BRIEF REPORT



Some young adults hyper-bind too: Attentional control relates to individual differences in hyper-binding

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Abstract

Hyper-binding – the erroneous encoding of target and distractor information into associative pairs in memory – has been described as a unique age effect caused by declines in attentional control. Previous work has found that, on average, young adults do not hyper-bind. However, if hyper-binding is caused by reduced attentional control, then young adults with poor attention regulation should also show evidence of hyper-binding. We tested this question with an individual differences approach, using a battery of attentional control tasks and relating this to individual differences in hyper-binding. Participants (N = 121) completed an implicit associative memory test measuring memory for both target-distractor (i.e., hyper-binding) and target-target pairs, followed by a series of tasks measuring attentional control. Our results show that on average, young adults do not hyper-bind, but as predicted, those with poor attentional control show a larger hyper-binding effect than those with good attentional control. Exploratory analyses also suggest that individual differences in attentional control relate to susceptibility to interference at retrieval. These results support the hypothesis that hyper-binding in older adults is due to age-related declines in attentional control, and demonstrate that hyper-binding may be an issue for any individual with poor attentional control, regardless of age.

Keywords Implicit memory · Hyper-binding · Attentional control · Individual differences · Distraction

Introduction

Attention plays a crucial role in successful long-term memory encoding, such that attended stimuli are better remembered than unattended stimuli (for reviews, see Aly & Turk-Browne, 2017; Chun & Turk-Browne, 2007). This is the case for items that capture attention, like emotional (Carretié, 2014) and socially relevant stimuli (e.g., faces; Bindemann et al., 2005; Langton et al., 2008), as well as items or categories that participants are explicitly told to attend (e.g., Tozios & Fukuda, 2020; Williams et al., 2005). However, attention is not only important for the upregulation of taskrelevant information, but also for the suppression of distracting, task-irrelevant information (Gazzaley et al., 2005; Hasher & Zacks, 1988; Noonan et al., 2016). In memory tasks, distraction may be present both unintentionally (e.g., mind wandering; Blondé et al., 2022) and intentionally (e.g., Allen et al., 2020; Bergström et al., 2016), and has been shown to negatively affect memory performance. Distraction interrupts memory encoding by lessening the availability of attentional resources that can be allocated to task-relevant stimuli (Fernandes & Moscovitch, 2000; Weeks & Hasher, 2017) and reducing the fidelity of stimulus representations (Aly & Turk-Browne, 2016a, 2016b; Gazzaley et al., 2005). Further, distraction disrupts neural processes necessary for memory encoding (Uncapher & Rugg, 2005), including reducing connectivity between the frontal and medial temporal regions (Wais et al., 2010).

In some cases, when attentional resources are depleted or deficient, distracting information may not be sufficiently suppressed, resulting in that information being encoded to memory (Amer et al., 2016). For example, research with older adults – a population whose cognitive deficits can be partly explained by age-related changes in attentional control (Hasher et al., 1999; Lustig et al., 2007) – has shown that when task-irrelevant information cannot be adequately suppressed, it can become erroneously bound to task-relevant information and stored in long-term memory, ultimately influencing later behaviour (Campbell et al., 2010).

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Although there may be situations in which encoding excess information is beneficial (for reviews, see Healey et al., 2008; Yang et al., 2022), these excess associations can negatively impact memory performance by increasing competition at retrieval and causing forgetting (Biss et al., 2013; Gerard et al., 1991). This phenomenon (termed hyper-binding) was demonstrated initially by Campbell et al. (2010). In their experiment, older and younger adults completed a paired-associates task that included intact and rearranged picture-word pairs from a previous task in which the words had been distractors. Results showed that older adults were both helped and hindered by learning the previous targetdistractor pairs. In comparison to new pairs, older adults had better memory for pairs that stayed the same from the previous task, but they remembered fewer rearranged pairs. Young adults, a population with relatively good attentional control, showed no difference between these conditions, suggesting that young adults were able to suppress distracting information and stop the formation of erroneous associations.

Hyper-binding was originally presented as a "unique age effect" (Campbell et al., 2010). Indeed, several studies have failed to find evidence of hyper-binding in young adults (Campbell et al., 2014; Davis et al., 2021; James et al., 2016; Powell et al., 2018; Weeks et al., 2016; Weeks & Hasher, 2018). This is the case even if young adults are alerted to the relevance of previously distracting information for accomplishing their current goal (Campbell & Hasher, 2018; c.f. Ward et al., 2015). It has been hypothesized that age-related deficits in attentional control cause hyper-binding; however, to date there has been limited, if any, research that has specifically tested this. If hyper-binding in older adults is primarily driven by age-related deficits in attentional control, then there is no reason to suspect that this effect is unique to older adults; anyone with relatively poor attention should show evidence of hyper-binding. Some support for this comes from research showing that young adults are more likely to process distracting information under conditions of divided attention (Weeks & Hasher, 2017) or high working memory load (Lavie, 2005). Further, one study using the same paradigm as Campbell et al. (2010) showed that young adults bound target-distractor pairs when the distractors were salient (e.g., negatively valanced words) but not when they were neutral (Gallant et al., 2020). Finally, an EEG study by Powell et al. (2018) showed that although hyper-binding was most prevalent in older adults, there was some evidence for individual differences in the extent to which younger adults encoded target-distractor associations (though the correlation was small and not significant in their young adult sample).

