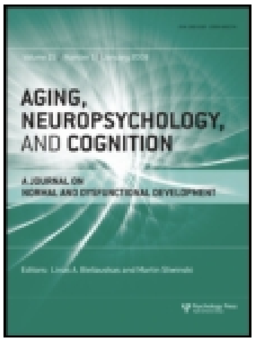

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Working Memory for Item and Temporal Information in Younger and Older Adults

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ABSTRACT

Two experiments examined age differences in mechanisms hypothesized to affect activation of item and temporal information in working memory. Activation levels were inferred from the ability to reject *n*-back lures matching items in different temporal positions. Information with the least decay had a performance advantage over less recent information, but was susceptible to the same temporal context errors found in all adjacent-to-target lure positions. Lures most distant from the current item showed a performance rebound. The pattern of increased magnitudes of age effects at adjacent-to-target positions indicated a reduction in older adults' working memory for temporal context information above and beyond item memory declines. Results overall support the emphasis on context information as a critical factor in working memory and cognitive aging.

Keywords: Working memory; Temporal memory; Age differences; Context memory; Cognition.

INTRODUCTION

The current experiments tested the contributions of reduced memory for item and temporal context information to age-related declines in working memory (WM). We grounded our predictions in Cowan's 'embedded-processes' WM model (Cowan, 1988, 1999), but extended the model to include the distinction between item and contextual information. In doing so, we tested predictions of the model for younger adults, and also examined the source of age differences. We used the *n*-back task, a WM task in which participants

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decide whether each stimulus in a sequence matches the identity of the one presented *n* positions previously, and focused primarily on lure items that match recently presented items in non-target positions. For example, when *n* is set to 2, a 4-back lure would match the non-target item presented four positions previously (e.g., the second ‘G’ is the 4-back lure in the sequence, ‘G–R–M–T–G’).

Processing Inside and Outside the Focus of Attention

WM is the system for temporary storage and manipulation of information (Baddeley & Hitch, 1974, 1994). In Cowan’s (1988, 1999) model, incoming information first enters the focus of attention (FOA), where activation levels are high as a result of the deployment of attention. Both item and contextual (e.g., temporal position) information are presumably activated in the FOA, and associations between item and contextual information are created through binding (Oberauer, 2005). Because the capacity of FOA is limited, when attention shifts to encode new items, relevant information needs to be maintained outside the FOA in *activated memory* until it is again retrieved or until it exits WM entirely (Cowan, 1998, 1999). Activation in activated memory is likely to be partly determined by the level of activation inside the FOA. In addition, activation levels in activated memory may decrease through decay (Cowan, 1988, 1999), interference (i.e., Cowan’s ‘overwriting’), and/or inhibition of no-longer-relevant information (e.g., Oberauer, 2001).

Cowan (2000) proposed that the FOA has a capacity limit of approximately 4 items, or chunks, of information; other researchers, however, have suggested that FOA capacity may be smaller, even one item, in tasks such as the *n*-back that involve sequential presentation of difficult-to-chunk stimuli (e.g., Garavan, 1998; McElree, 2001; Verhaeghen & Basak, 2005). Researchers utilizing the *n*-back task to explore Cowan’s model have argued that when *n* equals 1, information can be maintained entirely in the FOA, resulting in highly accurate responding and quick retrieval of information, but that when *n* is greater than 1, information must be maintained and retrieved from outside the FOA, resulting in slower and less accurate responding (Verhaeghen & Basak, 2005; Verhaeghen, Cerella, Bopp, & Basak, 2005; see also McElree, 2001).

One issue not previously addressed involves potential differences in activation patterns for different types of information. Of particular importance is the contrast between item and context information, given the need for both types of information on most tests of WM. For instance, performance of *n*-back tasks relies on encoding and retrieval of item information in WM, in order to recognize recently presented items, but it also requires WM for temporal context information, in order to determine whether the current item was the one presented *n* positions previously.

Memory for Temporal Context Information

The theoretical basis for the separation of item and temporal context information comes from research documenting a dissociation of the two types of information in memory (e.g., Burgess & Hitch, 2005; Nairne, Riegler, & Serra, 1991). Although temporal memory is always dependent on item memory to some extent (Tehan, Fallon, & Randall, 1997), item information is easier to remember (Healy, 1974), and is lost more slowly, at least in short-term memory (Bjork & Healy, 1974). In general, the requirements for attentional and strategic resources may be greater for temporal context than for item memory (Naveh-Benjamin, 1990; Troyer & Craik, 2000), and therefore may result in different patterns of activation in WM.

All theories of temporal memory assume an associative, or binding, process at the encoding stage, be it item-to-item (e.g., Lewandowsky & Murdock, 1989; Murdock, 1995) or item-to-position associations (e.g., Anderson & Matessa, 1997; Brown, Preece, & Hulme, 2000; Burgess, 1995; Howard & Kahana, 2002; Johnson, 1991; Lee & Estes, 1981). Regardless of the type of associative process, errors on tests involving temporal information tend to follow a predictable pattern, as described by Estes' (1972) perturbation model. Items that are close in terms of position, therefore having similar temporal contexts, are more easily confused than items with greater separation (e.g., Brown, 1997; Brown et al., 2000; Burgess & Hitch, 1992; Estes, 1972; Henson, 1998; Lee, 1992; Lee & Estes, 1977).

