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BRIEF REPORT

Age Differences in Visual Statistical Learning

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Recent work has shown that older adults' lessened inhibitory control leads them to inadvertently bind co-occurring targets and distractors. Although this *hyper-binding* effect may lead to the formation of more superfluous associations, and thus greater interference at retrieval for older adults, it may also lead to a greater knowledge of information contained within the periphery of awareness. On the basis of evidence that younger adults only show learning for statistical regularities contained within attended information, we asked whether older adults may also show learning for regularities contained within to-be-ignored information. Older and younger adults viewed a series of red and green pictures and performed a 1-back task on one of the colors. Unbeknownst to participants, both color streams were organized into triplets that occurred sequentially. Implicit memory for the triplets from both the attended and ignored streams was tested using a speeded detection task. Replicating previous work, younger adults demonstrated more learning for the attended triplets than the unattended triplets. Older adults, however, demonstrated similar learning for both the attended and ignored triplets, suggesting that contrary to popular belief, they may actually know *more* than younger adults about the world around them, including how seemingly irrelevant events co-occur.

Keywords: aging, inhibition, statistical learning, associative memory, binding

Individuals of all ages differ in their ability to ignore irrelevant information, but this ability declines with age (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999; Rabbit, 1965). Relative to younger adults, older adults are less able to suppress distracting information (Chao & Knight, 1997; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Hamm & Hasher, 1992), and this greater distractibility usually leads to reduced performance on ongoing tasks (e.g., Lustig, Hasher, & Tonev, 2006), although it can also result in a benefit when the distraction is relevant to the task at hand (e.g., May, 1999). Recent work suggests that the distraction effects are maintained over time, as older adults show implicit memory for previously irrelevant information as long as 15 min later, even though task demands and the experimental context have changed over this time period (Kim, Hasher, & Zacks, 2007; Rowe, Valderrama, Hasher, & Lenartowicz, 2006). Older adults' implicit memory for distraction is not limited to the distracting items themselves, as they actually also bind distractors with co-occurring targets and tacitly use this associative information to boost memory performance later on (Campbell, Hasher, & Thomas, 2010). This age-related *hyper-binding* effect, whereby older adults obligatorily encode seemingly extraneous co-occurrences in the environment, leads to the somewhat counterintuitive prediction that older adults may sometimes know more than younger adults about how events covary in everyday life.

One type of learning that may underlie our understanding of how events covary in everyday life, and potentially our ability to infer cause and effect (Griffiths & Tenenbaum, 2005), is statistical learning. Several studies have shown that human observers can learn subtle statistical regularities that occur within both spatial arrangements (e.g., Chun & Jiang, 1998; Fiser & Aslin, 2001) and temporal sequences (e.g., Fiser & Aslin, 2002; Saffran, Aslin, & Newport, 1996). For instance, after a relatively brief exposure to an artificial language consisting of several repetitions of novel three-syllable "words," both 8-month-old infants and young adults can distinguish between familiar and unfamiliar triplets (Saffran, Aslin, & Newport, 1996; Saffran, Newport, & Aslin, 1996). Al-

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though this type of learning often proceeds outside awareness and has been demonstrated for both passively viewed (Fiser & Aslin, 2001) and task-irrelevant information (Saffran, Newport, Aslin, Tunick, & Barrueco, 1997), stricter tests requiring selective attention to some stimuli at the expense of others have revealed that statistical regularities among unattended information are not learned, at least not by younger adults (Baker, Olson, & Behrmann, 2004; Turk-Browne, Jungé, & Scholl, 2005). However, the possibility remains that older adults, as well as others with inhibitory deficits, may show statistical learning for information that should be actively ignored.

This is a particularly interesting question because previous work has concluded that young adults show reliable statistical learning only for attended sequences (Turk-Browne et al., 2005); they do not show evidence of learning for irrelevant sequences within the same task. To explore the potentially greater learning of older adults, we adapted the paradigm used by Turk-Browne and colleagues (2005). Here, as in the earlier study, there was a learning phase, in which older and younger adults viewed a series of red and green pictures and performed a 1-back task on one of the colors, pressing a button to indicate repetitions in the attended stream (Figure 1A). Unbeknownst to participants, both the red and