In the current study, we aimed to explore whether individual differences in attentional control relate to younger adults' propensity to hyper-bind. To do so, we had participants complete an implicit associative memory task that included both a full-attention block and distraction block (or hyperbinding block). This task was selected because it has been previously used to investigate hyper-binding in younger and older adults (Davis et al., 2021), and hyper-binding is best measured under implicit conditions (Campbell & Hasher, 2018). In this task, participants are asked to make object categorization judgements for picture-word pairs. In the fullattention block, the judgement is made for both the picture and the word (i.e., would both objects fit together inside a common desk drawer?), while in the distraction block, the decision is made for the picture alone while ignoring the distracting word (i.e., would the pictured object fit in a drawer?). Implicit associative memory for the pairs is tested by showing intact and rearranged pairs at retrieval and having participants make the same categorization judgements (with faster responses to intact than rearranged pairs considered a marker of implicit associative memory). Following this task, participants completed a battery of attentional control tasks. We predicted that all participants should show evidence of implicit associative memory in the full-attention block. In contrast, we expected that, on average, participants should not show evidence of implicit associative memory in the hyper-binding block. This pattern of results would be in line with research showing that, on average, young adults do not hyper-bind (Campbell et al., 2010; Campbell & Hasher, 2018; Davis et al., 2021). However, we predicted that participants with worse attentional control would hyper-bind to a greater extent than participants with better attentional control.

Method

Participants

One hundred and eighty-seven participants aged 17-30 years were recruited during the 2022-2023 school year from Brock University and offered course credit or \$20 for their participation. We aimed to recruit at least 84 participants to obtain enough power ($\beta = .80, \alpha = .05$) to detect a correlation of r = .30 (Faul et al., 2007). We recruited as many participants as possible during the academic year, stopping data collection in April 2023 once classes were finished. Participants were excluded for the following reasons: they did not agree to have their anonymized data stored online (N = 4), researcher error (N = 1), program errors (N = 3), age > 30 years (N = 2), did not speak English sufficiently to understand task instructions (N = 1), did not pay attention (i.e., falling asleep during the task or, generally not engaging with the experiment; N = 4), accuracy on the object categorization task that was worse than 3.5 SD from the mean in either encoding block (hyper-binding encode < 61% accurate, full-attention encoding < 68%; N = 6), and reported switching to an explicit memory strategy during the implicit memory task (common in implicit memory research – see Awareness Questionnaire section below for further details; N = 46). This resulted in a final sample of 121 participants ($M_{age} = 20.28$, SD = 2.47 years; 91 women¹). Sensitivity analyses indicate that this sample size is sufficient to detect small-medium effects (r = .25).

Materials

Implicit associative memory test stimuli

One-hundred and seventy-six images of real-life, everyday objects $(300 \times 300 \text{ px})$ were selected from Hovhannisyan et al. (2021). Another 176 unique object-words were generated from other objects in the database that were not being used as pictures (e.g., a picture of a cardinal would generate the object word "bird"). These pictures and words were evenly split into living and non-living items and then randomly paired with some restrictions: Living pictures were paired with non-living words (and vice versa)², and 50% of the pairs needed to generate a yes response to the objectcategorization question (i.e., could the object(s) fit inside a common desk drawer). To ensure that participants always assessed both the picture and the word when asked to attend to both, the pairings were not always congruent (i.e., the picture did not always fit if the object-word did). This resulted in 30 incongruent and 50 congruent pairs in each list.

Once the images were paired, they were split into two lists of 80. The remaining 16 pairs were used for fillers at the beginning of the tasks (three per task) and for practice trials. For the memory test, the pairs were split evenly into intact and rearranged pairs. For rearranged items, the objects were re-paired such that responses to the object-categorization question remained the same from encoding to test to ensure that any changes in reaction time were a result of changes to the stimulus pairs and not to the stimulus-response binding (Gomes & Mayes, 2020). The lists were counterbalanced across participants such that each list was used in both the hyper-binding and full-attention blocks and in both the intact and rearranged conditions. The number of incongruent and congruent pairs were also evenly split between the intact and rearranged conditions. Word length and frequency were matched across the two lists and pair type conditions.

Awareness questionnaire

Participants completed a graded awareness questionnaire that probed whether they switched to an explicit memory strategy during the implicit associative memory tasks (as in previous studies on implicit associative memory; Dew & Giovanello, 2010; McKone & Slee, 1997). First, participants were asked if they noticed a connection amongst any of the object categorization tasks. If so, they were asked what they noticed and when. Then, whether they *tried* to remember previous responses they made when responding to the pairs. Participants who indicated that they tried to recall previous pairs and responses were marked as aware and excluded from the experiment. There was no significant difference in attentional control for aware (M = .19, SD = .62) versus unaware participants (M = .01, SD = .69), t (165) = 1.51, p = .132.

International cognitive ability resource assessment

If sufficient time remained in the session, participants also completed the International Cognitive Ability Resource as a measure of fluid intelligence (I-CAR; Condon & Revelle, 2014). We used the shorter 16-sample version of this test. The 16-sample test includes four questions from each of the following categories: Letter and Number Series, Verbal Reasoning, Three-Dimensional Rotation, and Matrix Reasoning. Participants were given 15 min to complete the questionnaire. Answers to each of the question was scored as 0 (incorrect) or 1 (correct). The outcome variable was the total number of correct answers across the four categories.

Procedure

The experiment was approved and carried out in line with the requirements instituted by the Office of Research Ethics at Brock University. Stimuli were presented using E-prime 3 (Psychology Software Tools, Pittsburgh, PA, USA) on a 14-in. Dell laptop $(1,366 \times 786 \text{ px})$. Participants were individually tested in-person between 10:00 a.m. and 7:00 p.m. to ensure that most young adults were not tested outside of their peak hours (for review on chronotype and cognition, see May et al., 2023). First, they completed the implicit associative memory tasks followed by four attentional control tasks. The implicit associative memory task was a modified version of the paradigm used by Davis et al. (2021). The attentional control tasks were downloaded from the Attention and Working Memory Lab's website (https://englelab. gatech.edu/). These tasks have been shown to reliably measure attentional control (Draheim et al., 2021). We opted to use a battery of tasks (as opposed to a single attentional control task) to get a more comprehensive and stable estimate of a participant's ability to control their attention. Following

¹ Missing sex data for two participants. Missing age data for three participants, but indicated to researcher that they were under 30 years.