Although not originally framed in the context of WM, theories of temporal memory can be couched in terms of Cowan's (1988, 1999) model. Memory for temporal context is dependent on the encoding and binding of item and context information in the FOA, the success of which is presumably an important determinant of activation outside the FOA. Activation of temporal information is further affected by the same factors impacting item memory, namely decay, interference (e.g., from nearby items, as the perturbation model predicts), and inhibition (Brown, 1997; Burgess & Hitch, 1992; Estes, 1972; Farrell & Lewandowsky, 2004; Oberauer, 2001). In the current study, we assumed that all or a subset of these FOA and non-FOA mechanisms determine the levels of activation for temporal context information in WM.

Aging and Working Memory

There is substantial evidence that older adults show declines in WM, as demonstrated on *n*-back tasks (Dobbs & Rule, 1989; Hartley, Speer, Jonides, Reuter-Lorenz, & Smith, 2001), as well as delayed matching-to-sample tasks (Hartman, Dumas, & Nielsen, 2001) and complex span tasks (Lustig, May, & Hasher, 2001; McCabe & Hartman, 2003; Myerson, Hale, Rhee, & Jenkins, 1999; Verhaeghen, Marcoen, & Goossens, 1993). Older adults have less WM for both item and contextual information; in addition, WM for context may be more age-sensitive than WM for items. For instance, context plays an important role in cognitive control aspects of WM, and age differences in context processing greatly impact cognitive performance (Braver & Barch, 2002; Braver et al., 2001; Braver, Satpute, Rush, Racine, & Barch, 2005). Further, Oberauer (2005) posited that creating and maintaining content-context bindings may be an essential function of WM, and a major source of age differences in WM tasks, including the *n*-back task. In addition, age differences in WM for temporal context may be related to a general reduction in associative ability (Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Oberauer, 2005; for evidence from long-term memory, see Balota, Duchek, & Paullin, 1989; Bayen, Phelps, & Spaniol, 2000; Chalfonte & Johnson, 1996; Howard, Kahana, & Wingfield, 2006; Naveh-Benjamin, 2000; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003). There is also evidence that temporal information in WM may be more sensitive to age than other types of associative memory (Hartman & Warren, 2005).

Although a few studies of aging and WM have situated their findings in relation to Cowan's (1988, 1999) model, focusing on the magnitude of age effects for information inside versus outside the FOA, none have separated out the roles of item and context information. We do know that accuracy within the FOA is near-perfect for both younger and older adults, although older adults are slower to access the information (Verhaeghen & Basak, 2005; Bopp, as described in Verhaeghen et al., 2005). In addition, older adults appear to 'remove' items from the FOA as efficiently as younger adults (Oberauer, 2001). Outside the FOA, however, age differences are evident in both accuracy and response times (Verhaeghen & Basak, 2005). Several mechanisms could drive these age differences. It is possible, for instance, that slowing (Salthouse, 1996) or other processes affecting the FOA leads to overall lower activation levels, and thus reduced item and context memory once information leaves the FOA. Any age-related decline in the ability to bind item and context (or inter-item) information would be expected to affect context more than item memory, and produce larger age effects when contextual information held outside the FOA is required.

Reduced WM for information outside the FOA may also be the result of decay and/or inhibitory mechanisms that affect both item and context information. Although there is no evidence that the rate of decay over time differs for younger and older adults (Hartman et al., 2001), an age-related decline in inhibitory functioning is sometimes invoked as a cause of WM age differences (Hasher & Zacks, 1988; Stoltzfus, Hasher, & Zacks, 1996). Although decay theoretically plays a role in the *n*-back task, the complex requirements for an inhibitory mechanism in this task (i.e., identifying and suppressing newly irrelevant information every few seconds), make it unlikely that inhibition plays a major role for either younger or older adults.

As such, inhibition is unlikely to account for age differences in *n*-back performance.

Overview of the Current Experiments

The current experiments examined age differences in WM by examining *n*-back lure performance in younger and older adults. We used *n* levels of 2 and 3, and included lures that matched recently presented items in non-target positions. With *n* always greater than 1, it was considered optimal for participants to switch their attention away from previous items each time a new item was presented, in order to focus on retrieving information from the target *n*-back position. Thus, non-FOA information was necessary for accurate responding to all lures.

The use of lures in the *n*-back task allowed us to draw inferences about the contributions of item and temporal memory, because accurate performance on lures requires temporal position as well as item information (i.e., recognition memory). Judgments that ignore temporal information and are based solely on item recognition will result in false alarms on lure trials (i.e., mistaking the lure for a target stimulus).

Overall we expected accuracy to be reduced for lures compared to new items (Gray, Chabris, & Braver, 2003; McElree, 2001). Performance on lures was further expected to vary as a function of lag due to the effects of decay (Cowan, 1988, 1999). Decay should decrease activation with increased distance of lure position (e.g., 2-back lures match items with lower activation than 1 back-lures). The impact of temporal context information should be seen in reduced performance for lures matching positions adjacent to the target (*n*-level) position (Estes, 1972; Lee & Estes, 1977, 1981).

We can summarize these predictions by means of a roughly U-shaped pattern for accuracy across lure positions (and an inverted U-shape for RTs), with high performance for lures involving either highly activated item and temporal information (i.e., 1-back lures) or very low levels of either type of activation (i.e., 5- and 6-back lures). In contrast, lower levels of performance were expected for lures that match items in intermediate lure positions with activated item information (i.e., the item is recognized) and reduced temporal information activation (i.e., the item is erroneously judged to have occurred in the target position). Lure performance should reach its lowest point for lures matching adjacent-to-target items.