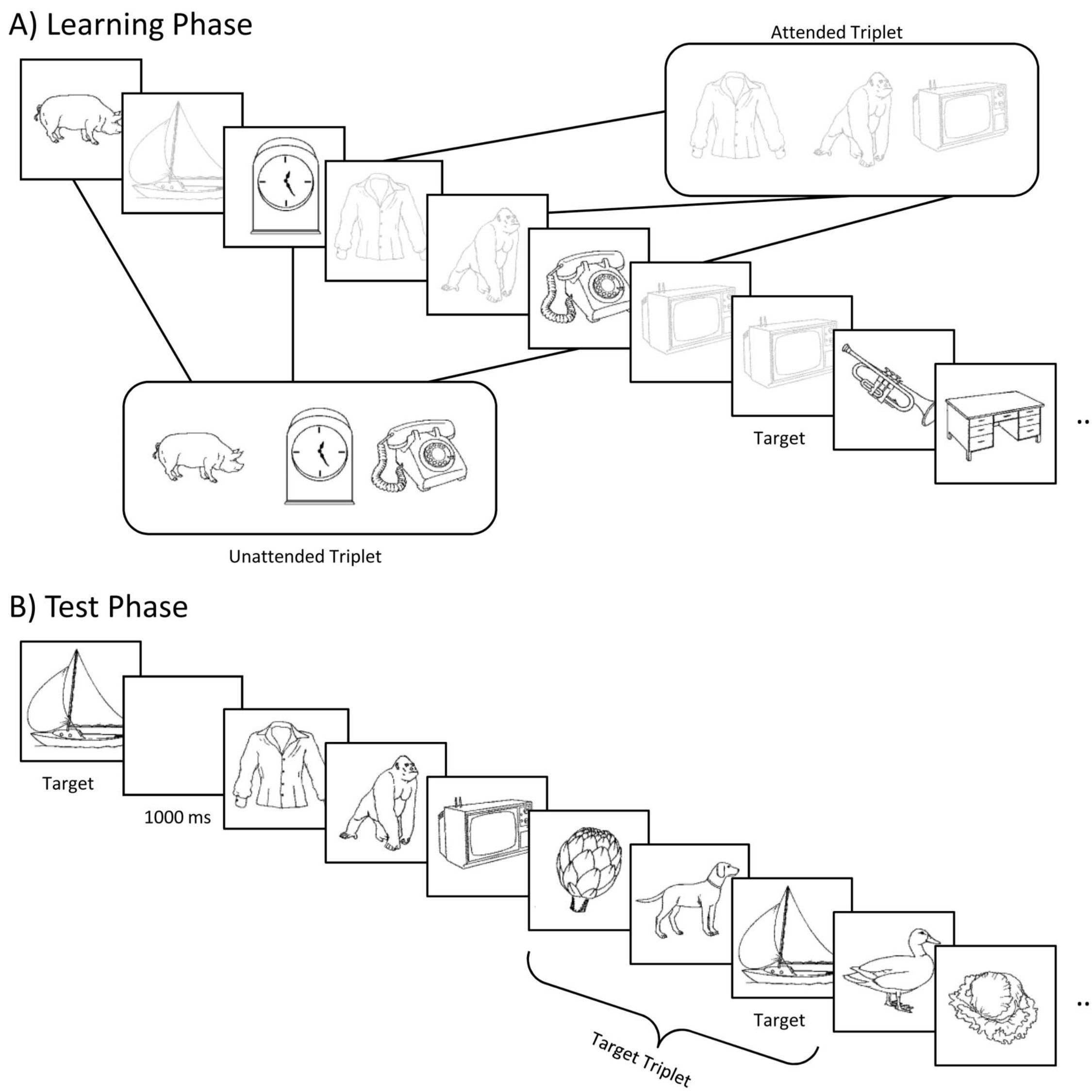

Figure 1. Experimental paradigm. (A) Example sequence from the learning phase of the experiment. In this example, participants attended to the red pictures (shown here in gray) and made a button response to repetitions in the attended stream (see "Target"), while ignoring pictures in the green stream (shown here in black). Both color streams were organized into triplets of pictures that always appeared sequentially. (B) A typical trial sequence from the test phase. Participants first viewed a target picture for that trial, followed by a blank screen, and then 18 pictures (6 triplets from the learning phase). Their task was to make a speeded button response when the target picture appeared.

green pictures were organized into triplets that always appeared together sequentially. Implicit memory for the triplets from both the attended and ignored streams was later tested using a speeded detection task (Figure 1B), with faster response times (RTs) across triplet position indicating interitem priming and hence, associative knowledge of the triplets. In replication of the earlier findings, younger adults were expected to show learning only for triplets from the attended stream, whereas older adults, with their reduced ability to ignore and suppress distraction, were expected to show learning for triplets from both the attended and the ignored streams.