² Using pictures and words from opposing living and non-living categories served as a pilot for a different experiment and does not serve any purpose in the current study.



Fig. 1 Implicit associative memory task example trials. Participants saw objects with superimposed text. In the hyper-binding encoding block, participants ignored the word and answered if the pictured object could fit inside a desk drawer. In the full-attention encod-

the computerized tasks, participants completed an awareness questionnaire, demographic questionnaire, Shipley Vocabulary test (Shipley, 1946), and if time remained in the session, the I-CAR 16 (this task was administered to 52 participants). The entire session took 2 h.

Implicit associative memory test

In the implicit associative memory tasks, participants completed two encoding-test blocks of an object categorization task. In the first ('hyper-binding') block, participants first completed an incidental encoding phase, in which they were shown pictures of everyday objects with superimposed yellow text (2,000 ms; see Fig. 1), separated by a fixation cross (1,000 ms). Participants were instructed to look only at the picture and ignore the overlapping text to answer whether the object could fit inside of a common desk drawer. Speed and accuracy were emphasized. If participants did not make a response within 2,000 ms, they could still respond for an additional 6,000 ms (8,000 ms total), but the stimulus was no longer visible. If participants responded within 2,000 ms, the stimulus remained on the screen for the entire 2,000 ms before the next trial began. This ensured that all stimulus pairs were viewed for the same time on each trial across participants, regardless of how quickly they responded. All pairs were presented twice at encoding. The pairs were presented once in random order before they were presented the second time. No pairs were shown twice in sequence (i.e.,

ing block, participants attended to both the picture and the word to answer if the objects could fit together inside a desk drawer. In both test blocks, participants attended to both the picture and word to answer if both objects could fit together inside a desk drawer

the first item in the second presentation was never the last item in the first presentation).

Immediately following encoding, participants completed an implicit associative memory test. In the test block, participants viewed the same objects and words from the encoding block, but the object-categorization question changed. Now, participants were asked to answer whether *both* objects could fit together inside a desk drawer. Unbeknown to the participants, some of the pairs at test were now intact (i.e., the same pairing from encoding) and some were rearranged (i.e., pictures and words previously presented, but not together).

In the second ('full-attention') block, the encoding phase remained the same, except participants were instructed to attend to both the picture *and* the word to answer whether *both* objects could fit inside a common desk drawer *together*. Immediately following encoding, participants completed the same implicit associative memory test as from the hyperbinding block. As such, participants viewed intact and rearranged pairs from encoding and were asked to answer whether *both* objects could fit inside a test drawer together. The outcome variable of interest for these tasks was reaction time (RT).

Anti-saccade

A full description of the attentional control tasks and outcome measures can be found in Draheim et al. (2021). Briefly, in the anti-saccade task, participants saw a centrally located fixation cross, followed by an alerting tone. After the tone, an asterisk appeared on either the left or the right side of the screen. Immediately after, a Q or an O appeared for 100 ms on the opposite side of the screen from the asterisk, followed by a mask (##). Participants had unlimited time to report which letter had been shown. The outcome variable was the number of target letters accurately identified.

Flanker deadline

This task is a modified version of the classic flanker. In this task, participants view five arrows that are either all pointing in the same direction (congruent), or the outside flanking arrows are pointing in a different direction to the center arrow (incongruent). Participants are asked to quickly, but accurately, indicate the direction of the center arrow. The modification from the original flanker paradigm is that each trial had a response deadline that participants needed to respond by. If participants did not respond by the deadline, then a loud beep would sound. The deadline increased or decreased after each block based on the accuracy of the previous block, such that if participants had high accuracy in the previous block, then the deadline was shortened, but if they had poor accuracy, then the deadline was extended. The outcome variable was the deadline value after the final block of trials (i.e., the deadline for the hypothetical next block). There were 18 blocks of 18 trials.

The reason this modified version of the Flanker task was selected (as opposed to the classic Flanker) is because Draheim et al. (2021) demonstrated that the outcome variable from deadline task was more highly correlated with other measures of attentional control than the outcome measures from classic versions of this task. This is also true of the Stroop task described below.

Stroop deadline

This task is a modified version of the classic Stroop task. Participants viewed colour words that were displayed either in the colour congruent to the word (e.g., *RED* displayed in red font), or incongruent to the colour word (e.g., *RED* displayed in blue font). Participants had to respond with the button that matched the colour the word was presented in (i.e., press the red button when any colour word was the colour red). Like the Flanker Deadline task, each block included a response deadline that got shorter or longer based on accuracy of the previous block. The outcome variable was the deadline value after the final block of trials (i.e., the deadline value for the hypothetical next block). There were 18 blocks of 18 trials.

Selective visual arrays

Participants were shown red and blue rectangles displayed in several orientations (set sizes: five per colour and seven per

colour). Before each trial, participants were provided with a cue (*RED* or *BLUE*) to indicate which coloured rectangles they should attend to. Following the study array there was a 900-ms delay, then participants were shown only the rectangles that were cued. Participants were asked to indicate whether the rectangle with a centrally placed white dot was facing the same direction or a different direction from the first display. The dependent variable was a capacity score (k; see Cowan et al., 2005; Draheim et al., 2021).

It is worth noting here that the Selective Visual Arrays task is often thought of as a working memory task. However, there is evidence to suggest that this task is more highly correlated with other attentional control tasks than working memory tasks (such as operation span tasks) and loads highly onto latent variables of attentional control (Draheim et al., 2021; Martin et al., 2021; Shipstead et al., 2015).