With respect to aging, we expected age differences in overall accuracy, given documented declines in item and temporal context memory (e.g., Spencer & Raz, 1995; Verhaeghen et al., 1993), and based on previous studies of the *n*-back task with *n* greater than 1 (Dobbs & Rule, 1989; Hartley et al., 2001; Verhaeghen & Basak, 2005). Consistent with an earlier study using lures (Burgess, Gray, & Braver, 2002), and because item memory was expected to show smaller age-related declines than temporal memory (Braver et al., 2001; Hartman & Warren, 2005; Oberauer, 2005), new items were predicted to elicit smaller age effects than lures. Across lure positions, an age-related deficit in WM for temporal context was expected to especially affect lures matching positions adjacent to the target. In addition, if older adults experience a reduction in WM for item information, items may not be recognized as being processed recently. One would then predict age differences for new items as well as for lures. If item information is the sole cause of older adults' difficulty, however, the magnitude of age differences should decrease as lure distance increases, because a lack of item information matching the lure would boost lure performance in these positions for older adults.

These general and age-related hypotheses were tested using the *n*-back lure paradigm with verbal stimuli in Experiment 1, and replicated with non-verbal stimuli in Experiment 2.

EXPERIMENT 1

Method

Participants

Participants included 36 younger adults between the ages of 18 and 30, and 36 older adults, ages 60 and over. Younger adults were undergraduates who participated for course credit. Older adults were recruited from the community and were paid for their participation. All participants were screened for vision as well as medical and psychological conditions known to affect cognitive performance (neurological conditions, chemotherapy in the past year, heart disease, type I diabetes, lung disease, kidney disease, uncontrolled hypertension, psychiatric problems requiring medication). All participants reported their health to be good or excellent. In addition, participants who scored above the normal-to-mild range of 0–19 on the Beck Depression Inventory – II (BDI, Beck, Steer, & Brown, 1996) or 0–15 on the Beck Anxiety Inventory (BAI, Beck & Steer, 1990) were excluded, as were older adults who consumed more than four alcoholic drinks per day, and those who scored less than 27 out of 30 on the Mini-Mental State Examination (MMSE, Folstein, Folstein, & McHugh, 1975). One younger adult was replaced due to high BDI and BAI scores and two older adults were replaced due to low MMSE scores. In the final sample, older adults had more years of education than younger adults, $t(70) = 9.97$, $p < .001$, higher scores on the Shipley Vocabulary test (Shipley, 1940), $t(70) = 8.01$, $p < .001$, but lower scores on the BDI, $t(70) = 2.27$, $p = .026$, and the BAI, $t(70) = 4.27$, $p < .001$ (see table 1). With age partialed out, none of these measures was correlated with overall *n*-back performance.

TABLE 1. Means (Standard Deviations) for Participant Characteristics in Experiments 1 and 2

Participant characteristic		Experiment 1	Experiment 2
Age	Young	19.1 (2.1)	19.1 (0.8)
	Old	68.2 (7.1)	71.5 (7.3)
Education	Young	12.7 (0.8)	13.1 (0.8)
	Old	16.8 (2.3)	16.8 (2.6)
Mini-Mental Status Exam (MMSE)	Young	--	--
	Old	29.1 (1.0)	29.2 (1.0)
Beck Depression Inventory (BDI)	Young	5.9 (4.0)	5.1 (4.6)
	Old	4.1 (3.0)	4.0 (3.6)
Beck Anxiety Inventory (BAI)	Young	5.7 (4.2)	3.0 (2.9)
	Old	2.2 (2.5)	2.2 (2.8)
Shipley Vocabulary	Young	31.1 (3.7)	30.7 (3.7)
	Old	37.0 (2.4)	36.8 (3.4)

Note. Age and education were measured in years. The maximum MMSE score was 30. BAI and BDI scores could range from 0 to 63. The Shipley Vocabulary Test was scored out a maximum of 40 points. A dashed line indicates that data were not collected on the measure for the given age group.

Materials

n-Back Tasks

Fifteen sequences were created for each level of *n* (e.g., 2 and 3). Each sequence consisted of 21 consonants chosen pseudo-randomly with replacement from B, C, D, F, H, J, K, L, M, P, R, S, T, V, X. Within each sequence, 5 items were targets, 11 were new, and 1 item each was a 1-back lure, 2-back lure (for 3-back task only), 3-back lure (for 2-back task only), 4-back lure, 5-back lure, and 6-back lure. The ‘new items’ that occupied the first two positions in each sequence for *n* level 2 and the first three positions in each sequence for *n* level 3 were excluded from analyses.

In each *n*-back task, the letters were presented one at a time in white 18-point font on a black background, at a rate of 750 ms per item and 1500 ms inter-stimulus interval (ISI). For each letter, participants pressed the ‘Yes’ key if it was identical to the item presented *n* positions previously or the ‘No’ key if it was not.

Procedure

Participants were tested individually in one 90-min session. After completing practice using the ‘Yes’ and ‘No’ keys on the response box, the *n*-back tasks were administered. The order of trials with *n* levels of 2 and 3 was counterbalanced across participants. A sample item was provided prior to each *n*-back task, followed by a self-paced practice sequence, and two computer-paced practice sequences. During the test, there were 10-s breaks between the sequences and 20-s breaks after every set of 5 sequences. Feedback regarding accuracy was provided after each sequence. Between the two *n*-back tasks, participants completed the vocabulary test. At the end of the session, they completed the BDI and BAI.

Results

The alpha level was set at .05 for both experiments. The significance levels for the follow-up contrasts of the analyses of variance (ANOVAs) were corrected with the Rom modification of the Bonferroni procedure (Olejnik, Li, Supattathum, & Huberty, 1997). Partial η^2 values are reported as effect size estimates. For reference, partial $\eta^2 = .01$ represents a small effect, .06 a medium effect, and .14 a large effect (Cohen, 1988).