Method

Participants

Participants were 24 younger adults (17–25 years; $M = 19.25$, $SD = 2.19$; four men) and 24 older adults (59–81 years; $M = 66.88$, $SD = 6.32$; five men). Younger adults were undergraduate students at the University of Toronto and received partial course credit for their participation. Older adults were recruited from the community and received monetary compensation for their participation. Data from four younger and two older participants were replaced: three for not understanding task instructions (one young, two old) and three younger adults for slow responding on the test phase task (mean RTs >2.5 *SD*s away from the group mean). Each of these outlying younger adults took more than 500 ms on average to respond to targets on the speeded detection task—usually responding during the interstimulus interval (ISI; i.e., after the target stimulus had offset) as well as responding more slowly than any of the older adults. Thus, it could be said that these participants were also not following task instructions, which were to respond as quickly as possible.

Younger adults had an average of 13.50 ($SD = 1.96$) years of education and a mean score of 29.69 ($SD = 2.71$) on the Shipley Vocabulary Test (Shipley, 1946). Older adults had more years of education ($M = 17.25$, $SD = 3.22$), $t(46) = 4.88$, $p < .001$, and scored higher on the vocabulary test, $M = 36.35$, $SD = 2.57$, $t(46) = 8.74$, $p < .001$, than younger adults. All participants reported being in good health and had normal or corrected-to-normal vision and hearing.

Materials

Thirty line drawings (24 critical and six practice) were selected from Snodgrass and Vanderwart (1980). The critical pictures were divided into two sets, one colored red and the other colored green. Within each color, the 12 pictures were further divided into four sets of three pictures that always appeared in the same order (e.g., ABC, DEF, GHI). Pictures within and across triplets were not semantically related in any obvious way.

To develop the input list for the learning phase, we first created separate temporal streams for each color that consisted of 24 repetitions of each triplet in a semirandom order, with the constraints that no triplets were immediately repeated (e.g., ABCABC) and no pairs of triplets were repeated (e.g., ABCGHIABCGHI). Each stream also included six repetitions of the final picture in each triplet (e.g., ABCCDEF), for a total of 24 repetitions that served as targets for the 1-back task. Thus, each stream consisted of 312 pictures in total. We then interleaved the red and green pictures by randomly sampling from the two color streams in order and without replacement, with the constraint that the remaining pool of pictures from one color could not exceed that of the other color by more than six pictures. Two different orders were created and counterbalanced across participants, as was the color to which they attended.

Procedure

Learning phase. In the first phase of the experiment, participants were instructed to attend to either the red or green stream and to press a response key whenever they saw the same picture twice in a row. They were warned that pictures from the other color stream would intervene between repetitions in the relevant stream, and thus, this task required that they limit their attention to the relevant color in order to detect any repetitions. They were not told that the pictures would occur in triplets. Participants first performed 13 practice trials with unique picture stimuli to become accustomed to the task. They then began the experimental task, which displayed each picture in the center of the screen for 800 ms, followed by a 400-ms ISI.

Test phase. The test phase began immediately after the learning phase. To test participants' implicit knowledge of the triplets, we used a speeded detection task. At the start of each test trial, participants were shown a single target picture for that trial (e.g., B, from the triplet ABC). Their task was to look for that target in an upcoming series of 18 pictures (e.g., . . .DEFJKLA*B*CGHI. . .) and to press the response key as quickly as possible whenever it appeared. The pictures were once again organized into triplets, and thus, if participants had learned the triplet sequences in the first phase, then they should show progressively faster RTs across triplet position (i.e., A > B > C), because position 1 should prime position 2, which in turn should prime position 3.

