Trends in
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Review

Cluttered memory representations shape cognition in old age

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Declines in episodic memory in older adults are typically attributed to differences in encoding strategies and/or retrieval processes. These views omit a critical factor in age-related memory differences: the nature of the representations that are formed. Here, we review evidence that older adults create more cluttered (or richer) representations of events than do younger adults. These cluttered representations might include target information along with recently activated but no-longer-relevant information, prior knowledge cued by the ongoing situation, as well as irrelevant information in the current environment. Although these representations can interfere with the retrieval of target information, they can also support other memory-dependent cognitive functions.

Highlights

Healthy aging is accompanied by declines in control of attention.

These reductions in the control of attention, result in older adults processing too much information, creating cluttered memory representations.

Cluttered representations can impair memory by interfering with the retrieval of target information, but can also provide an advantage on tasks that benefit from extensive knowledge.

Older adults store too much information

Wisdom and knowledge, cognitive functions that surely depend on being able to access and use memory, grow into old age [1–4]. Yet, the literature on memory shows that intentional, episodic memory declines with age [5–9]. How are we to account for this paradox [10]? To do so, we need to understand three aspects of memory differences associated with aging, two of which have received extensive investigation: age differences in memory encoding [11–13] and in retrieval [14–19]. A third aspect, differences in the contents of memory representations, has received relatively little empirical attention. Here, we argue that this aspect is central to a full understanding of age differences in memory and memory-related cognitive functions.

We propose that, relative to younger adults, healthy older adults (typically between 60 and 85 years of age) process and store too much information, the result of reductions in cognitive control or inhibitory mechanisms. When efficient, these mechanisms enable a focus on target or goal-relevant information to the exclusion (or suppression) of irrelevant information (Box 1) [20–23]. Due to poor control (or reduced efficiency), the mnemonic representations of older adults can include: (i) recently activated but no-longer-relevant information; (ii) task-unrelated thoughts and/or prior knowledge elicited by the target information; and/or (iii) task-irrelevant information cued by the immediate environment. This information is then automatically bound together with target information [11,21], creating cluttered memory representations that contain more information than do those of younger adults (Figure 1, Key figure). While some of these additional elements (e.g., cued prior knowledge or previously relevant information) might also be present in the memory representations of younger adults [24,25], their activation and links to target information might be attenuated or suppressed relative to older adults (i.e., younger adults' representations largely comprise, and reflect a focus on, target information) [26–30]. Despite this, there is evidence that older adults' memory for target information (items and associations), as tested using implicit measures, does not differ from that of younger adults [15,16,31,32]. Accordingly, we argue that older and younger adults' memories contain similar target features, but that older adults' memories contain more non-target features and, thus, are cluttered with excessive information.

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Box 1. Inhibitory mechanisms shape mnemonic representations

The notion of cluttered memory representations has its roots in Inhibitory Theory [21–23]. According to this theory, attention is subserved by the component processes of excitation and inhibition. Excitation is automatic and does not change with age. By contrast, inhibition is a controlled process by which goal-relevant information is selected from among activated representations by downregulating irrelevant information. Unlike excitation, inhibition shows significant age-related declines. Inhibitory Theory further proposes that inhibition relies on three major functions (access, deletion, and restraint), which together govern individuals' mental workspace and, consequently, cognitive patterns. Critically, reductions in the efficiency of these functions with old age result in mnemonic representations that are more cluttered than those of younger adults and, in consequence, pose challenges for retrieval. First, the access function regulates how much information is initially activated in response to cues. Inefficiencies in that function enable more information (both relevant and irrelevant) to be processed, allowing for a greater spread of activation of related thoughts/representations. As a result, older adults' memories may contain both irrelevant information (that passed through a 'leaky' attentional filter) and an over-representation of prior knowledge or semantically related thoughts. Second, the deletion function enables the suppression of no-longer-relevant information, as when a task or goal is changed. As this function declines, older adults tend to show sustained activation and maintenance of previously activated information in memory. Finally, the restraint function supports attentional selection by regulating competing responses in action and thought. In older adults, reductions in restraint, along with an overabundance of information in memory, hamper the ability to resolve competition necessary for the retrieval of target information. Together, these age-related changes in inhibitory functions likely shape the memory representations of older adults and can account for differences in memory performance. Lastly, inefficiencies in inhibitory functions likely vary among individuals and have also been seen in, and might similarly impact the representations of children (see [127] for evidence that children's memories contain non-target features).