Results

Statistical analysis

Data were initially processed with E-prime's proprietary software. Other data processing and analysis were completed using R (version 4.0.3). We used the *tidyverse* (Wickham et al., 2019) and *englelab* (Tsukahara, 2022) libraries. Data and statistical analyses are posted on the Open Science Framework (see Open Practices Statement). Descriptions of data pre-processing and task reliability can be found in the Online Supplementary Material (OSM). All dependent variables (except for intelligence and the visual arrays task score) were not normally distributed so non-parametric statistical tests are used when necessary.

Implicit associative memory for target-target and target-distractor pairs

To assess whether young adult participants showed implicit associative memory in the full-attention block, but not the hyper-binding block, RTs were entered into a 2 (Block Type: hyper-binding, full-attention) \times 2 (Pair Type: intact, rearranged) within-subjects ANOVA. One participant had missing data from the full-attention block due to technical error, and was not included in this analysis. RT data were trimmed such that anticipatory responses less than 200 ms were removed, then RTs greater than 2.5 SD from an individual's mean for each condition were removed (see OSM). There was a significant main effect of Block Type, $F(1, 119) = 174.89, p < .001, np^2 = .595$, and a significant main effect of Pair Type, $F(1, 119) = 23.15, p < .001, \eta p^2$ = .163. However, these main effects were superseded by a Block Type \times Pair Type interaction, F(1, 119) = 11.65, p $< .001, \eta p^2 = .089$. Follow-up Wilcoxon signed-rank paired

| | Hyper-binding block | | Full-attention block | |
|------------------|---------------------|-----------|----------------------|-----------|
| | RT | Accuracy | RT | Accuracy |
| Encoding | | | | |
| 1st presentation | 826.7 (160.35) | .90 (.05) | 962.09 (201.85) | .89 (.06) |
| 2nd presentation | 732.86 (134.60) | .92 (.05) | 815.64 (176.76) | .91 (.05) |
| Test | | | | |
| Intact | 902.83 (178.65) | .91 (.06) | 769.11 (172.44) | .91 (.06) |
| Rearranged | 909.77 (191.40) | .91 (.05) | 808.63 (192.26) | .91 (.06) |

 Table 1
 Means and standard deviations of reaction time and accuracy for the implicit associative memory tasks

RT = reaction time in milliseconds. Accuracy is represented as a proportion of correct responses. Standard deviations are given in parentheses

t-test revealed that this interaction was driven by participants responding faster to intact compared to rearranged pairs in the full-attention condition, z = 5.44, p < .001, $r_{rb} = .572$, but not the hyper-binding condition, z = 0.76, p = .450, $r_{rb} = .079$. See Table 1 for means and standard deviations. This finding suggests that when participants attended to both the pictures and the words in the full-attention block, they formed target-target associations. However, participants did not form associations for the target-distractor pairs in the hyper-binding block, which is in line with previous work showing that young adults do not hyper-bind (Campbell & Hasher, 2018; Davis et al., 2021).

Does attentional control relate to implicit associative memory?

The variable of interest for the individual differences question was the extent to which there was a difference in RTs for the intact compared to rearranged pairs in the hyperbinding and full-attention blocks. Instead of using difference scores, which are known to be more variable than the individual means that go into them (Draheim et al., 2019) and to account for between-individual variability in baseline RT, we regressed mean RTs for intact pairs onto rearranged pairs across participants for each block type and used the residual as the *hyper-binding score* and *full-attention score* for that individual (see Healey et al., 2014, for a similar approach). The regression is as follows:

Rearranged pairs = $\beta_0 + \beta_1$ intact pairs.

Higher positive values indicate greater binding (i.e., faster responding to intact than rearranged pairs). It is worth noting that using a typical difference score (rearranged – intact) does not change the results, but we opted to use this regression measure because attentional control related to RTs overall. As such, controlling for baseline RT was important (see Faust et al., 1999). A composite overall *attentional control score* was calculated for each participant by averaging their z-scores across all four tasks (see OSM). Attentional control scores were then correlated with the hyper-binding and full-attention scores using Spearman's rank correlations.

In support of our prediction, hyper-binding was negatively and significantly related to attentional control, $\rho =$ -.216, p = .017 (see Fig. 2), such that poorer attentional control related to greater binding of target-distractor pairs. Correlations between hyper-binding and each attentional task separately were also computed (see OSM), and suggest that this effect was primarily driven by performance on the Flanker task (a task thought to measure inhibition of distraction; Friedman et al., 2004). Interestingly, there was also a trend towards attentional control negatively relating to the full-attention score, $\rho = -.171$, p = .062, suggesting that poor attentional control may also relate to implicit associative memory for target-target pairs.

Exploratory analyses

To further explore the somewhat counterintuitive finding that worse attentional control relates to greater implicit associative memory in the full-attention block, we first wanted to determine whether participants with high levels of attentional control showed memory for these pairs at all. We split the sample into four quartiles based on attentional control scores. In the high attentional control group (top 25% of participants, N = 31), we conducted a 2 (Block Type: hyperbinding, full-attention) \times 2 (Pair Type: intact, rearranged) ANOVA.³ There was a significant main effect of Block Type, $F(1, 30) = 63.39, p < .001, \eta p^2 = .679$, but no main effect of Pair Type, F(1, 30) = 2.48, p = .126, $\eta p^2 = .076$. However, there was a significant Block Type \times Pair Type interaction, F $(1, 30) = 5.30, p = .028, \eta p^2 = .150$. A follow-up Wilcoxon signed-rank paired t-test revealed that this interaction was driven by participants responding faster to intact compared to rearranged pairs in the full-attention condition, z = 2.31, p = .020, $r_{rb} = .476$, but not the hyper-binding condition, z = 0.86, p = .399, $r_{rb} = .177$. This analysis confirms that despite a negative relationship between attentional control and implicit associative memory for target-target pairs, on average, high-performing participants showed evidence of implicit associative memory in the full-attention block, but not the hyper-binding block (Fig. 3).