Each trial sequence consisted of six triplets from the same color stream as the target for that trial (now all shown in black): the target triplet and one other triplet were shown twice, and the other two triplets were shown once. Each of the 24 pictures served as a test target three times, so for each occurrence of a particular target, a different "nontarget" triplet was shown twice along with the target triplet. On each test trial, the triplets were shown in semi-random order, with the constraint that the test target never occurred as the first or last triplet. Each trial was initiated by a button press, followed by a blank screen for 1000 ms, and then each shape was presented for 500 ms, followed by a 500-ms ISI. Participants first completed two practice trials and then the 72 test trials (36 from the attended stream, 36 from the unattended stream) in random order.

Data Analysis

This study used a mixed $2 \times 2 \times 3$ design, with age (young, old) as a between-subjects factor and stream (attended, unattended) and triplet position (first, second, third) as within-subject factors, with a maximum possible correct of 24 RTs recorded for each experimental cell. RT time means were calculated from correct trials using a 2.5 *SD* trim within each participant, within each experimental cell (this resulted in the removal of 2.5% of trials for younger adults and 2.7% of trials for older adults).

Results

Learning Phase

Accuracy rates for the 1-back task were very high and did not differ between older, $M = 97.4\%$, $SD = 4.6\%$, and younger adults, $M = 97.1\%$, $SD = 4.3\%$, $t(46) = 0.27$, $p = .79$. Furthermore, despite the length of the task, the total number of false alarms was also extremely low, with older adults, $M = 2.29$, $SD = 3.75$, showing slightly but not reliably more errors than younger adults, $M = 0.83$, $SD = 0.96$, $t(46) = 1.85$, $p = .07$. Response times to targets on the 1-back task also did not differ between older, $M = 537.76$, $SD = 72.08$, and younger adults, $M = 545.80$, $SD = 73.27$, $t(46) = 0.39$, $p = .70$, suggesting that both groups spent the same amount of time viewing and responding to each picture during the learning phase.

Test Phase

Target detection accuracy during the test phase was also very high and did not differ between older, 95.7%, 5.0 *SD*, 95.0%, 4.6 *SD*, 96.5%, 5.2 *SD*; and 95.0%, 6.3 *SD*, 97.0%, 3.6 *SD*, 96.4%, 4.6 *SD*, for Attended and Unattended Positions 1, 2, and 3, respectively, and younger adults, 96.0%, 7.1 *SD*, 97.7%, 4.4 *SD*, 96.2%, 4.4 *SD*; and 95.8%, 4.4 *SD*, 98.6%, 3.2 *SD*, 96.0%, 6.1 *SD* (for the same order of conditions as above), $F(1, 46) < 1$. Detection accuracy also did not vary with stream, $F(1, 46) < 1$, but there was a trend toward an effect of triplet position, $F(2, 92) = 2.91$, $p = .06$, $MSE = 52.51$, due to participants being slightly more accurate for Position 2. However, these factors did not interact with each other or with age, stream × triplet position: $F(2, 92) = 1.22$, $p = .30$, $MSE = 25.74$; stream × age: $F(1, 46) < 1$; triplet position × age: $F(2, 92) = 2.15$, $p = .12$, $MSE = 38.76$; stream × triplet position × age: $F(2, 92) < 1$.

As can be seen in Figure 2, older adults (Figure 2a) demonstrated a similar learning function for both the attended and unattended triplets, whereas younger adults (Figure 2b), closely replicating the findings of Turk-Browne et al. (2005), only demonstrated progressively faster RTs for triplets from the attended stream. To confirm this impression, RTs were submitted to an ANOVA with age (young, old) as a between-subjects factor and stream (attended, unattended) and triplet position (first, second, third) as within-subjects factors. Younger adults ($M = 410.10$, $SD = 36.15$) responded faster than older adults ($M = 435.44$, $SD = 40.43$) overall, as indicated by the main effect of age, $F(1, 46) = 5.98$, $p < .05$, $MSE = 46218.64$, partial $\eta^2 = .12$. Furthermore, RTs did not differ based on whether the target shape was previously attended or not, $F(1, 46) = 1.25$, $p = .27$, $MSE = 320.79$, but there was a general decrease across triplet position, $F(2, 92) = 12.85$, $p < .001$, $MSE = 3073.16$, partial $\eta^2 = .22$. The interaction between stream and triplet position was almost significant, $F(2, 92) = 2.68$, $p = .07$, $MSE = 641.97$, partial $\eta^2 = .06$, as was the three-way interaction between age, stream, and triplet position,[1] $F(2, 92) = 2.81$, $p = .065$, $MSE = 674.60$, partial $\eta^2 = .06$, reflecting a difference between the attended and unattended triplets in the younger group, but not in the older group. No other interactions were significant, stream × age: $F(1, 46) < 1$; triplet position × age: $F(2, 92) < 1$.

