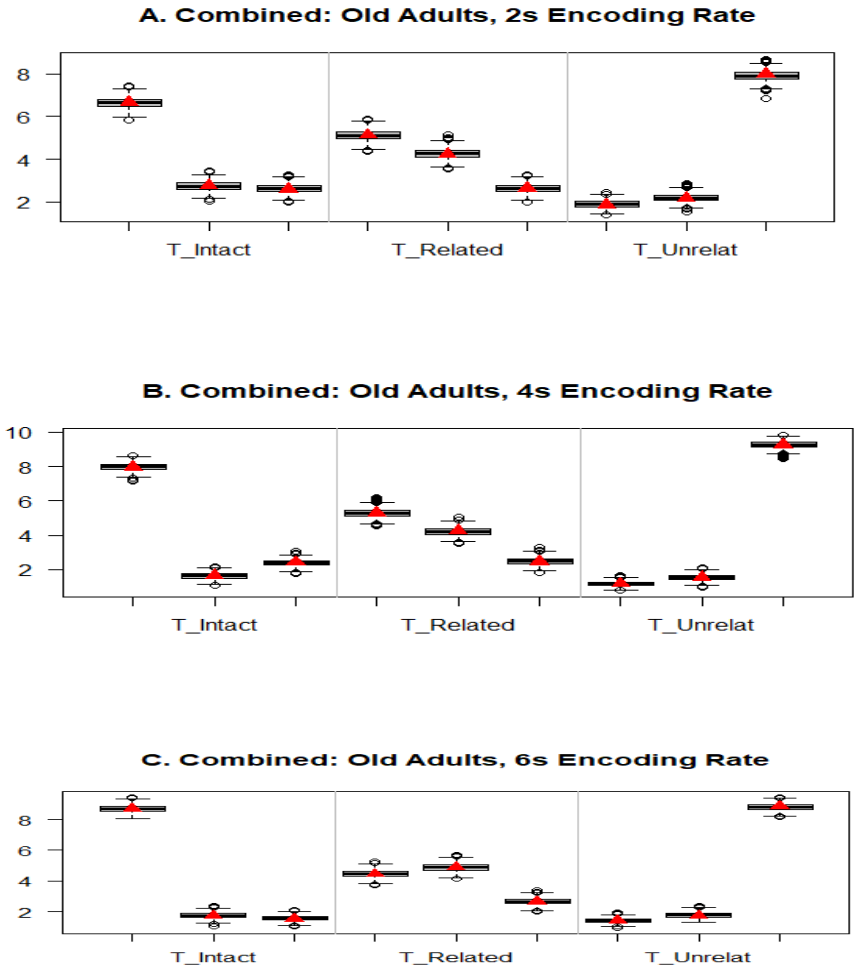
Note. Model fit for MPT model to young adult data combined from Experiments 1 and 2 at the 1s (A), 2s (B), and 4s (C) encoding rates. The y-axis gives the frequencies of "intact" (first tick on x-axis in each tree), "related" (second tick on x-axis in each tree), and "unrelated" (third tick on x-axis in each tree) responses to each probe, modeled in different MPT trees (T_Intact, T_Related, T_Unrelated). Red triangles are posterior-predicted mean frequencies from 1,000 samples drawn from the posterior distribution. Boxplots are the observed frequencies in the data.

Figure A7. *Comparison of Observed and Posterior-Predicted Mean Response Frequencies for Older Adults Combined Across Experiments 1 and 2 in Original Model*



Note. Model fit for MPT model to old adult data combined from Experiments 1 and 2 at the 1s (A), 2s (B), and 4s (C) encoding rates from original model. Y-axis gives the frequencies of "intact" (first tick on x-axis in each tree), "related" (second tick on x-axis in each tree), and "unrelated" (third tick on x-axis in each tree) responses to each probe, modeled in different MPT trees (T_Intact, T_Related, T_Unrelated). Red triangles are posterior-predicted mean frequencies from 1,000 samples drawn from the posterior distribution. Boxplots are the observed frequencies in the data.

Figure A8. *Comparison of Observed and Posterior-Predicted Mean Response Frequencies for Older Adults Combined Across Experiments 1 and 2 in Modified Model*



Note. Model fit for MPT model to old adult data combined from Experiments 1 and 2 at the 1s (A), 2s (B), and 4s (C) encoding rates in modified model. The y-axis gives the frequencies of "intact" (first tick on x-axis in each tree), "related" (second tick on x-axis in each tree), and "unrelated" (third tick on x-axis in each tree) responses to each probe, modeled in different MPT trees (T_Intact, T_Related, T_Unrelated). Red triangles are posterior-predicted mean frequencies from 1,000 samples drawn from the posterior distribution. Boxplots are the observed frequencies in the data.

Vita

Nathaniel Greene, who was valedictorian of his graduating high school class in 2013 at a large public school in rural Mississippi, is a first-generation college student who graduated *Magna Cum Laude* with a Bachelor of Art in Psychology and a Minor in Neuroscience from the University of Mississippi in 2017. While enrolled at the University of Mississippi, Nathaniel completed a summer research internship program in 2016 as a Ronald McNair Scholar. The program recognizes students from underrepresented backgrounds, including first-generation and low-income college students, and prepares them for future advanced study toward a doctoral degree.

Nathaniel enrolled in the doctoral program in the Department of Psychological Sciences, in the Cognition and Neuroscience concentration, at the University of Missouri in fall 2017 as a Ronald McNair Fellow. He obtained a Master of Arts in Psychology, with a concentration in Cognition and Neuroscience, in summer 2019. His Master Thesis and related scholarly works conducted while a graduate student at the University of Missouri have been published in more than fifteen peer-reviewed academic journals. Nathaniel was first author on the majority of these publications and has been recognized for his scholarly work with an American Psychological Association (APA) Editor's Choice Award for a 2023 article appearing in the journal *Psychology and Aging*. He was also the recipient of a 2018 Psychonomic Society Graduate Travel Award, allowing him to present his research at the premiere symposium of cognitive psychology. His doctoral dissertation represents an important continuation of his earlier established research and a steppingstone for his future planned career as a researcher of memory and aging.