Although we use the term 'cluttered' to capture the nature of older adults' memory representations, they could also be described as 'enriched', 'elaborated', or 'overloaded'. While these representations pose a challenge for retrieving target information from within the clutter and set the stage for age differences in memory patterns, there might also be treasure in the clutter that can support other memory-dependent cognitive functions. In other words, the clutter of irrelevant information

Key figure

Visualization of the nature of older adults' memory representations

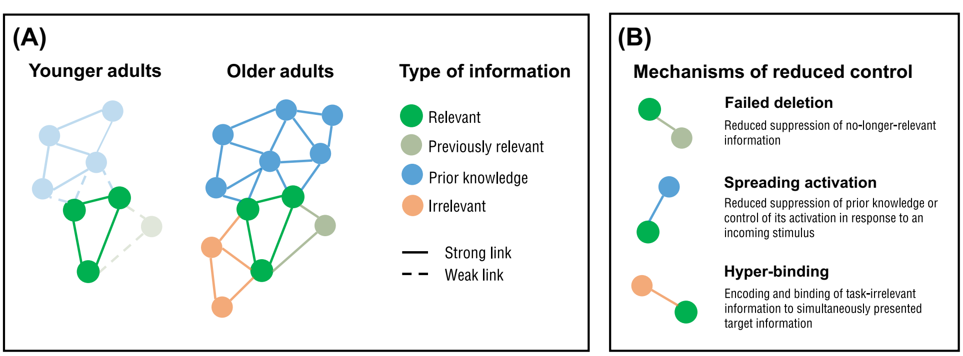

Figure 1. (A) Relative to younger adults, whose memory representations predominantly contain relevant or target information, older adults' memories are cluttered with no-longer-relevant information that was never suppressed, prior knowledge representations cued by the target information, and irrelevant or distracting information from the current environment. Some of these elements might also be contained in the memory representations of younger adults, but, as pictured here, are less strongly activated and only weakly linked to target information. The additional information represented in older adults' memory representations can pose problems for retrieval of target information and (positively) impact other memory-dependent functions. (B) The cluttered nature of older adults' memory representations can be attributed to reduced inhibitory or cognitive control with age. Specifically, older adults show reduced suppression and/or deletion of information that is no longer relevant to the present task. Relative to younger adults, they also have difficulty suppressing, or controlling the spread of, prior knowledge that is cued by the incoming stimulus. Finally, older adults show increased encoding and binding of task-irrelevant information to simultaneously presented task-relevant target information.

might interfere with target memory retrieval in one context, but might also provide surprising advantages in other tasks or contexts that benefit from extraneous knowledge. In these latter situations, the term 'enriched' might be a more appropriate descriptor of older adults' representations than is cluttered. Whatever the term, both behavioral and neuroimaging evidence suggests that the contents of memory representations contain more information for older than for younger adults. As will be seen, this excessive information stems from previously relevant information, from general knowledge, and from the current environment, some or all of which become bound together with targets and so have a large role in the mental lives of older adults.

Reduced suppression of previously relevant information in memory

Behavioral evidence

Mnemonic representations can be flexibly updated or modified, a process that relies on cognitive control mechanisms and typically entails deleting or suppressing no-longer-relevant information to prioritize currently relevant information. Several tasks demonstrate efficient updating in young adults. For example, in directed forgetting paradigms, participants are first presented with items to study and then are instructed to remember or forget some of the items. Young adults show suppression of to-be-forgotten (TBF) items, as evidenced by poor recall (and few intrusions) of TBF relative to be-remembered (TBR) items and intact memory for TBR relative to control items (i.e., no interference from TBF items) [26]. Similarly, in retrieval-induced forgetting paradigms, in which target information needs to be recalled at the expense of competing, related items, young adults show impaired recall of competing items relative to baseline controls [27,33]. Neuroimaging studies indicate that these effects are associated with increased activity in brain regions implicated in cognitive control, such as lateral frontal and parietal regions, suggesting that memory updating depends on cognitive control mechanisms [34–37].