³ A sensitivity analysis indicated that this analysis had 80% power to detect a small to medium effect ($\eta p^2 = .065$) in the Block type × Pair type interaction.



Note. Scatterplots of correlations between (A) Attentional control and Hyper-binding scores and (B) Attentional Control and Full-attention scores. Hyper-binding and full-attention scores greater than 0 are indicative of implicit associative memory.

Fig. 2 Scatterplots for the correlation between attention and implicit associative memory task scores

This analysis stands in contrast to participants with the lowest attentional control performance (bottom 25% of participants, N = 31). For this group, there was a significant main effect of Block Type, F(1, 30) = 24.66, p < .001, $\eta p^2 = .451$. Critically, there was a main effect of Pair Type, F(1, 30) = 18.02, p < .001, $\eta p^2 = .375$, an effect driven by faster responding to intact compared to rearranged items across both the hyper-binding (z = 2.08, p = .037, $r_{rb} = .427$) and full-attention blocks (z = 3.61, p < .001, $r_{rb} = .742$), indicating that participants with poor attentional control showed evidence of implicit associative memory in both block types. There was no significant Block Type × Pair Type interaction, F(1, 30) = 2.66, p = .113, $\eta p^2 = .082$.

A possible explanation for the negative relationship between implicit associative memory in the full-attention block and attentional control is that the scores in this task are partly driven by interference to the rearranged pairs at test (causing slower responses), as well as faster responding to intact pairs. It is well known that participants respond faster to repetitions of familiar items and this priming effect is indicative of learning (Tulving & Schacter, 1990). However, unlike most priming studies, we lack a true baseline condition, in that we did not include any completely novel pairs. Instead, rearranged pairs consisted of familiar items previously paired with other items that may inadvertently come to mind and cause interference at retrieval. These interfering associations are not relevant to the task (i.e., not relevant for deciding if the current objects fit inside of a desk drawer) and, therefore, need to be suppressed. Suppression takes time (Healey et al., 2010, 2014) and relates to attentional control (Gerard et al., 1991; Healey et al., 2013; Ngo et al., 2021). While all participants likely experienced some degree of interference for rearranged pairs, those with poor attentional control may have been worse at overcoming this interference and slowed down more for rearranged pairs than those with better attentional control. Thus, difference scores on this task are likely being driven by *both* faster RTs for intact pairs (indicative of learning) *and* slower RTs for rearranged pairs (indicative of interference at retrieval) relative to RTs at encoding.

To explore this possibility, we regressed the mean RTs from the second time participants saw the pairs at encoding onto mean RTs to rearranged pairs in the full-attention block across participants. The residual of this was used as an *interference score* for that individual (i.e., the degree to which a person was slowed down for rearranged pairs at retrieval relative to encoding). The regression is as follows:

Rearranged pairs = $\beta_0 + \beta_1$ encoding trials (second presentation only)

Using this same method for the intact pairs, we also calculated an *intact-advantage score* (i.e., the degree to which a person sped up for intact pairs at retrieval relative to encoding):



Note. Mean reaction times to intact and rearranged pairs for participants with the lowest levels of attentional control (lowest 25%) and the highest levels of attentional control (highest 25%). Error bars are within-subject 95% confidence intervals.



Intact pairs = $\beta_0 + \beta_1$ encoding trials (second presentation only)

If participants with low levels of attentional control have difficultly overcoming interference when deciding about rearranged pairs at retrieval, then the interference score should be negatively related to attentional control. This is precisely what we saw: Interference scores were significantly associated with attentional control, $\rho = -.228 p = .012$ (see Fig. 4). In contrast, there was no evidence of a relationship between attentional control and the intact-advantage scores, $\rho = -.106 p = .251$, indicating that having better attentional control did not result in faster responding to pairs learned at encoding. That said, all participants were significantly faster each time that they viewed the pairings in the fullattention block (first encoding presentation RTs > second encoding presentation RTs > intact pairs at test RTs), ps < .001, suggesting that there was evidence for priming of the intact pairs. The lack of relationship between attentional control and the intact-advantage indicates that the extent of this priming was not related to attentional control. This finding is in line with classic views that associations are formed relatively automatically when two things are simultaneously attended (Logan & Etherton, 1994; Moscovitch, 1992).

Together, these results suggest that the difference scores in this implicit associative memory task may be driven by two separate cognitive functions (i.e., priming and interference) and that attentional control has a stronger influence on rearranged trials, which require suppression of no-longerrelevant, competing associations.

Discussion

The ability to suppress distracting information is essential for encoding and recalling task-relevant information (Aly & Turk-Browne, 2017; Hasher & Zacks, 1988). When distracting information cannot be suppressed, then participants may bind this distraction to task-relevant information (i.e., hyper-bind), which can lead to interference at retrieval and forgetting (Gerard et al., 1991). To date, hyper-binding has primarily been observed in older adults, likely due to age-related declines in attentional control. In these studies,



Note. Scatterplots of correlations between (A) Attentional control and Interference scores and (B) Attentional Control and Intact-Advantage scores. Scores greater than 0 are indicative of greater interference or greater priming, respectively.

Fig. 4 Scatterplots for correlations in exploratory analyses

young adults have not shown evidence of hyper-binding (Campbell et al., 2010, 2014; Campbell & Hasher, 2018; Davis et al., 2021). Here, we used an individual differences approach to demonstrate that young adults with poor attentional control hyper-bind to a greater extent than those with relatively better attentional control. These results support the hypothesis that the critical mechanism underlying hyperbinding in older adults is attentional control or inhibition of distraction (Campbell et al., 2010). Further, this study advances our understanding of the implications of attention on memory by showing for the first time that hyper-binding can also affect young adults.

