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Hyper-Binding: Older Adults Form Too Many Associations, Not Too Few

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Abstract
Associative memory declines with age, and this decline is thought to stem from a decreased ability to form new associations or bind information together. However, a growing body of work suggests that (a) the binding process itself remains relatively intact with age when tested implicitly and (b) older adults form excessive associations (or "hyper-bind") because of a decreased ability to control attention. In this article, we review evidence for the hyper-binding hypothesis. This work shows that older adults form more nontarget associations than younger adults, which leads to increased interference at retrieval and forgetting, an effect that may extend to others with poor attentional control, such as children and people with attention-deficit disorder. We discuss why hyper-binding is apparent only under implicit test conditions and how it affects memory for everyday events. Although hyper-binding likely contributes to forgetting, it may also confer certain advantages when seemingly irrelevant associations later become relevant.

Keywords
aging, memory, attention, hyper-binding, frontoparietal control network, hippocampus

Associations are the building blocks of episodic memory, or memory for events from our lives. Remembering that you saw your old friend Barbara at the movies last Tuesday requires associating Barbara with a particular location on a particular date. Age-related impairments in episodic memory have been attributed to older adults' lessened ability to form these associations (sometimes referred to as a "binding deficit"; Chalfonte & Johnson, 1996), leading them to do worse on a range of associative memory tasks relative to younger adults (Naveh-Benjamin & Mayr, 2018). According to this view, you might forget where you saw Barbara last week because you failed to associate her with the movies. Although there is no doubt that older adults do worse on explicit tests of associative memory, the precise cause of this deficit has been called into question by work showing that (a) associative memory remains intact with age when tested implicitly (e.g., Dew & Giovanello, 2010) and (b) older adults seem to form more nontarget associations (or "hyper-bind"; Campbell et al., 2010) because of a decreased ability to control their attention. According to this hyper-binding view, you might misremember seeing Barbara at the supermarket because you went there just before the movies (erroneously binding Barbara to both the store and movies, leading to confusion at retrieval). In this article, we review evidence of hyper-binding. This work shows that older adults are less able to ignore concurrent distractions in the environment and to suppress previously attended information that is no longer relevant. As a result, they form more nontarget associations that lead to interference at retrieval and increased forgetting. We discuss why hyper-binding is apparent only under implicit test conditions, how it affects memory for more complex events such as those experienced in everyday life, and when it may be advantageous.

Binding and Attention Are Separate Processes

An important distinction needs to be made between the binding process in long-term memory, which links information together and depends on structures in the medial temporal lobe, and attention. The binding process has long been viewed as a relatively automatic process, present in other species and human infants

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(Rovee-Collier & Cuevas, 2009), that associates features or representations simultaneously held within the focus of attention (Logan & Etherton, 1994). From an evolutionary perspective, it makes sense that binding should be automatic—we are born with much to learn, things that co-occur in space and time are likely causally related, and you never know when something may prove to be useful later (e.g., the shrimp you ate yesterday made you feel sick). In contrast, top-down attention is a controlled process, dependent on frontal and parietal regions, that serves to restrict processing to "target" or goal-relevant information and suppress irrelevant distractions, leading to sharper representations in the medial temporal lobes and successful encoding of target associations (Aly & Turk-Browne, 2016). Thus, attention restricts binding to target information, allowing you to learn the things you want to learn (e.g., Barbara at the movies) and block out the things you want to ignore (e.g., the supermarket).