In older adults, growing evidence shows reduced suppression of no-longer-relevant information relative to younger adults along with maintained access to that information. For example, older adults show reduced directed forgetting [38,39] and also reduced retrieval-induced forgetting [40]. Indeed, several studies indicate that older adults in fact show increased accessibility of rejected/no-longer-relevant items in memory. For example, unlike younger adults, older adults show priming of words that should have been previously suppressed to resolve competition [28,41]. Older adults are also more likely than younger adults to complete new, unfinished sentences with previously rejected words relative to normative completion probabilities [42].

Age-related reduced suppression is also seen in paradigms that specifically measure task disengagement or cross-task bleeding. For example, in classic task-switching paradigms, which require alternating between task rules based on instructions (e.g., classifying object shapes versus color), older adults show greater switching costs than do younger adults [43]. These increased age-related costs are typically interpreted as a reduced ability to maintain different task-set instructions and flexibly update those instructions due to control deficits. These abilities have been shown to be highly correlated with inhibition/suppression [44], consistent with the view that age-related reduced suppression of no-longer-relevant instructions negatively impacts performance. Similarly, older adults are more likely than younger adults to spontaneously retrieve irrelevant instructions from a previous different task (an effect correlated with inhibitory functioning), resulting in slower performance and increased error rates on the new task ([45,46]; see also [47] for evidence of age-related cross-task bleeding from an upcoming task). Finally, older adults' poor performance on working memory tasks, often thought to result from capacity limits [48], can instead be attributed to increased proactive interference from previous, unsuppressed trial items [49,50] (see 'Retrieval difficulties' for more details). Therefore, reduced suppression of information from the past (the deletion function of Inhibitory Theory [23]) is a critical component of older adults' cluttered memory representations.

Neural evidence

Recent neuroimaging studies directly test for age differences in neural activation of no-longer-relevant information. In one study [51], older and younger adults performed a delayed recognition task, in which they were initially presented with images from two different categories (e.g., faces and scenes), and then informed which category would be tested (rendering items in the other category irrelevant). Using multivoxel pattern analysis, age differences in the neural activation of images from the relevant and no-longer-relevant categories (measured through accuracy/performance of a classifier trained to distinguish between the categories) were assessed during a 10-s delay. There were no whole-brain age differences in activation of images from the cued, relevant category. However, older adults showed higher activation (i.e., better classification performance) of images from the no-longer relevant category, despite their irrelevance to the recognition test. The most prominent differences were seen in medial temporal lobe and hippocampal regions, structures involved in forming links between encoded items [52,53], suggesting that relevant and irrelevant images were bound together in memory.

In another study [54], older and younger adults incidentally encoded words superimposed on different background scenes, with the word–image pair presented in one of three locations on the screen. During retrieval, participants were required to remember either the location or the background scene image for words rated as old. Neural measures of scene reinstatement were examined during both retrieval tasks. Consistent with findings of age-related sustained activation and reduced suppression of previously relevant information, older adults showed scene reinstatement irrespective of task demands (i.e., scenes were reinstated even when they were no longer relevant in the location task). By contrast, younger adults showed evidence of retrieval gating. Together, these findings suggest that, relative to young adults, older adults are more likely to maintain access to recent but no-longer-relevant information in memory and retrieve that information, along with target information. This is consistent with the proposal that the memory representations of older adults are more cluttered than those of young adults.

Over-representation of prior knowledge in memory

Prior knowledge shapes memory patterns in older adults

Further contributing to clutter in older adults' memories is a lifetime of accumulated knowledge, which research suggests is over-represented in activated memories. Indeed, growing evidence indicates that, across a range of tasks, older adults rely more heavily on established forms of knowledge to support performance than do younger adults [2,3,55–57]. This increased reliance likely stems from greater knowledge in older relative to young adults, as well as a reduced ability to suppress or control activation of that knowledge in response to incoming stimuli (the access function of Inhibitory Theory) [23,56].