These findings fit with several lines of work showing that when young adults' attention is divided (Weeks & Hasher, 2017) or cognitive resources are depleted (de Fockert et al., 2001), they are more likely to process distraction. For example, Weeks and Hasher (2017) showed that divided attention during a selective attention task resulted in young adults showing greater priming for distractors from that task compared to those in a full-attention condition. Relatedly, other work has shown that priming for distraction is associated with individual differences in activation in the frontoparietal control network (thought to be important for attentional control) when faced with distraction (Campbell et al., 2012). Sustaining attention over time also seems critical, as individuals who naturally experience more attentional lapses are more likely to learn task-irrelevant statistical regularities (Decker et al., 2022). Together, it seems that the erroneous processing of distracting or irrelevant information occurs in situations where young adults either naturally have poor attentional control or have been experimentally deprived of attentional resources. The current study advances these findings by demonstrating that the consequence of processing distractors is that they can be automatically bound to task-relevant information, stored in long-term memory, and influence behaviour on cognitive tasks later.

Attentional control was marginally related to implicit associative memory in the full-attention block. We did not make specific predictions for how attention would relate to performance in this block. However, exploratory analyses indicated that this negative relationship may result from participants with poor attentional control experiencing greater interference for rearranged pairs at retrieval. When rearranged pairs appeared at test, participants may have had the previously paired picture/word come to mind (e.g., if radish-dress and chair-dodo were seen at encoding, encountering radish-dodo at retrieval should automatically activate dress and chair to some degree). To complete the current goal (e.g., decide if radish and dodo can fit in a drawer together), participants need to suppress any competing representations that also come to mind (e.g., dress and chair; Anderson & Nelly, 1996; Healey et al., 2014). Overcoming interference at retrieval requires attentional control (Gerard et al., 1991; Healey et al., 2013; Ngo et al., 2021), hence participants with worse attentional control showing a greater slow-down for rearranged pairs than those with better attentional control. A parallel analysis for the hyper-binding block was not possible as the object-categorization question changed from encoding to test (going from "does the pictured object fit?" to "do both objects fit?"). This change resulted in significantly slower RTs for *both* intact *and* rearranged pairs during the hyper-binding test relative to encoding, whereas participants showed priming for intact pairs from the full-attention block (encoding RTs > intact RTs). Thus, a similar analysis for the hyper-binding block would be difficult to interpret.

One limitation of these findings is that our hyper-binding score is based on RTs at retrieval, and we do not have a measure of associative binding at encoding. Thus, we cannot say for certain that participants with relatively better attentional control did not encode the target-distractor pairs at all. An alterative explanation is that all participants, regardless of attentional control status, encoded target-distractor pairs, but only those with good attentional control were able to overcome interference from the rearranged pairs at retrieval. However, exploratory analyses suggest that this is not likely the case. Participants in the highest quartile of attentional control showed no evidence for a difference between intact and rearranged pairs from the hyper-binding block. Indeed, mean RTs were not even in the direction of rearranged > intact ($M_{difference} = -6.45$; see Fig. 3). In contrast, the lowest quartile group showed significant learning for both the hyper-binding ($M_{difference} = 30.50$) and full-attention blocks $(M_{difference} = 68.60)$. Together, this suggests that participants with the highest attentional control can suppress distractors at encoding, while participants with the lowest attentional control cannot or at least do so to a lesser extent. That said, experiments tackling this issue in future might consider using an online measure of distractor processing at encoding to help address this issue.

Encoding extraneous information can sometimes be helpful (Weeks et al., 2016), but we think it may more often lead to forgetting (Biss et al., 2013; Gerard et al., 1991). Here, we show that hyper-binding can affect young adults with relatively poor attentional control. Hyper-binding in older adults has been shown to affect memory in implicit memory tasks as well as explicit memory tasks (Campbell et al., 2014; James et al., 2016; Powell et al., 2018). Future research should consider exploring hyper-binding in explicit memory tasks in young adults to study the extent to which non-target associations affect them in these contexts. It may also be important to investigate other populations with attentional deficits, such as children and individuals with attention-deficit hyperactivity disorder, as excess associations may be a cause of forgetting in these groups as well.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13423-024-02464-w.

Open practices statement The datasets generated during the current study are available via the Open Science Framework (OSF) at: https://osf.io/678nh/?view_only=354cb066ec8442fb84a32e0c22e15e37. Scripts used to analyze data are available at the same repository. The implicit associative memory task programmed in our lab is available

from the corresponding author upon request. This experiment was not pre-registered.

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Declarations

Conflicts of interest Not applicable.

Ethics approval All components of this research project were carried out were approved by the Office of Research Ethics at Brock University (REB 16-306-CAMPBELL).

Consent to participate/Publish Informed consent was obtained from all individual participants included in the study. All participants included in the final sample consented to their anonymized data being released online for other researchers to access.