Although the predictions were based mainly on accuracy differences, both accuracy and reaction times (RTs) were analyzed, with the expectation that RTs would mirror the accuracy effects (i.e., more difficult items should elicit slower RTs). Logarithmic transformations of RTs were planned in the case of any interactions between age group and lure position. To preview, no such interactions were found, and raw RTs are reported throughout.

Accuracy was analyzed using the proportion of correct responses in a sequence. RT analyses were conducted on correct responses. RTs more than three standard deviations from a participant's mean for each task were excluded. The mean percentages of excluded RTs were 1.3% for younger adults and 1.5% for older adults.

Overall performance for the two levels of *n* was examined using separate ANOVAs for accuracy and RT data. For accuracy, *n* level 2 was easier than 3, $F(1, 70) = 180.30$, $MSE = 0.001$, $p < .001$, partial $\eta^2 = .72$, and younger adults performed better than older adults, $F(1, 70) = 42.82$, $MSE = 0.004$, $p < .001$, partial $\eta^2 = .38$. The interaction between age and task was not significant. For RTs, a similar pattern emerged. Responses for *n* level 2 were faster than 3, $F(1, 70) = 27.50$, $MSE = 3486.01$, $p < .001$, partial $\eta^2 = .28$, younger adults were faster than older adults, $F(1, 70) = 21.68$, $MSE = 39086.15$, $p < .001$, partial $\eta^2 = .24$, and the absence of an interaction indicated that the age effect was similar across tasks (see table 2).

To examine performance patterns for non-target items, we present analyses in the following sections that are separated by *n* level. Alternative

TABLE 2. Means (Standard Deviations) of *n*-Back Accuracy Levels and Response Times (RTs) for Overall Performance in Younger and Older Adults in Experiments 1 and 2

	n Level 2		*n* Level 3	
n-Back Performance	Young	Old	Young	Old
Experiment 1				
Accuracy	0.94 (0.03)	0.88 (0.06)	0.87 (0.05)	0.79 (0.06)
RT	564 (115)	717 (149)	615 (143)	769 (172)
Experiment 2				
Accuracy	0.93 (0.04)	0.81 (0.10)	0.86 (0.06)	0.72 (0.09)
RT	671 (98)	934 (139)	729 (101)	959 (142)

Note. Accuracy was measured as proportion correct. RTs were measured in milliseconds.

analyses were conducted that examined lures common to both *n* levels and are discussed in footnote 1.[1]

Non-Target Items for *n* Level 2

Accuracy

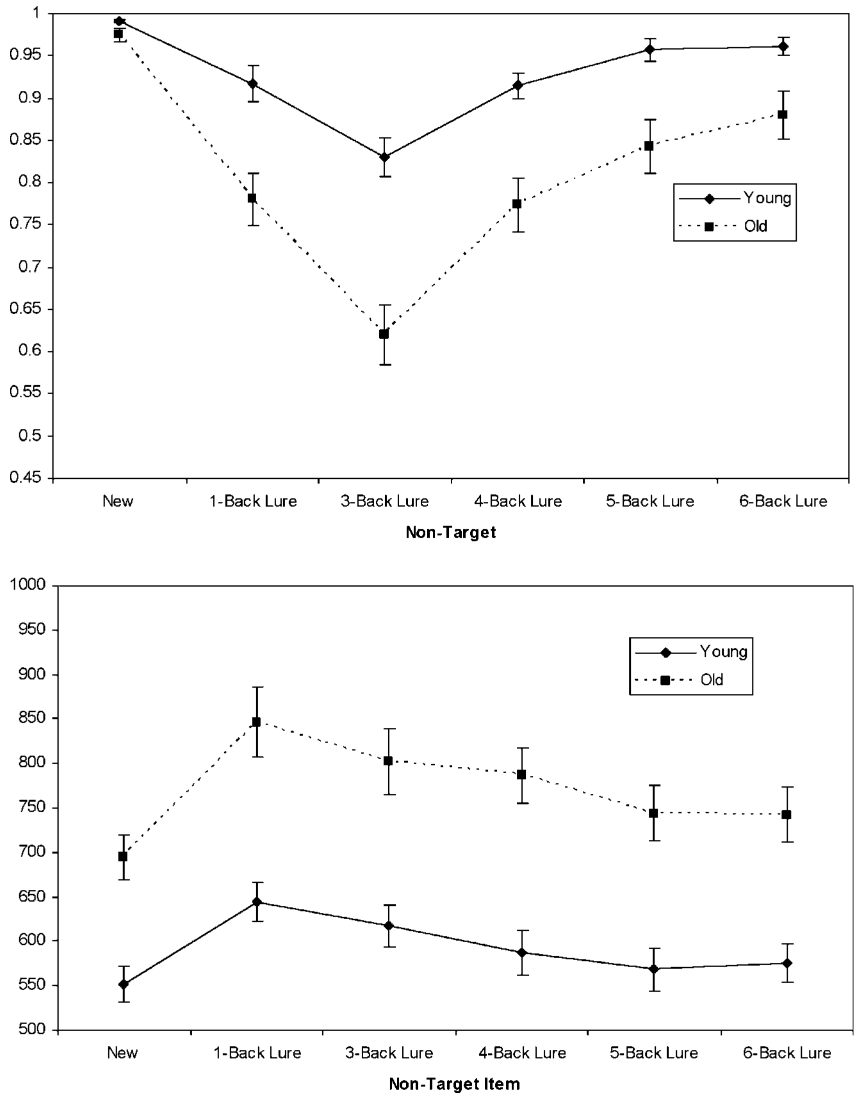
A 2 (Age: younger, older) × 6 (Non-target item type: new, 1-back lure, 3-back lure, 4-back lure, 5-back lure, 6-back lure) ANOVA for accuracy (see figure 1a) showed that younger adults outperformed older adults, $F(1,70) = 23.23$, $MSE = 0.06$, $p < .001$, partial $\eta^2 = .25$, and accuracy differed among item types, $F(5, 350) = 49.32$, $MSE = 0.01$, $p < .001$, partial