We acknowledge that because the omnibus three-way interaction between age, stream, and triplet position was only marginally significant, caution must be exercised in interpreting any simple main effects (Nieuwenhuis et al., 2011). However, others have argued that planned comparisons are justified and more robust when testing a priori hypotheses (Loftus, 1996; Rosenthal & Rosnow, 1985). In this case, we had well-defined a priori hypotheses for both groups: younger adults were expected to replicate an established finding (Turk-Browne et al., 2005), and older adults were expected to show similar learning for both streams, as based on previous work (Campbell et al., 2010). Moreover, the most important conclusion to be drawn from this work is that older adults show greater learning of regularities contained within distraction than younger adults. This conclusion does not rest on the aforementioned three-way interaction between age, stream, and triplet position. Rather, the conclusion that older adults learn the unattended triplets more than younger adults relies on the interaction between age and triplet position within the unattended stream, and this interaction was significant (see below).

As can be seen by comparing Figure 2a and b, the two groups primarily differed from each other at Position 3, as confirmed by a significant interaction between age and stream at this position, $F(1, 46) = 3.90$, $p = .05$, $MSE = 955.87$, partial $\eta^2 = .08$. Younger adults responded faster to the third shape in the attended triplets ($M = 399.63$, $SD = 38.61$) relative to that in the unat-

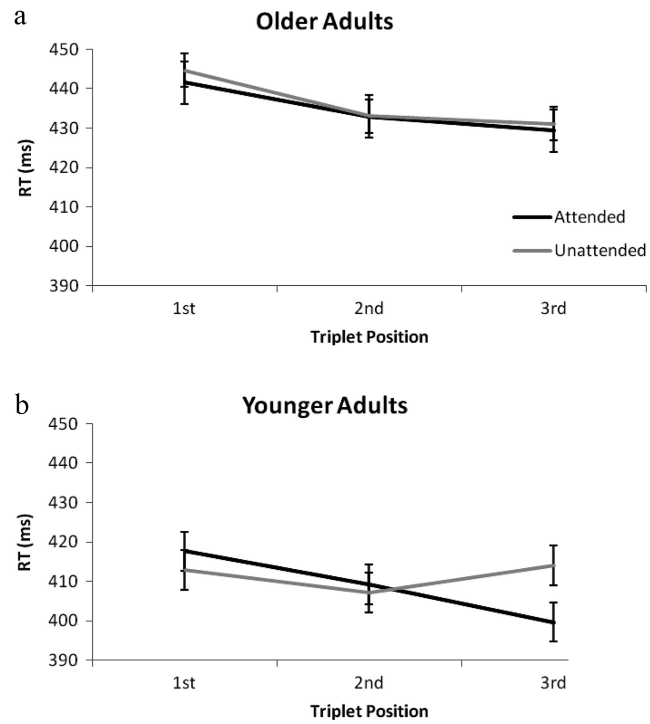

Figure 2. Average response times on the target detection task for older (a) and younger adults (b). Error bars represent 95% within-subject confidence intervals (Masson & Loftus, 2003).

[1] If we increase our power to detect this interaction by simply focusing on the two ends of the triplets, positions 1 and 3, then the interaction between age, stream, and triplet position is significant, $F(1, 46) = 4.48$, $p < .05$, $MSE = 1269.90$, partial $\eta^2 = .09$.

tended triplets, $M = 414.03$, $SD = 41.82$, $t(23) = 3.38$, $p < .01$, whereas older adults responded similarly to both, $M = 429.34$, $SD = 34.63$, and $M = 431.11$, $SD = 39.86$, for attended and unattended, respectively, $t(23) = 0.37$, $p = .71$.