References

- Allen, J., Hellerstedt, R., Sharma, D., & Bergström, Z. M. (2020). Distraction by unintentional recognition: Neurocognitive mechanisms and effects of aging. *Psychology and Aging*, 35(5), 639.
- Aly, M., & Turk-Browne, N. B. (2016a). Attention promotes episodic encoding by stabilizing hippocampal representations. *Proceedings* of the National Academy of Sciences, 113(4), E420–E429.
- Aly, M., & Turk-Browne, N. B. (2016b). Attention stabilizes representations in the human hippocampus. *Cerebral Cortex*, 26(2), 783–796.
- Aly, M., & Turk-Browne, N. B. (2017). How hippocampal memory shapes, and is shaped by, attention. In D. E. Hannula & M. C. Duff (Eds.), *The Hippocampus from Cells to Systems* (pp. 369–403). Springer International Publishing. https://doi.org/10.1007/978-3-319-50406-3_12
- Amer, T., Campbell, K. L., & Hasher, L. (2016). Cognitive control as a double-edged sword. *Trends in Cognitive Sciences*, 20(12), 905–915.
- Anderson, M. C., & Nelly, J. H. (1996). Interference and inhibition in memory retrieval. In *Memory* (pp. 237–313). Academic Press.
- Bergström, Z. M., Williams, D. G., Bhula, M., & Sharma, D. (2016). Unintentional and intentional recognition rely on dissociable neurocognitive mechanisms. *Journal of Cognitive Neuroscience*, 28(11), 1838–1848.
- Bindemann, M., Burton, A. M., Hooge, I. T. C., Jenkins, R., & De Haan, E. H. F. (2005). Faces retain attention. *Psychonomic Bulletin & Review*, 12(6), 1048–1053.
- Biss, R. K., Campbell, K. L., & Hasher, L. (2013). Interference from previous distraction disrupts older adults' memory. *The Journals* of Gerontology: Series B, 68(4), 558–561.
- Blondé, P., Girardeau, J.-C., Sperduti, M., & Piolino, P. (2022). A wandering mind is a forgetful mind: A systematic review on the influence of mind wandering on episodic memory encoding. *Neuroscience & Biobehavioral Reviews*, 132, 774–792.
- Campbell, K. L., Grady, C. L., Ng, C., & Hasher, L. (2012). Age differences in the frontoparietal cognitive control network: Implications for distractibility. *Neuropsychologia*, 50(9), 2212–2223.
- Campbell, K. L., & Hasher, L. (2018). Hyper-binding only apparent under fully implicit test conditions. *Psychology and Aging*, 33(1), 176.

- Campbell, K. L., Hasher, L., & Thomas, R. C. (2010). Hyper-Binding: A unique age effect. *Psychological Science*, 21(3), 399–405.
- Campbell, K. L., Trelle, A., & Hasher, L. (2014). Hyper-binding across time: Age differences in the effect of temporal proximity on paired-associate learning. *Journal of Experimental Psychol*ogy: Learning, Memory, and Cognition, 40(1), 293–299.
- Carretié, L. (2014). Exogenous (automatic) attention to emotional stimuli: A review. Cognitive, Affective, & Behavioral Neuroscience, 14(4), 1228–1258.
- Chun, M. M., & Turk-Browne, N. B. (2007). Interactions between attention and memory. *Current Opinion in Neurobiology*, 17(2), 177–184.
- Condon, D. M., & Revelle, W. (2014). The international cognitive ability resource: Development and initial validation of a publicdomain measure. *Intelligence*, 43, 52–64.
- Cowan, N., Elliott, E. M., Scott Saults, J., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. A. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, 51(1), 42–100.
- Davis, E. E., Foy, E. A., Giovanello, K. S., & Campbell, K. L. (2021). Implicit associative memory remains intact with age and extends to target-distractor pairs. *Aging, Neuropsychology,* and Cognition, 28, 455–471.
- de Fockert, J. W., Rees, G., Frith, C. D., & Lavie, N. (2001). The role of working memory in visual selective attention. *Science*, 291(5509), 1803–1806.
- Decker, A., Dubois, M., Duncan, K., & Finn, A. S. (2022). Pay attention and you might miss it: Greater learning during attentional lapses. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/ s13423-022-02226-6
- Dew, I. T. Z., & Giovanello, K. S. (2010). Differential age effects for implicit and explicit conceptual associative memory. *Psychology and Aging*, 25(4), 911–921.
- Draheim, C., Mashburn, C. A., Martin, J. D., & Engle, R. W. (2019). Reaction time in differential and developmental research: A review and commentary on the problems and alternatives. *Psychological Bulletin*, 145(5), 508.
- Draheim, C., Tsukahara, J., Martin, J., Mashburn, C., & Engle, R. (2021). A toolbox approach to improving the measurement of attention control. *Journal of Experimental Psychology: General*, 150(2), 242–275.
- Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Meth*ods, 39(2), 175–191.
- Faust, M. E., Balota, D. A., Spieler, D. H., & Ferraro, F. R. (1999). Individual differences in information-processing rate and amount: Implications for group differences in response latency. *Psychological Bulletin*, 125(6), 777–779.
- Fernandes, M. A., & Moscovitch, M. (2000). Divided attention and memory: Evidence of substantial interference effects at retrieval and encoding. *Journal of Experimental Psychology: General*, 129(2), 155.
- Friedman, N. P., Profile, S., Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology, General*, 101–135.
- Gallant, S. N., Carvalho, M., Hansi, J., & Yang, L. (2020). The effect of emotional distraction on hyper-binding in young and older adults. *Cognition and Emotion*, 34(4), 839–847.
- Gazzaley, A., Cooney, J. W., Rissman, J., & D'Esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature Neuroscience*, 8(10), 1298–1300.
- Gerard, L., Zacks, R. T., Hasher, L., & Radvansky, G. A. (1991). Age deficits in retrieval: The fan effect. *Journal of Gerontology: Psychological Sciences*, 46(4), 131–136.