Binding Is Preserved With Age

In the lab, associative memory is usually tested explicitly. For instance, participants are shown a list of unrelated word pairs (e.g., shoe-diamond, phone-horse, chair-doctor) and later asked to recall one member of the pair when cued by the other or differentiate between intact (phone-horse) and rearranged (shoe-doctor) pairs. Older adults usually fail to recall or falsely recognize more rearranged pairs than younger adults, whereas their ability to recognize intact pairs remains unchanged. Poorer performance on these explicit associative tests is often taken as evidence that the binding process declines with age (Naveh-Benjamin & Mayr, 2018). However, the binding account cannot explain why age differences are not observed on implicit (i.e., indirect) tests of associative memory (e.g., Davis et al., 2021; Dew & Giovanello, 2010; Kan et al., 2011). For instance, Dew and Giovanello (2010) asked younger and older adults to make speeded decisions about pairs of objects at encoding (e.g., whether both objects fit together inside a common desk drawer). During testing, participants performed the same decision task, but now some of the pairs remained intact and some were rearranged. Both younger and older adults were faster to respond to intact than rearranged pairs, and there was no age difference in this effect, suggesting that both groups were speeded by their implicit memory for the associations. Thus, implicit associative memory seems to remain intact with age, but explicit access to these associations is clearly impaired. In the following sections, we argue that this is due partly to increased interference at retrieval from nontarget associations inadvertently formed at encoding.

Reduced Attentional Control With Age Leads to Hyper-Binding

Attentional control declines with age (Hasher & Zacks, 1988). Relative to younger adults, older adults are less able to ignore distracting information in the external environment. Older adults also experience more internal distraction while maintaining access to previously attended information when it is no longer relevant (e.g., faces they were instructed to forget; Weeks et al., 2020) and activate semantically related information that is not relevant to the task at hand (Qiu & Johns, 2020; Ramscar et al., 2017). As a result, older adults and others with poor attentional control often have more information in mind at any one time (see Fig. 1). If binding is an automatic process that links together co-attended information, then older adults should form more unwanted associations between whatever representations they have in mind.

In the first study to show this hyper-binding effect (Campbell et al., 2010), older and younger adults first performed a 1-back task on pictures that were overlapped with distracting words (see Fig. 1). Participants were told to ignore the words and press a button when the same picture repeated twice in a row. After a delay, participants completed an ostensibly unrelated paired-associate learning task in which they learned a series of picture-word pairs. Unbeknownst to participants, one third of those pairs remained intact from the 1-back task, one third were rearranged, and one third were new. Older adults showed a learning advantage for intact pairs and a disadvantage for rearranged pairs relative to new pairs, suggesting that they had incidentally learned the target-distractor pairs on the 1-back task, and this influenced later memory performance. Young adults, on the other hand, showed no difference between the pair types, suggesting that they ignored the words on the 1-back task. This hyper-binding effect has now been replicated with face-name pairs (Weeks et al., 2016), object-context pairs (Powell et al., 2018), and when distractors co-occur over time (Campbell, Zimerman, et al., 2012). Taken together, this work suggests that older adults may form more associations than younger adults, albeit between representations that never should have been attended in the first place.

It is important to note that hyper-binding is not specific to older adults. Anyone with impaired attentional control is likely to form more nontarget associations (Rovee-Collier & Cuevas, 2009). For instance, Davis et al. (2024) recently had younger adults complete a hyper-binding version of the Dew and Giovanello (2010) paradigm in which they were asked to decide whether a pictured object could fit in a desk drawer while ignoring an overlapping object word. During testing, picture-word pairs were either intact or rearranged,