[1] Additional analyses were conducted to assess the similarity of lure patterns between the two *n* levels, when the lures were defined in terms of their distance from the current time (i.e., recency) and in terms of their distance from the target item. The results, however, did not show a qualitative difference between analyses; also, there were inconsistencies in the conclusions from Experiment 1 and Experiment 2. Thus, we were unable to draw any theoretically meaningful conclusions from these alternative analyses. The results of the relevant interaction terms are reported here.

We computed for each experiment, and for accuracy and RTs, ANOVAs with age, *n* level (2, 3) and lure position (4-, 5-, and 6-back) as factors. There were no significant task × lure position interactions in either experiment. The only interactions involved age. The accuracy analysis for Experiment 1 revealed an interaction of age and task (i.e., larger age differences for *n* level 3 compared to 2), and of age and lure position (i.e., steadily increasing accuracy as lure distance increased for older adults, but a leveling-off of performance as of the 5-back position for young). There were no such interactions with age in Experiment 2, however. The same patterns were mirrored in the RT data.

To examine lure position in relation to the target, we conducted analyses examining performance for lures that were identical for the two *n*-back tasks in terms of distance to the target position (i.e., $n + 1$ referred to 3-back lures for *n* level 2, and 4-back lures for *n* level 3; $n + 2$ referred to 4-back lures for *n* level 2, and 5-back lures for *n* level 3; and $n+3$ referred to 5-back lures for *n* level 2, and 6-back lures for *n* level 3). There were no interactions between task and lure position. The only interaction from Experiment 1 was between age and lure position, characterized by significant improvement in accuracy for older adults as lure distance increased and the leveling-off of younger adult accuracy and RT after the $n + 2$ position. No interactions were found in the accuracy data of Experiment 2. The interaction between age and task in the RT data was driven by only younger adults showing a difference in RTs between the two *n* levels.

FIGURE 1. Performance on non-targets for *n* level 2 in Experiment 1: (a) accuracy; (b) response times. Error bars represent standard errors.



η^2 = .41. Follow-up contrasts revealed a significant decline from performance on new items, which showed a ceiling effect, to 1-back lures ($p < .001$), and another significant decline for 3-back lures ($p < .001$), the condition with the lowest accuracy. There was then a significant increase in accuracy from the 3-back to the 4-back lure position ($p < .001$), and also from the 4- to 5-back lure position ($p = .001$), with accuracy leveling off for the 6-back position. Neither age group showed a return to the baseline, new item level for the most distant lures. There was also a significant interaction of age and item type, $F(5, 350) = 6.72$, $MSE = 0.01$, $p < .001$, partial $\eta^2 = .09$. An exploration of this interaction revealed a smaller, non-significant, age difference in new items ($p = .062$) compared to larger, significant, age effects in each of the lure items, and a larger age difference in 3-back lures compared to the other lures, which all showed similar age effects (all p values < .05).[2]

Response Times

A similar ANOVA using RTs revealed faster responses for younger than older adults, $F(1, 70) = 22.58$, $MSE = 152695.04$, $p < .001$, partial $\eta^2 = .24$, differences among the item types, $F(5, 350) = 34.28$, $MSE = 3949.44$, $p < .001$, partial $\eta^2 = .33$, and a trend toward an interaction between age group and item type, $F(5, 350) = 2.20$, $MSE = 3949.44$, $p = .05$, partial $\eta^2 = .03$ (see figure 1b). Follow-up tests showed that RTs were faster for new items than for 1-back lures ($p < .001$), 1- and 3-back lures were similar, as were 3- and 4-back lures; however, 1-back lures were significantly slower than 4-back lures ($p < .001$). There was a significant decrease in RTs from the 4- to the 5-back position ($p = .003$), and no further change for the 6-back position. In neither age group did RTs for lures return to baseline, new item levels. All non-target items had significant age differences, but follow-up contrasts of the interaction trend showed that the age effect was significantly larger for each of the lures compared to new items (all p values < .05).

Non-Target Items for *n* Level 3

Accuracy

The 2 (Age) × 6 (Non-target item type: new, 1-back lure, 2-back lure, 4-back lure, 5-back lure, 6-back lure) ANOVA showed a decrease in performance for older compared to younger adults, $F(1, 70) = 25.25$, $MSE = 0.09$, $p < .001$, partial $\eta^2 = .27$, a significant effect of item type, $F(5, 350) = 88.72$, $MSE = 0.016$, $p < .001$, partial $\eta^2 = .56$, and an interaction between the factors, $F(5, 350) = 6.54$, $MSE = 0.02$, $p < .001$, partial $\eta^2 = .09$ (see figure 2a). Follow-up tests examining the effect of item type revealed a significant decline in accuracy from new items to 1-back lures, and from 1- to 2-back lures ($p < .001$), similar performance levels for the 2- and 4-back lures, an increase from the 4- to 5-back position ($p < .001$), and a leveling off of performance for the 6-back lures. Although the least recent lures did not return to baseline for either age group, they did show a rebound in comparison to the 2- and 4-back lures. Follow-up tests to explore the interaction showed that