- Gomes, C. A., & Mayes, A. (2020). Study-test congruence of response levels in item stimulus-response priming. *Memory & Cognition*, 48(5), 839–855.
- Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 22, pp. 193–225). Academic Press.
- Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), Attention and Performance. Cognitive Regulation of performance: Interaction of Theory and Application (Vol. 17, pp. 653–675). MIT Press.
- Healey, M. K., Campbell, K. L., & Hasher, L. (2008). Chapter 22 Cognitive aging and increased distractibility: Costs and potential benefits. In W. S. Sossin, J.-C. Lacaille, V. F. Castellucci, & S. Belleville (Eds.), *Progress in Brain Research* (Vol. 169, pp. 353–363). Elsevier.
- Healey, M. K., Campbell, K. L., Hasher, L., & Ossher, L. (2010). Direct evidence for the role of inhibition in resolving interference in memory. *Psychological Science*, 21(10), 1464–1470.
- Healey, M. K., Hasher, L., & Campbell, K. L. (2013). The role of suppression in resolving interference: Evidence for an age-related deficit. *Psychology and Aging*, 28(3), 721–728.
- Healey, M. K., Ngo, K. W. J., & Hasher, L. (2014). Below-baseline suppression of competitors during interference resolution by younger but not older adults. *Psychological Science*, 25(1), 145–151.
- Hovhannisyan, M., Clarke, A., Geib, B. R., Cicchinelli, R., Monge, Z., Worth, T., Szymanski, A., Cabeza, R., & Davis, S. W. (2021). The visual and semantic features that predict object memory: Concept property norms for 1,000 object images. *Memory & Cognition*, 49(4), 712–731.
- James, T., Strunk, J., Arndt, J., & Duarte, A. (2016). Age-related deficits in selective attention during encoding increase demands on episodic reconstruction during context retrieval: An ERP study. *Neuropsychologia*, 86, 66–79.
- Langton, S. R. H., Law, A. S., Burton, A. M., & Schweinberger, S. R. (2008). Attention capture by faces. *Cognition*, 107(1), 330–342.
- Lavie, N. (2005). Distracted and confused?: Selective attention under load. Trends in Cognitive Sciences, 9(2), 75–82.
- Logan, G. D., & Etherton, J. L. (1994). What is learned during automatization? The role of attention in constructing an instance. *Journal* of Experimental Psychology Learning Memory and Cognition, 20(5), 1022–1050.
- Lustig, C., Hasher, L., & Zacks, R. T. (2007). Inhibitory deficit theory: Recent developments in a "new view." In D. S. Gorfein & C. M. MacLeod (Eds.), *Inhibition in cognition*. (pp. 145–162). American Psychological Association. https://doi.org/10.1037/11587-008
- Martin, J. D., Tsukahara, J. S., Draheim, C., Shipstead, Z., Mashburn, C. A., Vogel, E. K., & Engle, R. W. (2021). The visual arrays task: Visual storage capacity or attention control? *Journal of Experimental Psychology: General*, 150(12), 2525–2551.
- May, C. P., Hasher, L., & Healey, K. (2023). For Whom (and When) the Time Bell Tolls: Chronotypes and the Synchrony Effect. *Perspectives on Psychological Science*, 17456916231178553. https://doi. org/10.1177/17456916231178553
- McKone, E., & Slee, J. A. (1997). Explicit contamination in "implicit" memory for new associations. *Memory & Cognition*, 25(3), 352–366.
- Moscovitch, M. (1992). Memory and working-with-memory: A component process model based on modules and central systems. *Journal of Cognitive Neuroscience*, 4(3), 257–267.
- Ngo, K. W. J., Amer, T., Healey, M. K., Hasher, L., & Alain, C. (2021). Electrophysiological signature of suppression of competitors during interference resolution. *Brain Research*, 1767, 147564. https:// doi.org/10.1016/j.brainres.2021.147564
- Noonan, M. P., Adamian, N., Pike, A., Printzlau, F., Crittenden, B. M., & Stokes, M. G. (2016). Distinct mechanisms for distractor

suppression and target facilitation. *The Journal of Neuroscience*, 36(6), 1797–1807.

- Powell, P. S., Strunk, J., James, T., Polyn, S. M., & Duarte, A. (2018). Decoding selective attention to context memory: An aging study. *NeuroImage*, 181, 95–107.
- Shipley, W. C. (1946). *Institute of Living Scale*. Western Psychological Services
- Shipstead, Z., Harrison, T. L., & Engle, R. W. (2015). Working memory capacity and the scope and control of attention. *Attention*, *Perception*, & *Psychophysics*, 77(6), 1863–1880.
- Tozios, C. J. I., & Fukuda, K. (2020). Indirect, but not direct, downregulation of visual long-term memory encoding through strategic biasing of attentional allocation. *Journal of Experimental Psychology: General*, 149(7), 1294–1310.
- Tsukahara, J. S. (2022). englelab: An R package for processing complex-span and attention control tasks (1.1.0) [Zenodo]. https://doi. org/10.5281/zenodo.6987145
- Tulving, E., & Schacter, D. L. (1990). Priming and human memory systems. Science, 247(4940), 301–306.
- Uncapher, M. R., & Rugg, M. D. (2005). Effects of divided attention on fMRI correlates of memory encoding. *Journal of Cognitive Neuroscience*, 17(12), 1923–1935.
- Wais, P. E., Rubens, M. T., Boccanfuso, J., & Gazzaley, A. (2010). Neural mechanisms underlying the impact of visual distraction on retrieval of long-term memory. *Journal of Neuroscience*, 30(25), 8541–8550.
- Ward, E. V., de Mornay Davies, P., & Politimou, N. (2015). Greater priming for previously distracting information in young than older adults when suppression is ruled out. *Aging, Neuropsychology,* and Cognition, 22(6), 712–730.

- Weeks, J. C., Biss, R. K., Murphy, K. J., & Hasher, L. (2016). Facename learning in older adults: A benefit of hyper-binding. *Psychonomic Bulletin & Review*, 23(5), 1559–1565.
- Weeks, J. C., & Hasher, L. (2017). Divided attention reduces resistance to distraction at encoding but not retrieval. *Psychonomic Bulletin* & *Review*, 24(4), 1268–1273.
- Weeks, J. C., & Hasher, L. (2018). Older adults encode more, not less: Evidence for age-related attentional broadening. *Aging, Neuropsychology, and Cognition*, 25(4), 576–587.
- Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., ... Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, 4(43), 1686. https://doi.org/10.21105/joss.01686
- Williams, C. C., Henderson, J. M., & Zacks, F. (2005). Incidental visual memory for targets and distractors in visual search. *Perception* & *Psychophysics*, 67(5), 816–827.
- Yang, L., Kandasamy, K., & Hasher, L. (2022). Inhibition and creativity in aging: Does distractibility enhance creativity? *Annual Review of Developmental Psychology*, 4(1), 353–375.

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