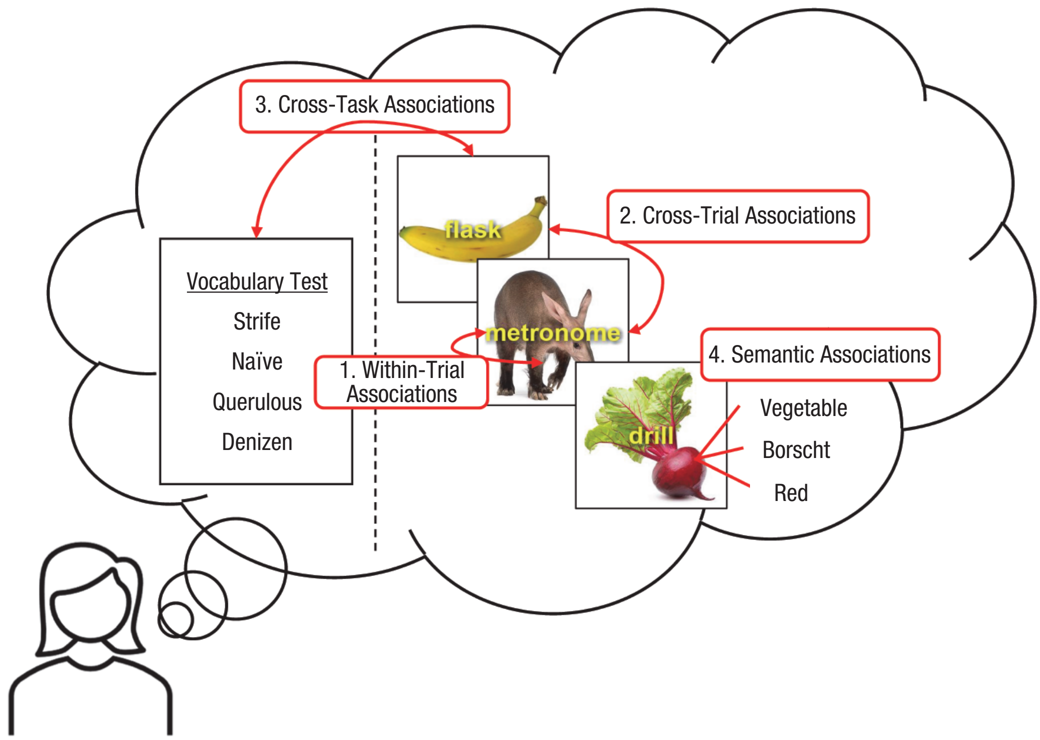

Fig. 1. Potential sources of nontarget associations. Older adults and others with poor attentional control may inadvertently form associations within a trial whenever targets and distractors co-occur (e.g., a target picture overlapped with a distracting word; 1), across trials because of a lessened ability to put recently attended information out of mind (sometimes referred to as "working memory updating"; 2), across tasks (e.g., from an earlier vocabulary test to a current memory task; 3), and between target information and semantically related concepts (to which activation spreads automatically when attentional control is lacking; 4).

and participants now had to decide whether both objects could fit in the drawer, with faster response times (RTs) to intact than rearranged pairs indicative of hyper-binding. Participants also completed a battery of attentional control tasks that involved inhibiting distraction (including Stroop deadline, flanker deadline, antisaccade, and selective visual arrays; see Draheim et al., 2021). These measures were then used to form a composite attentional control score that was related to individual differences in hyper-binding (rearranged – intact RTs). Young adults with low attentional control showed significant hyper-binding, whereas those with high attentional control did not, suggesting that poor suppression of distraction, rather than age, is the critical mechanism responsible for hyper-binding. However, another recent study (Justus et al., 2021) found no difference in hyper-binding between typically developing young adults and those with autism spectrum disorder (ASD), and in the ASD group, worse executive functioning was associated with less hyper-binding. Although this study was not designed to look at individual differences because it used only a single measure of executive control (the Trail Making Test, Part B) and a relatively small sample (n = 23 in the ASD group), it does suggest that the suppression of distraction is relatively preserved in ASD. Going forward, it will be important to test whether hyper-binding is exhibited by others with poor attentional control, such as those diagnosed with attention-deficit disorder, and whether these effects are exacerbated by age.

Hyper-Binding Is Apparent Only on Implicit Tests

To date, hyper-binding has been observed only when tested implicitly. For instance, Campbell et al. (2010) had a separate sample of younger and older adults perform the same 1-back task followed by an explicit cued recall test, showing the picture alone and asking participants to recall the associated distracting word. Neither group could recall the distracting words or match up the pictures with their corresponding words on a subsequent matching test. This suggests that despite being better able to learn the intact target-distractor pairs (an implicit measure of memory), older adults could not intentionally recall them. Implicit