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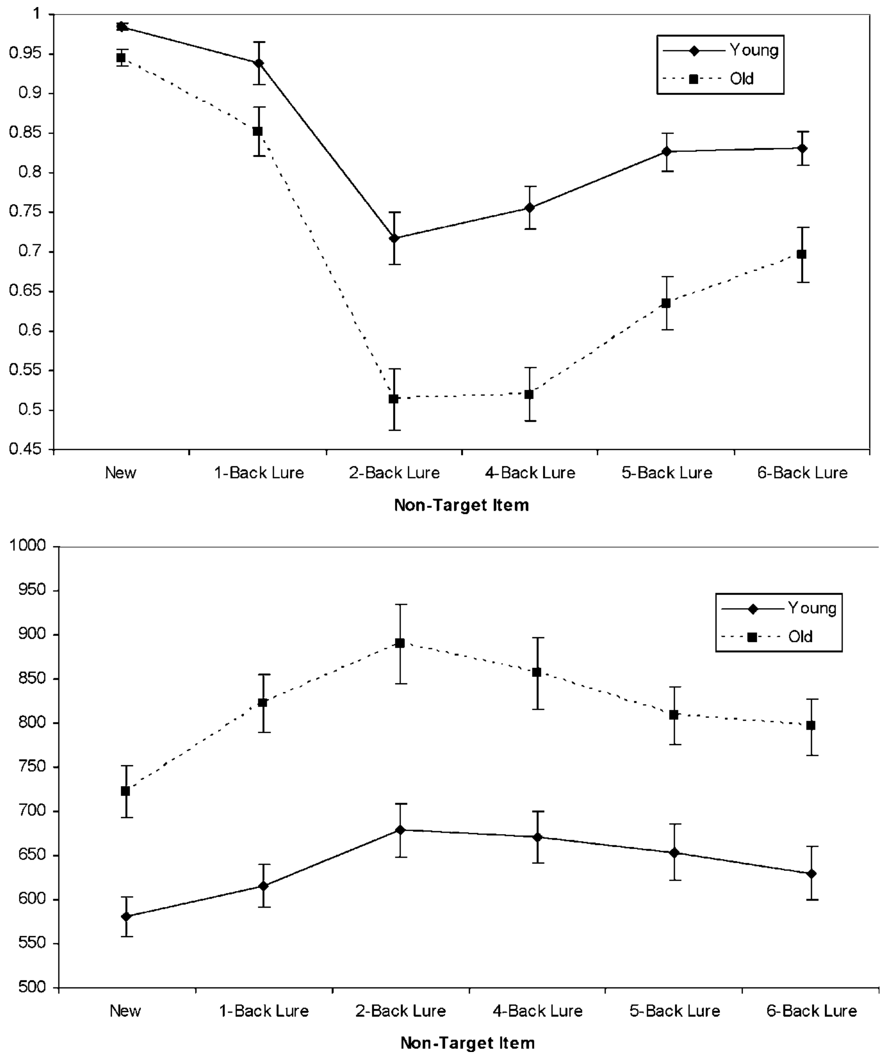
[2] Omitting new items from the ANOVA, as one anonymous reviewer suggested, resulted in identical findings with regard to the main effects and the interaction between age group and non-target item type. Thus, the interactions we report were not driven by the inclusion of new items in our analyses.

FIGURE 2. Performance on non-targets for *n* level 3 in Experiment 1: (a) accuracy; (b) response times. Error bars represent standard errors.



although new items and 1-back lures had similar and significant age effects, these were smaller than for the other lures. The age effect was similar for the 2- through 6-back lures, with the exception of a significantly larger age effect for the 4-back lures compared to that of the 6-back lures (all p values < .05).[2]

Response Times

The analogous ANOVA using RTs showed main effects of age, $F(1, 70) = 17.81$, $MSE = 191040.00$, $p < .001$, partial $\eta^2 = .20$, and of item type, $F(5, 350) = 23.93$, $MSE = 6353.45$, $p < .001$, partial $\eta^2 = .26$, as well as an interaction between them, $F(5, 350) = 2.27$, $MSE = 6353.45$, $p = .047$, partial $\eta^2 = .03$ (see figure 2b). Follow-up contrasts demonstrated an increase in RTs from new items to 1-back lures ($p < .001$), a further increase from the 1- to 2-back positions ($p < .001$), but no significant change from the 2- to 4-, nor from the 4- to 5- and 5- to 6-back lure positions. Although the adjacent data points for the more distant lures did not show significant change, there were decreases in RTs when comparing the 2- and 5-back positions ($p < .001$), and the 4- and 6-back positions ($p = .001$). There was no return to baseline for either age group. Follow-up tests for the age $\times$ item type interaction revealed significant age differences for all non-target items, but smaller age differences for new items compared to the lures (all p values $< .05$). The magnitudes of age effects were similar across the lure positions.

Discussion

The results of Experiment 1 were consistent with our predictions regarding differences in the ability to reject lures based on their positions in *n*-back sequences. Before discussing the patterns of age differences, we focus on general results for younger and older adults. We also note that the accuracy of rejecting new items was nearly perfect for younger adults, and that new items elicited the fastest RTs for both *n* levels. This pattern argues for the use of new items as an appropriate baseline for lure performance.

To begin our discussion of overall lure performance patterns, lures matching positions subject to the least decay (i.e., 1-back lures) should be rejected relatively easily. Consistent with predictions, results for both *n* levels showed that 1-back lure accuracy was higher compared to the intermediate lure positions, but lower than new items. In further support of the predictions of a decay mechanism, combined with a perturbation account, the 2-back lures for *n* level 3 had low accuracy and long RTs, and performance was significantly worse compared to 1-back lures.