Classic behavioral work illustrates that prior knowledge shapes memory representations and recall patterns in older adults, resulting in benefits or detriments depending on the task and context (reviewed in [58]). When encoded information is consistent with, or capitalizes on, older adults' prior knowledge, that knowledge can support episodic memory, and even bolster it to the same level as that of younger adults [14,59–62]. Indeed, multiple studies report that typical age differences in associative memory [63] are mediated by the meaningfulness of the stimuli and their consistency with prior knowledge, such that age differences are minimized in conditions that use naturally co-occurring elements and engage prior knowledge [14,61,62,64–66]. Thus, when novel information activates prior knowledge representations, a process more likely to occur under circumstances of reduced control [22,23], older adults show a greater memory benefit than younger adults (see [57,58,61] for evidence and discussion of 'schematic support' in older adults).

However, over-reliance on prior knowledge by older adults can also increase memory errors, including recall of false memories. For example, older adults are more likely than younger adults to falsely recall or recognize items that are semantically related to encoded information (e.g., falsely remember seeing a pot after studying a kitchen scene) [67,68]. One study illustrated this effect by experimentally manipulating the extent to which older adults could rely on prior knowledge [69]. Older and younger adults studied ambiguous pictures that could be interpreted as common objects. In one condition, the pictures were presented with disambiguating labels to elicit the use of semantic knowledge and, in another condition, the pictures were presented without labels. Although older and younger adults performed similarly in the no-label condition, older adults showed higher rates of false recognition of new pictures in the semantic label condition, consistent with an age-related increase in reliance on prior knowledge.

Compared with younger adults, older adults over-rely on prior knowledge when forming memory representations, by drawing links between novel information and nonsuppressed existing knowledge. Lending support to this hypothesis, research suggests that prior knowledge and novel target information can be maintained concurrently in memory. For example, in one study [70], older and younger adults read passages in which an expected inference (based on prior knowledge) was confirmed or disconfirmed by subsequent information. The disconfirmed condition required a reinterpretation of the original inference (e.g., a 'shot' was fired by a camera, not a gun as originally assumed). On a speeded decision task following the paragraph, older adults retained access to both the original and the reinterpreted inference, while younger adults had only the final, appropriate inference accessible. That is, older adults retained both the target and competing (prior knowledge-based) inferences in memory.

Evidence from eye-tracking work is consistent with the conclusion that prior knowledge has a larger role in older adults' representations than is the case for younger adults. For example, in one recent study [71], participants performed a visual search task, with target objects placed in either congruent or incongruent locations in real-world scenes (e.g., a kettle on the stove or on the kitchen floor). Scenes were presented multiple times across blocks, such that targets in incongruent locations could be found using episodic memory after the first block. Whereas both younger and older adults detected incongruent targets more quickly across repetitions, older adults continued to view the congruent locations (not containing the target) to a greater extent than younger adults. In other words, older adults were less likely than younger adults to suppress their pre-existing knowledge, and that knowledge guided their visual attention (see also [72]). Finally, on a subsequent memory task, older adults were marginally more likely than younger adults to incorrectly report that previously detected incongruent targets had been located in congruent locations. Thus, prior knowledge representations not only guided older adults' viewing behavior, but were also maintained in memory along with newly learned target items (for further eye-tracking evidence of excessive information storage with age, see [73]).