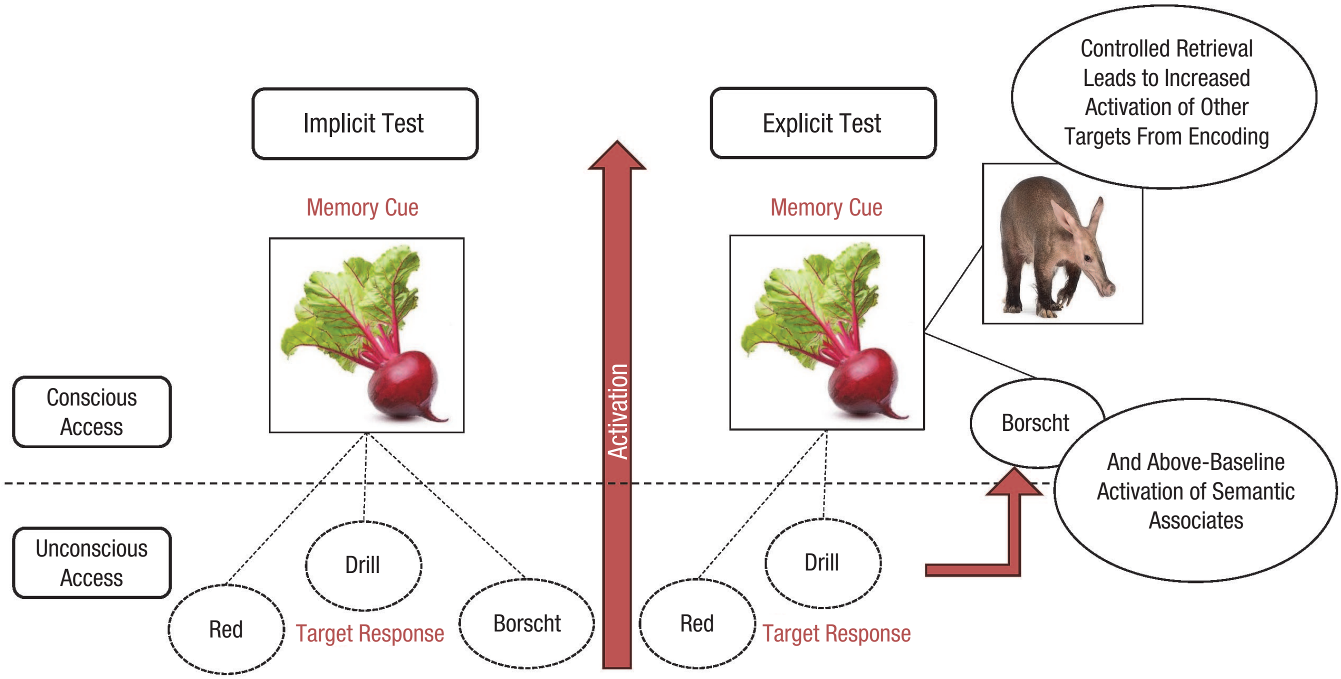

Fig. 2. Why is hyper-binding apparent only on implicit tests? This schematic illustrates how an implicit test (shown on the left) may differ from an explicit test (shown on the right). On implicit tests, participants are not actively trying to remember. Memory is inferred, for instance, by faster responding to previously associated stimuli relative to a baseline condition (e.g., faster responding to intact than rearranged pairs when deciding whether both objects could fit in a desk drawer; Davis et al., 2021, 2024; Dew & Giovanello, 2010). When a memory cue is shown (in this case, a beet), its previously distracting associate (in this case, "drill"; see Fig. 1) may have a higher level of activation than other associates, including semantically related words. This higher level of activation leads to faster responding to the associated target response (i.e., priming or implicit memory). However, on explicit tests, participants actively try to remember the word that was paired with "beet." This may lead to increased activation of other related stimuli, such as other stimuli seen at encoding (e.g., the aardvark) and semantically related concepts (e.g., "borscht"). Increased activation of these related concepts (possibly even to conscious levels) then interferes with memory for the relatively weak target-distractor association. Thus, participants cannot explicitly report these nontarget associations despite showing implicit memory for them.

memory tests tend to be more sensitive than explicit tests, detecting memory for materials long after they can be recognized (Mitchell & Brown, 1988), and implicit memory is relatively spared with age (Light & Voie, 1993). The fact that the young adults in the Campbell et al. (2010) study did not show implicit memory for the target-distractor pairs on this highly sensitive relearning task suggests that they did not learn the pairs in the first place.