As noted earlier, inhibitory mechanisms were not hypothesized to play a role in this task for either age group. To provide empirical evidence of this assumption, we tested whether items more distant than the target position were inhibited once they were no longer needed, focusing on the lures that matched positions adjacent to, but more distant than, the target (i.e., 3-back lures for *n* level 2- and 4-back lures for *n* level 3). We found that these positions showed low accuracy and slow RTs for both *n* levels in both age groups. Assuming that efficient inhibition would make these lures easy to reject, it appears that there was no immediate inhibition of no-longer-relevant information.

For lures referring to information more distant from the target, we found significant rebounds in performance from the 4- to 5-back lures for both *n* levels, after which there was no further improvement, as seen in both accuracy and RTs. None of these lures elicited performance at the level of new items. This pattern suggests the presence of residual item (but faulty temporal) information activation outside the FOA.

With respect to aging, older adults showed reductions in both accuracy and speed for all lures for both *n* levels. Age differences in 1-back lures, combined with the fact that these age differences were greater than those for new items, suggests that older adults experience difficulty with the encoding and/or maintenance of temporal context information, even for information which has had the least time to decay. Overall, there were similar age differences across the various lures, with the important exception of a significantly increased age effect for lures matching the position more distant than and adjacent to the target (i.e., 3-back position for *n* level 2, 4-back position for *n* level 3). Temporal context information is most critical in these positions because item information is more highly activated here compared to more distant lures and because these adjacent-to-target items are especially vulnerable to perturbation errors. The results therefore suggest that older adults experience a decline in WM for temporal information, beyond an item memory decline.

In contrast to the evidence for age differences in WM for temporal context, we found mixed support for reduced item WM. Using new item performance as one indicator of item memory, age differences were nonsignificant for *n* level 2, and significant (though relatively small in size compared to lure age differences) for *n* level 3. Arguing against the item WM hypothesis is the equivalence of age differences for the most distant lure positions. Overall, we cannot rule out an item WM decline given older adults' difficulty with nearly all item types, but our results strongly suggest that age-related changes in WM for temporal context are more heavily involved in *n*-back lure performance.

Although not the main focus of our predictions, RT age effects generally mirrored those of accuracy, showing smaller age differences for new items compared to lures; however, all lure positions elicited comparable age differences, failing to show the exaggerated accuracy effects involving age for the adjacent-to-target positions. Possible explanations for the partial independence of accuracy and RT age effects are provided in the General Discussion.

In sum, the roughly U-shaped pattern of lure performance across positions was shown in both age groups. Although information which had little time to decay was more easily and accurately processed than less recently presented information, temporal information was still error-prone. Consistent with hypotheses about the importance of temporal information and in agreement with the perturbation model (Estes, 1972), lures in positions adjacent to the target showed the poorest performance, and performance improved for both less and more distant positions. Critically, none of the lure positions appeared to lose enough item and temporal activation as to exit WM entirely. Age effects appeared linked to declines in WM for temporal context information above and beyond an item memory deficit.

EXPERIMENT 2

Method

Participants

New samples of 36 younger adults and 36 older adults were tested in Experiment 2 (see table 1). All screening procedures were identical to those in Experiment 1. Two younger adults were replaced due to high scores on the BAI. As in Experiment 1, older adults outperformed younger adults on the vocabulary test, $t(70) = 7.33$, $p < .001$, and had completed more years of education, $t(70) = 8.32$, $p < .001$. There were no age differences in BDI or BAI scores. With age partialed out, there were no correlations of participant characteristics with overall *n*-back performance

Materials

Fifteen line drawings, each consisting of six line segments, were created using two criteria: (1) a lack of resemblance to nameable objects; and (2) easy discrimination from the other drawings. These criteria were independently evaluated by five members of the research laboratory. Each line drawing was presented in white on a black background in a box measuring 1.125″ × 1.125″ on the computer screen. The line drawings were presented one at a time inside the box with 1250 ms stimulus duration time and 1250 ms ISI.

The sequences for *n* levels of 2 and 3 were constructed in the same way as in Experiment 1. Five sequences with *n* level set to 1 were also created as practice stimuli, each consisting of 15 items with 5 target 1-back matches. All other details regarding the presentation of items during the *n*-back tasks were identical to those from Experiment 1.

Procedure

The procedure was the same as in Experiment 1, with two exceptions. First, prior to the start of the *n*-back test trials, participants were given 30 s to examine the line drawings. Second, participants completed practice trials with *n* level set to 1 before completing the tasks with *n* levels 2 and 3. These two modifications were included to familiarize participants with the 15 line drawings used during the task.

Results

Trimming of RTs more than three standard deviations from a participant's mean for each task resulted in the exclusion of 1.1 and 1.6% of trials for young and older adults, respectively.

To assess age differences in overall *n*-back performance, ANOVAs with *n* level and age group as factors were computed separately for accuracy and RTs (see table 2). *N* level 2 showed higher accuracy than 3, $F(1, 70) = 128.30$, $MSE = 0.002$, $p < .001$, partial $\eta^2 = .65$, and younger adults were more accurate than older adults, $F(1, 70) = 65.97$, $MSE = 0.01$, $p < .001$, partial $\eta^2 = .49$. For RTs, *n* level 2 was faster than 3, $F(1, 70) = 10.76$, $MSE = 4830.03$, $p = .002$, partial $\eta^2 = .13$, and younger were faster than older adults, $F(1, 70) = 88.90$, $MSE = 23990.93$, $p < .001$, partial $\eta^2 = .56$. In none of the analyses were there interactions between *n* level and age group.