To further examine the effects of stream and triplet position within each group, separate analyses were conducted for younger and older adults. The young adult data very closely replicated the findings of Turk-Browne and colleagues (2005), in that the main effect of stream for this group was not significant, $F(1, 23) < 1$, but there was a main effect of triplet position, $F(2, 46) = 3.64$, $p < .05$, $MSE = 990.64$, partial $\eta^2 = .14$, and, crucially, the interaction between stream and triplet position was significant, $F(2, 46) = 5.81$, $p < .01$, $MSE = 1286.12$, partial $\eta^2 = .20$. Here, as in Turk-Browne et al. (2005), this effect was due to younger adults showing progressively faster RTs across triplet position for pictures from the attended stream, $F(2, 46) = 7.99$, $p < .01$, $MSE = 1952.38$, partial $\eta^2 = .26$, but not for those from the unattended stream, $F(2, 46) = 1.30$, $p = .28$, $MSE = 324.38$.

Within attended triplets, younger adults showed a trend toward significant speeding between Positions 1, $M = 417.66$, $SD = 39.06$, and 2 $M = 409.25$, $SD = 34.95$, $t(23) = 1.74$, $p = .095$, and faster responses to Position 3, $M = 399.63$, $SD = 38.61$, relative to Position 2, $t(23) = 2.17$, $p < .05$.[2] In contrast, for the unattended triplets, younger adults showed a relatively flat response function. Specifically, they showed a trend toward significant speeding between Positions 1, $M = 412.94$, $SD = 30.42$, and 2, $M = 407.19$, $SD = 31.82$), $t(23) = 1.88$, $p = .074$, and they were actually slower to respond to Position 3, $M = 414.03$, $SD = 41.82$, relative to Position 1, though not statistically, $t(23) = 0.21$, $p = .84$. Thus, younger adults showed some speeding between Positions 1 and 2 for the unattended triplets, but this speeding did not extend to Position 3. Clearly, they did not learn the unattended triplets as well as they had learned the attended triplets.

Older adults demonstrated a different pattern of results. Although the main effect of triplet position was significant, $F(2, 46) = 10.69$, $p < .001$, $MSE = 2204.45$, partial $\eta^2 = .32$, the main effect of stream, $F(1, 23) < 1$, and, crucially, the interaction between position and stream, $F(2, 46) < 1$, were not significant, suggesting that older adults' RTs decreased at the same rate for both the attended and unattended triplets. Within attended triplets, older adults showed a significant effect of triplet position, $F(2, 46) = 3.24$, $p < .05$, $MSE = 932.72$, partial $\eta^2 = .12$, with a trend toward significant speeding between Positions 1, $M = 441.49$, $SD = 43.53$, and 2, $M = 432.99$, $SD = 40.16$, $t(23) = 1.87$, $p = .074$, and numerically, if not significantly, faster responses to Position 3, $M = 429.34$, $SD = 34.63$, relative to Position 2, $t(23) = 0.81$, $p = .43$. Within the unattended triplets, older adults also showed a significant effect of triplet position, $F(2, 46) = 7.34$, $p < .01$, $MSE = 1302.18$, partial $\eta^2 = .24$, speeding up significantly between Positions 1, $M = 444.73$, $SD = 45.92$, and 2, $M = 433.05$, $SD = 38.56$), $t(23) = 3.29$, $p < .01$, and less so between Positions 2 and 3, $M = 431.11$, $SD = 39.86$, $t(23) = 0.53$, $p = .60$. Note that unlike the younger adults, older adults' RTs to Position 3 in unattended triplets were faster than those to Position 1, $t(23) = 3.15$, $p < .01$. Thus, older adults demonstrated similar evidence of learning for both the attended and unattended triplets.

Finally, as a direct test of age differences in learning of the two types of regularities—attended and unattended—we ran separate ANOVAs for these two conditions, with age (young, old) as a between-subjects factor and triplet position (first, second, third) as a within-subjects factor. For the attended triplets, RTs decreased across triplet position, $F(2, 92) = 10.32$, $p < .001$, $MSE = 2744.85$, partial $\eta^2 = .18$, and they did so to the same extent for younger and older adults, as indexed by the nonsignificant interaction between age and triplet position, $F < 1$. Younger adults did respond faster than older adults overall, $F(1, 46) = 6.01$, $p < .05$, $MSE = 23891.62$, partial $\eta^2 = .12$. Thus, both groups showed comparable learning for the attended triplets.