In a later study, Campbell and Hasher (2018) showed that even alerting participants to the relevance of previous distraction prior to the paired associate learning task is sufficient to disrupt the benefit for intact pairs in older adults. This may be because attempts at controlled retrieval can block implicit access (e.g., Ikier et al., 2008), possibly by increasing the activation of other target information from encoding and/or failing to prevent the automatic spread of activation to semantic associates while searching for the correct response (see Fig. 2). Future work should aim to test these hypotheses.

Nontarget Associations Lead to Increased Interference at Retrieval

Although nontarget associations may sometimes be useful, such as when previously irrelevant associations later need to be learned (Weeks et al., 2016), we think they more often contribute to increased interference at retrieval—a major cause of forgetting. A classic finding in the memory literature known as the "fan effect" (Anderson, 1974) shows that the more responses associated to a single memory cue, the worse memory is for any one response (e.g., you may have trouble recalling Jennifer Hudson's last name because you know so many other famous Jennifers). By encoding more nontarget associations, older adults are creating a larger "fan" and setting themselves up for greater interference at retrieval. Moreover, because inhibition is also required to suppress competing responses at retrieval, and this process also declines with age (Healey et al., 2013), older adults may be particularly vulnerable to interference from unwanted associations.

In support of this, Davis et al. (2024) found that individuals with poor attentional control showed a greater slowdown in deciding whether rearranged pairs could fit in a desk drawer relative to RTs at encoding, suggesting that attentional control is needed to overcome interference from competing responses in the fan for rearranged pairs at retrieval. Further, Campbell et al. (2010) showed that older adults were worse at learning disrupted pairs relative to new picture-word pairs, suggesting that the original associations interfered with their ability to learn new associations using the same stimuli. Older adults may also experience more interference from preexisting semantic associations that are automatically activated at retrieval (Healey et al., 2014). For instance, Qiu and Johns (2020) recently showed that older adults' cued recall of paired associates was worse when the cue word had several semantic associates in the language (i.e., high semantic diversity) than when it had few associates. Young adults' recall was unaffected by the semantic diversity of the words, suggesting that they experience less interference than older adults (who know more thanks to their greater exposure to the language; Ramscar et al., 2017) and/or young adults are better able to suppress semantic associates at retrieval (Healey et al., 2014). Older adults may also experience more interference from cross-trial associations formed at encoding, which has been shown to contribute to their heightened rate of false alarms on associative recognition tasks (Campbell et al., 2014). At a neural level, interference from nontarget associations seems to increase the demands on the frontal control processes required to resolve interference at retrieval (James et al., 2016). Taken together, these findings suggest that hyper-binding may be a major source of interference for older adults and, as a result, age-related forgetting.

Modifying Factors

Recent work has started to identify a number of factors that can modify the hyper-binding effect, including motivation, emotion, and fluctuations in attention over time. In one study, older and younger adults performed a face-name hyper-binding task, and motivation on the 1-back task was manipulated (between-subjects) by either awarding points for successful performance or not (Swirsky & Spaniol, 2020). Whereas older adults in the standard (unrewarded) condition showed the usual hyper-binding effect, those in the incentivized condition did not (and young adults did not hyper-bind in either condition). This work suggests that increasing motivation can help older adults focus their attention and avoid forming nontarget associations. In another study (Gallant et al., 2020), the emotional valence of the distracting words was manipulated. Older and younger adults performed a 1-back task on pictures that were overlapped by either positive, negative, or neutral distracting words. Older adults showed hyper-binding when the distraction was neutral but not emotional. In contrast, young adults showed hyper-binding when the distraction was negative but not positive or neutral, which is in line with other work showing an attentional bias toward negative information in young adults that fades with age (Carstensen & DeLiema, 2018).