Mechanisms of incorporating prior knowledge into memory

Given evidence of the impact of prior knowledge on older adults' memory, recent studies have examined how knowledge in older adults interacts with, and modulates, encoding mechanisms and is ultimately incorporated into memory. At the neural level, semantic processing, which requires access to prior knowledge or stored mnemonic representations, is associated with a distributed network of intrinsically connected brain regions known as the default mode network

(DMN) [74–78]. This network, comprising regions including medial prefrontal, medial and lateral parietal, and medial and lateral temporal cortex, has been characterized by its involvement in internally directed cognition [77,79]. This is evidenced by greater network activity during internally oriented (e.g., rest) relative to externally oriented tasks, and by research suggesting a role for the network in organizing incoming sensory information in relation to contextual or prior knowledge [77,78]. During externally oriented tasks, such as intentional learning and preparation for an upcoming memory test, DMN regions are suppressed or show decreased activity relative to a passive baseline [76]. This suppression is thought to be mediated by cognitive control, as evidenced by negative correlations in activity between control and DMN regions, as well as causal evidence (using transcranial magnetic stimulation) of direct negative modulation of the DMN by control regions [80–84]. Some researchers have proposed that this top-down suppression serves to facilitate memory formation by promoting a shift from internal thought to externally focused attention, thus reducing internally based distraction (e.g., task-unrelated thoughts) [82,85–88]. Consistent with the idea that older adults' memory representations contain more knowledge-based details, there is evidence that, with old age, DMN regions show reduced suppression relative to that seen in younger adults. Furthermore, this pattern is associated with poorer task performance (e.g., recall and recognition) [88–90]. These findings are consistent with an age-related decline in top-down control or modulation of the network [85,89].

Although heightened DMN activity is associated with poorer target memory, other work in young adults suggests that, when a task particularly engages prior knowledge (e.g., by using famous as opposed to non-famous faces), greater DMN activity might support memory performance by activating that knowledge and incorporating it into encoded memory representations [25,91]. This might be the case particularly for older adults [14,61]. One study [92] examined whether reduced DMN suppression in older adults is related to the integration of novel, meaningful information into existing knowledge networks and, consequently, enhanced memory for that information. Older and younger adults learned the prices of common grocery store items in an associative memory task. The prices were either unrealistic or realistic and, thus, could engage prior knowledge. Consistent with previous work [14,59,61], older, but not younger, adults showed better performance in the realistic, relative to the unrealistic, condition, displaying a memory advantage for information consistent with prior knowledge. Neurally, performance in the realistic, but not unrealistic, condition was associated with DMN activity during encoding, as well as at retrieval, in both older and younger adults. Additionally, increased interaction between the DMN and a cognitive control network during encoding, a network interaction pattern implicated in accessing internal representations and typically seen during successful memory retrieval [93–95], was associated with realistic memory performance in both age groups. These findings suggest that, in older adults, the incorporation of prior knowledge into memory is mediated by naturally elevated DMN activity and connectivity with control regions [96], a brain pattern that can also be flexibly expressed by younger adults. Evidence consistent with this conclusion is also seen in a study of autobiographical memory; connectivity between the DMN and a lateral prefrontal control region at rest was associated with the extent to which older adults recalled semantic (generalized), rather than episodic, details [97]. Together, these findings suggest that this age-related DMN interaction pattern is associated with the representation of knowledge-based details in memory. In conjunction with behavioral evidence, these findings suggest that prior knowledge has a prominent role in the encoding of new information in older adults, resulting in its over-representation in memory.

Binding of task-irrelevant information to target information

In addition to the over-representation of previously relevant and knowledge-based details in the memories of older adults, evidence suggests that task-irrelevant information, present in or cued by the immediate environment, is encoded along with target information. For example, concurrent irrelevant information is disproportionately disruptive to older adults, slowing performance on simple tasks [98] and increasing errors in problem-solving [99]. Work also suggests that older adults retain previously concurrent distraction to solve new problems [100], to complete fragments [101], and even to answer general knowledge questions [102] (see also [31,54,103–106]). Thus concurrent, task-irrelevant information is also part of what comprises representations formed by older adults.