For the unattended triplets, RTs also decreased across triplet position, $F(2, 92) = 4.55$, $p < .05$, $MSE = 970.27$, partial $\eta^2 = .09$, but this effect was mainly driven by the older group, as reflected by the significant interaction between age and triplet position, $F(2, 92) = 3.08$, $p = .05$, $MSE = 656.29$, partial $\eta^2 = .06$. Furthermore, younger adults also responded faster overall, $F(1, 46) = 5.57$, $p < .05$, $MSE = 22340.05$, partial $\eta^2 = .11$. Taken together, these results suggest that older adults not only know more about the sequential relations among unattended triplets, but this knowledge did not come at the expense of their knowledge of the sequential relations among attended triplets, as might be expected based on previous work showing that older adults' greater distractibility often leads to poorer memory for target information (e.g., Hamm & Hasher, 1992).

Discussion

In this experiment, two streams of information were interleaved, each containing statistical regularity. During learning, participants responded to 1-back targets in one of the two streams while ignoring stimuli in the other. Both older and younger adults demonstrated learning of the statistical regularities present in the target, to be attended stream. The two groups differed, however, in their knowledge of regularities in the unattended stream: Younger adults did not show significant learning for triplets from that stream, whereas older adults showed reliable learning, such that, within the same period of time, older adults actually learned more than did younger adults.

It is worth noting that although the critical planned comparisons were significant, the three-way interaction between age, stream, and triplet position was only marginally significant. This was likely due to the pattern shown by younger adults, who showed a trend toward significant speeding between Positions 1 and 2 for unattended triplets. This same pattern of means was reported by Turk-Browne et al. (2005) in their Figure 5, although no pairwise comparisons for the unattended triplets were reported there. Taken together these findings suggest that, at least within this paradigm, younger adults may be learning *something* about the unattended regularities—namely, the association between Positions 1 and 2—but not as much as they learn about the attended regularities and not as much as older adults. During the lengthy learning phase, younger adults may have eventually started to divide their attention between the two color streams, allowing them to form an association between the first shape pair in the unattended triplets.

[2] However, it should be noted that these pairwise comparisons between triplet positions are quite liberal and thus, a more reliable indication of learning within the attended and unattended streams can be taken from the overall effect of triplet position within each stream, within each age group.

Previous work looking at statistical learning of triplet sequences has shown that even for attended sequences, young adults sometimes only demonstrate learning of the first pair in the sequence (Fiser & Aslin, 2002), suggesting that learning may proceed in a pairwise manner with the first pair in a sequence taking precedence. Unfortunately, the present paradigm does not contain a continual measure of learning throughout the training phase and thus, cannot speak to when knowledge of these pairwise associations began to emerge. Furthermore, the possibility remains that with an even longer training phase, younger adults may eventually start to learn the association between Positions 2 and 3. Nevertheless, within the present study and that of Turk-Browne et al. (2005), younger adults demonstrated *more* learning for attended triplets than they did for unattended triplets—a difference that did not hold for older adults who actually learned relations within both attended and unattended streams of information.

The finding that older adults show more extensive statistical learning than younger adults is in accordance with recent work showing that older adults not only encode more distracting information than younger adults (Kim et al., 2007; Rowe et al., 2006), but they also form associations between co-occurring targets and distractors and tacitly use this associative information to influence subsequent memory performance (Campbell et al., 2010). We have suggested that rather than binding too little (Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000), older adults may actually bind too much, in that their inability to down regulate irrelevant information may lead them to form overly broad associations between events occurring in close temporal and spatial contiguity (Campbell et al., 2010). The present study extends this hyper-binding effect to the encoding of sequential statistical regularities that solely exist within distracting information and that younger adults more successfully ignore.

Although older adults' excessive binding may create retrieval problems on explicit memory tasks (Anderson, 1974; Gerard, Zacks, Hasher, & Radvansky, 1991), it may also afford them greater knowledge of how seemingly irrelevant events co-occur. At the other end of the developmental spectrum, similarly deficient cognitive control mechanisms may allow children to incidentally extract meaning from the world, particularly when the information that is most relevant is not explicitly obvious (Saffran et al., 1997; Thompson-Schill, Ramscar, & Chrysikou, 2009). However, even as adults, with goals and ambitions to guide our attention and subsequent learning, much information is contained within the periphery of our awareness (Bargh & Williams, 2006; Hasher & Zacks, 1988; Kahneman, 1973). With their broader bandwidth of attention, older adults may be better equipped to detect and potentially use these peripheral regularities.

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