Another factor that may affect hyper-binding is fluctuations in attention over time. Recent work suggests that young adults are more likely to learn distracting information when they are mind wandering (or "out of the zone"; Decker et al., 2023), suggesting that susceptibility to hyper-binding may fluctuate across trials depending on one's attentional state, but this remains to be seen. The ability to focus attention also fluctuates across the day with one's circadian rhythm (May et al., 2023). Although no study has looked at time of day and hyper-binding directly, related work has shown that older adults encode more distracting information at their nonoptimal time of day, when attentional control is lowest (i.e., the afternoon for most older adults; May et al., 2023). Indeed, in our previous hyper-binding studies, we have tended to test participants in the afternoon, when research assistants and undergraduate participants are most available. Future work should manipulate the time of testing to see whether hyper-binding is minimized for older adults in the morning.

Implications for Memory and Problem-Solving in Everyday Life

Outside the lab, poor attentional control may lead to the formation of broader associations across events. As we move around the world, we tend to divide our continuous experience up into a series of discrete events (e.g., eating breakfast, brushing teeth, commuting to work). Event segmentation theory (Zacks, 2020) posits that we experience event boundaries whenever we are no longer able to predict what will happen next, such as when there is a change of scene or goals. Event boundaries affect how information is encoded into long-term memory, with stronger associations formed within events than across event boundaries (e.g., Ezzyat & Davachi, 2011). Recently, Henderson and Campbell (2023) used a movie-watching paradigm to show that individual differences in attentional control relate to less distinct events being stored in long-term memory in older adults, suggesting that hyper-binding may extend to the encoding of more naturalistic stimuli. Those who blurred across event boundaries (i.e., showed relatively stronger associations between events) also had worse memory for the movie overall, suggesting that cross-event binding may contribute to forgetting more complex, lifelike events. However, blurring across events may give older adults an advantage when it comes to linking together distant pieces of information to form an overarching narrative (Cohn-Sheehy et al., 2021). This may help explain why several aspects of narrative processing are relatively well preserved with age (Stine-Morrow & Radvansky, 2018).

Conclusions and Future Directions

We have shown that reduced attentional control with age leads to the formation of more nontarget associations, which may contribute to age-related declines in associative memory via increased interference at retrieval. Hyper-binding has been observed across a range of behavioral paradigms, but more work is needed to establish the neural underpinnings of this effect. Powell and colleagues (2018) used electroencephalography and multivariate pattern analyses to show that when a central object was flanked by both target and distracting contexts at encoding (i.e., a scene and a color), better classification of the target context related to better subsequent target memory and worse distractor memory. Critically, they also showed that a decrease in target classification over the first 500 ms of the trial related to greater hyper-binding, particularly in older adults, possibly reflecting a shift of attention away from the target context and toward the distractor. At retrieval, older adults' greater encoding of nontarget contextual information seems to place increased demands on control processes, as indexed by a larger late posterior negativity effect in older than younger adults (James et al., 2016). Going forward, it will be important to determine whether these nontarget associations depend on the hippocampus or are formed elsewhere in the cortex (e.g., Verfaellie et al., 2012) and the extent to which altered input from the frontoparietal control network is responsible for nontarget binding (Campbell, Grady, et al., 2012). Interestingly, Nyberg et al. (2019) showed that hippocampal hyperactivity at encoding (which is often observed in older adults at heightened risk for dementia) relates to altered frontal-hippocampal connectivity, and it remains to be seen whether hippocampal hyperactivity relates to hyper-binding.

Another important question for future research is to determine why nontarget associations are only accessible at an implicit level. We have speculated that controlled retrieval attempts disrupt access to these associations, but clear evidence remains to be seen. This could be tested, for instance, by measuring priming for competing information after implicit versus explicit retrieval of nontarget associations. We would expect to see greater priming for competitors, and less priming for the previously associated distractor (i.e., "drill" in Fig. 2), after an attempt at explicit retrieval compared with implicit retrieval.

Finally, we have mainly focused on the negative effects of hyper-binding throughout this article, but as mentioned above, hyper-binding may sometimes put older adults at an advantage. In the lab, we primarily test memory for target information. But in the real world, one moment's distraction may become the next moment's solution. Future work should examine whether older adults outperform their younger counterparts whenever previously irrelevant associations later become relevant.

Recommended Reading

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Henderson, S. E., & Campbell, K. L. (2023). (See References). Shows potential hyper-binding across event boundaries during movie watching.

Transparency

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