A related series of studies demonstrates that distraction is not only encoded, but is also bound to co-occurring target information, a phenomenon termed 'hyperbinding' [11]. This phenomenon is another consequence of reduced cognitive control that adds information to older adults' memory representations. Hyperbinding was first seen in a set of studies that showed that previous distractors could impact older but not younger adults' performance on a subsequent paired-associates memory task [11,107]. During the initial phase of these studies, older and younger adults performed a one-back task on target pictures with superimposed irrelevant words that they were instructed to ignore. After a brief delay, participants performed an intentional picture–word associative memory task, which, unbeknown to the participants, included preserved and repaired (disrupted) picture–word pairs from the initial one-back task, as well as new pairs. Unlike younger adults, who showed similar performance across pair types, older adults showed an advantage on the preserved pairs and a disadvantage on the disrupted pairs relative to the new pairs, evidence that older adults bound the distractors to the original targets and maintained that information over a delay. Several other studies showed a similar age-related hyperbinding effect by demonstrating that, when studying an object presented with both a task-relevant (e.g., color) and task-irrelevant (e.g., scene) context, older adults were more likely than younger adults to show conditional dependence between the two contexts. In other words, older adults were more likely to recall one context if they accurately recalled the other context ([108,109]; see also [110]).

A recent study also examined whether a delayed re-presentation of one component of a 'hyperbound' or cluttered memory representation could evoke, and possibly even increase accessibility of, another component of that representation [111]. In the study, older adults initially performed a one-back task on target pictures with superimposed irrelevant words. They then performed a living/non-living judgment task on pictures, half of which had been seen as targets in the initial one-back task. The assumption was that, given the creation of strong links between targets and distractors, a single re-presentation of the target could elicit spontaneous reactivation of its previously paired distractor and, thus, increase its subsequent accessibility. Implicit memory for the original distractors was tested in a general knowledge task in which answers to the questions were the words seen as distractors in the initial one-back task. Consistent with a cluttered memory interpretation, older adults showed greater memory for reactivated distractors, the original targets of which were seen in the living/nonliving phase, relative to distractors, the targets of which were not seen in that phase. These findings provide direct evidence that memory representations are cluttered in old age, containing task-irrelevant information bound to target information (see also [112]).

Considered together, the discussed studies suggest that, with age-related reductions in cognitive control or inhibitory mechanisms, older adults are less likely than are young adults to suppress no-longer-relevant information, to control or suppress the activation of prior knowledge, to ignore task-irrelevant information and to prevent its automatic binding with target information (Figure 1 and Box 1). These control mechanisms, as well as additional contributing factors (Box 2), can at least partly account for the cluttered nature of older adults' memory representations.

Box 2. Contributors to age differences in mnemonic representations

Mounting evidence suggests that changes in cognitive control due to age shape the mnemonic representations of older adults. In evaluating this evidence, it is important to consider additional factors that might contribute to age-related differences in cognitive control. For example, research suggests that cognitive control fluctuates in a circadian fashion, and that these patterns differ with age. As a result, younger adults perform at peak levels in the evening, while older adults' performance peaks in the early morning [128]. Indeed, behavioral evidence indicates that, when tested at their peak time (morning), relative to later in the day, older adults show reduced processing and memory for task-irrelevant information, reflecting enhanced cognitive control [99,101]. Neural evidence indicates that when tested in the morning, older adults show enhanced activity and connectivity patterns in brain regions supporting cognitive control, more closely mirroring the patterns typically observed in younger adults [129,130]. In addition to time of testing, older adults' performance is heavily influenced by mood. Research shows that, compared with younger adults, older adults report a more positive mood [131], and this has been associated elsewhere with a broader focus of attention and increased processing of distraction [132,133]. Finally, the goals and values of older adults are likely to differ from those of young adults, and this can also contribute to differences in cognition [134]. These factors critically contribute to age-related differences in cognitive control and, as a result, the nature of mnemonic representations.

Functional outcomes of cluttered memory representations

Retrieval difficulties

How can the unique nature of older adults' memory representations account for age-related cognitive patterns? Classic memory studies of fan and cue overload effects demonstrate that cues associated with many responses result in poorer retrieval of those responses than of cues associated with fewer responses [113–115]. Older adults can be seen as models of these retrieval effects, given that their memory representations contain more information than do those of younger adults. That is, given that older adults form and maintain extraneous links between target and irrelevant information in memory, they are more likely than younger adults to experience interference from irrelevant information during memory retrieval. This spontaneous retrieval of irrelevant information is particularly disruptive to target retrieval, considering that older adults also show a reduced ability to resolve interference by suppressing competitors [18,19,28,29,41].

Converging evidence supports an age-related link between cluttered memories and retrieval difficulties. For example, older adults are more susceptible than younger adults to interference and retrieval deficits in the fan effect paradigm, in which a target item is studied with an increasing number of associates ([116]; see also [17,117]). Similarly, retrieval difficulties due to maintenance of previously relevant information in memory are also reported in episodic and working memory tasks. For example, in older adults, neural activation of no-longer-relevant items during the retention period in a recognition task is associated with poorer recognition memory for relevant items [51]. Additionally, in tasks designed to measure working memory capacity, testing the longest set of items first rather than last improves older adults' working memory capacity scores to the same level as that of younger adults [49,50,118]. That is, in the former condition, older adults are less likely to have too much information from prior trials maintained or active in memory and, thus, are less likely to display retrieval difficulties. Clearly, cluttered memories in older adults can induce interference and disrupt retrieval of target information.

Potential benefits of cluttered or 'enriched' memories

Although cluttered memories that include both relevant and less relevant information can be particularly problematic for retrieval of target information, the enriched nature of these representations can sometimes benefit older adults. One example is creativity, in which problems are solved through novel solutions reached by forming broad associations between weakly linked elements and accessing seemingly irrelevant information. Evidence suggests that older adults show preserved, and at times enhanced, creativity as a function of enriched memories. For example, one study demonstrated that on the Remote Associates Task, in which three weakly related words (e.g., ‘room’, ‘bubble’, and ‘salts’) can be linked by a fourth missing word (‘bath’), older, but not younger, adults showed enhanced performance when exposed to solutions (i.e., the missing words) as distractors on a previous unrelated task [100]. Similarly, older adults showed a greater performance benefit than younger adults on the Alternate Uses Task (requiring generation of unusual uses for a common item), when useful suggestions were presented as distractors on a previous task [119]. These findings suggest that access to distractors in enriched memories can sometimes aid creativity. Finally, other studies show that access to prior knowledge representations in memory, indexed by DMN-control network interactions, is also associated with improved performance by older adults on the Alternate Uses Task [120,121]. These findings suggest that representation of additional elements in memory, whether previous distractors or knowledge-based details, can provide older adults with an advantage on open-ended tasks, such as creativity, that benefit from aggregating diverse bits of information from different sources.

Decision-making is another domain that might benefit from enriched memories. Although some studies have reported an age-related decline on decision-making tasks that depend on ‘fluid’ cognitive abilities [122,123], others have reported that older adults show an advantage on decision-making tasks when experience and prior knowledge are relevant. For example, older adults outperform younger adults on tasks in which optimal performance depends on: (i) accounting for previous decisions within the context of the experiment [4]; and (ii) incorporating accumulated knowledge to reason about social conflicts or make sound financial decisions [1–3]. This ability to incorporate prior knowledge, which contributes to older adults’ ‘wisdom’, is potentially afforded by enriched memories containing an over-representation of knowledge-based details. Clearly, however, more research is needed to establish a direct link between memory representations and decision-making in older adults (see Outstanding questions).

Finally, it is possible that the increased binding and richer encodings of older adults can even be leveraged to improve older adults’ learning and memory. For example, excessive linking of targets and distractors (i.e., hyperbinding) by older adults can be exploited to reduce forgetting [112] and to improve memory for face–name associations, a common memory complaint among older adults [124–126]. Specifically, presenting superimposed task-irrelevant names on faces in an initial selective attention task improved performance on a subsequent face–name association task when face–name pairs were maintained (as opposed to disrupted) from the initial task (i.e., enriched memories formed from the initial phase supported performance on the subsequent associative memory task) [126]. Additionally, prior knowledge representations that can clutter memory and be considered irrelevant in some contexts (e.g., price of a movie ticket 40 years ago) can provide age-related associative memory advantages should that information become useful (e.g., remembering item prices in different eras relative to now) [62]. In sum, although excessive information in older adults’ memory representations can interfere with the retrieval of specific target information and hurt performance, it can also provide an advantage on more open-ended tasks that benefit from extraneous knowledge.

Concluding remarks

Older adults have greater knowledge of the world but generally show poorer episodic memory performance on many laboratory-based tasks relative to young adults. Here, we propose that this paradox can be accounted for, at least partially, by the uniquely cluttered/enriched memory representations of older adults (see Box 3 for alternative accounts). Specifically, unlike young adults, older adults’ memory representations contain target information bound to irrelevant and/or knowledge-based details, likely formed as a function of reduced cognitive control. With these cluttered or rich representations, older adults are more likely to activate excessive information. This, in turn, can pose retrieval difficulties for target information (and negatively impact

Outstanding questions

How do older adults’ cluttered memory representations contribute to their knowledge base? Although it is well established that knowledge grows into old age, it is unclear how (and whether) excessive information associated with target information in a memory trace is eventually integrated into older adults’ long-term knowledge.

Do individual differences in cognitive control contribute to differences in memory representations? An extensive literature has illustrated that cognitive abilities show large variability with old age (e.g., differences in ‘brain maintenance’). Individual differences in the content of memory in relation to cognitive control would establish a strong link between cognitive control and the nature of memory representations.

How does age-related hippocampal function contribute to cluttered memory representations? The hippocampus, known to be critical for forming associations between encoded items, typically shows structural and functional decline with old age. How does this decline account for forming extraneous associations between items? Does reduced modulation of the hippocampus by cognitive control regions account for forming too many associations in memory?

How do cluttered representations provide a potential advantage on open-ended or knowledge-based tasks? Although the spontaneous retrieval of excessive information in memory might provide a boost on tasks that benefit from that information, it is unclear whether this process only occurs under implicit conditions, and whether older adults show similar benefits when control-based evaluation of retrieved information is important for task success. Similarly, it is unclear how cluttered memories containing knowledge-based details might allow incorporation and usage of such details on decision-making tasks that require retrieval and manipulation of prior knowledge for optimal performance.

Box 3. Alternative explanations for age-related memory differences

Although there is convincing evidence that interference from irrelevant information, as a result of cluttered memories, contributes to age-related memory differences/deficits, alternative accounts have been proposed to explain these differences. One account, the associative deficit hypothesis, posits that age-related difficulties in binding or integrating individual elements into a cohesive unit during encoding is the source of age differences in memory performance [12]. According to this view, binding deficits result in spare records of experience, which result in poor retrieval in associative memory tasks [63,135,136]. However, older and younger adults show equivalent associative memory performance when memory for target associations is tested implicitly [15,16,32]. These findings are consistent with the cluttered memory account, suggesting that, in contrast to binding deficits, older adults form too many associations (between both target and irrelevant items [11,111]), and then are differentially vulnerable to interference.

Another approach to age differences in memory that might appear to contradict the notion of age-related cluttered memories is the environmental support account [137,138]. This account proposes that, due to difficulties in maintaining internal task or cognitive representations, older adults rely on external information (or 'outsource' control to the environment) to support cognitive performance. The environmental support hypothesis received empirical support in memory studies showing that older adults tend to perform progressively worse on memory tasks that require self-initiated processing relative to tasks with supporting information provided by the environment (e.g., repetition priming versus recognition versus free recall) [139]. However, this approach does not account for data showing the role of the recent past, of general knowledge, and of irrelevant information in the cognitive functioning of older adults. It also does not account for the susceptibility of older adults to interference from excessive information and from reduced ability to suppress irrelevant information. The current environment might well play a substantial role in the mental lives of older adults and might even help to offset some clutter-related retrieval difficulties, but, in our view, it is the ability to control excessive information that is the more powerful source of age differences in memory.

episodic and working memory tasks), but can also aid performance on tasks, such as creativity, decision-making, and sometimes new learning, which benefit from access to knowledge from various sources. Future research can investigate how negative and positive outcomes of cluttered/enriched memory representations converge to influence functional behavior in everyday life (see Outstanding questions).

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Declaration of interests

None declared by authors.

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