Non-Target Items for *n* Level 2

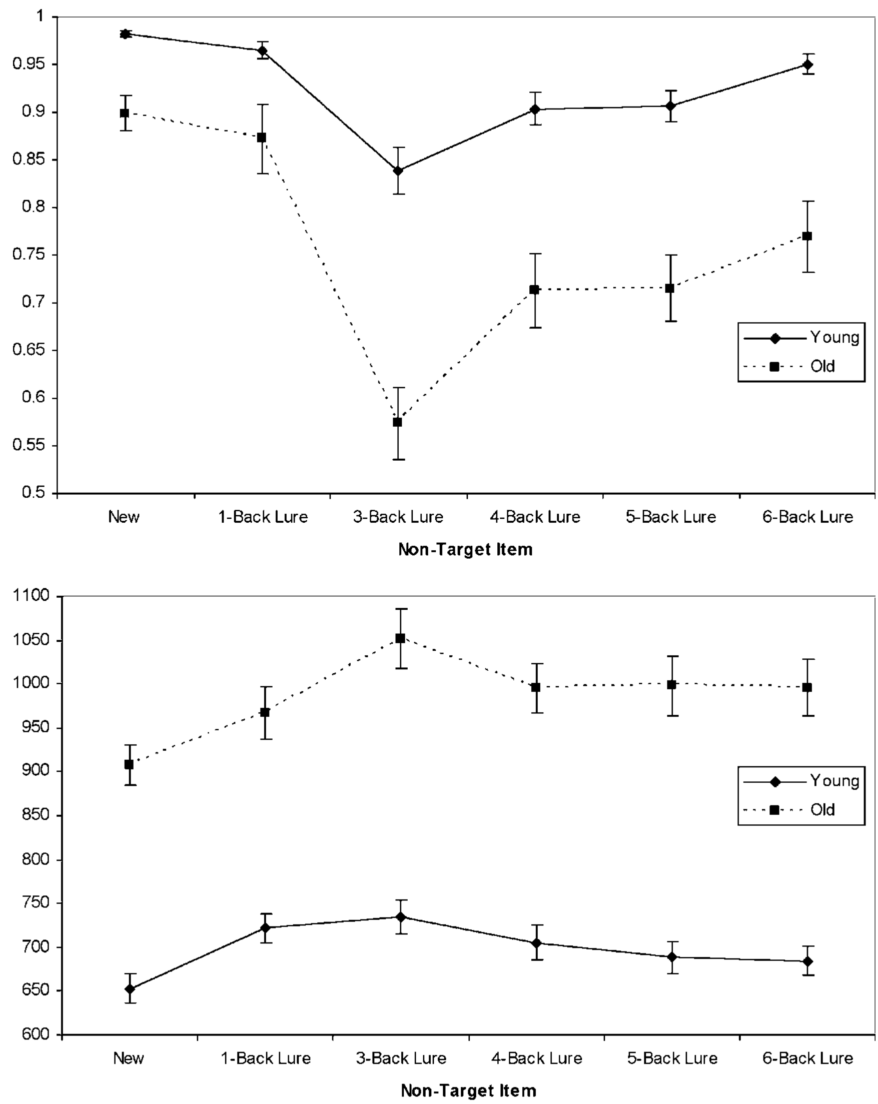
Accuracy

The results of a 2 (Age) × 6 (Non-target item type: new, 1-back lure, 3-back lure, 4-back lure, 5-back lure, 6-back lure) ANOVA revealed higher accuracy for younger than older adults, $F(1, 70) = 31.48$, $MSE = 0.10$, $p < .001$, partial $\eta^2 = .31$, and significant differences among the item types, $F(5, 350) = 45.30$, $MSE = 0.01$, $p < .001$, partial $\eta^2 = .39$ (see figure 3a). Follow-up tests revealed no difference between new items and the 1-back lures, a significant decrease from the 1- to the 3-back lures ($p < .001$), a significant increase from the 3- to the 4-back position ($p < .001$), no change from the 4- to the 5-back position, and another significant increase from the 5- to 6-back position ($p = .022$). Neither younger nor older adults' 6-back lure performance returned to the baseline new item level. There was also an age by item type interaction, $F(5, 350) = 7.50$, $MSE = 0.01$, $p < .001$, partial $\eta^2 = .09$. Follow-up tests showed similar and significant age effects for the new items and 1-back lures, which were smaller than the age differences for the 4-, 5-, and 6-back lures (all *p* values < .05). Importantly, an increased age difference was evident at the 3-back lure position, in comparison to the age effect at each other lure position, with the exception of a trend toward this pattern for the 4-back position ($p = .055$).[2]

Response Times

A parallel ANOVA based on RT data showed main effects of age, $F(1, 69) = 83.66$, $MSE = 105458.60$, $p < .001$, partial $\eta^2 = .55$, and item type, $F(5, 345) = 15.11$, $MSE = 6123.32$, $p < .001$, partial $\eta^2 = .18$ (see figure 3b). Older adults were slower than younger adults. Follow-up tests for the effect of item type showed a significant increase in RTs from new items to 1-back lures ($p < .001$) and significant decreases when comparing the 3- to the 5-back ($p = .003$) and 6-back ($p = .002$) positions. RTs did not return to the baseline new item level even at the most distant position. There was also an interaction between age and item type, $F(5, 345) = 2.80$, $MSE = 6123.32$, $p = .039$, partial $\eta^2 = .04$. Follow-up tests revealed that age effects were similar, and significant, for new items and 1-back lures, with larger (all *p* values < .05) but similar age differences for all other lures.

FIGURE 3. Performance on non-targets for *n* level 2 in Experiment 2: (a) accuracy; (b) response times. Error bars represent standard errors.

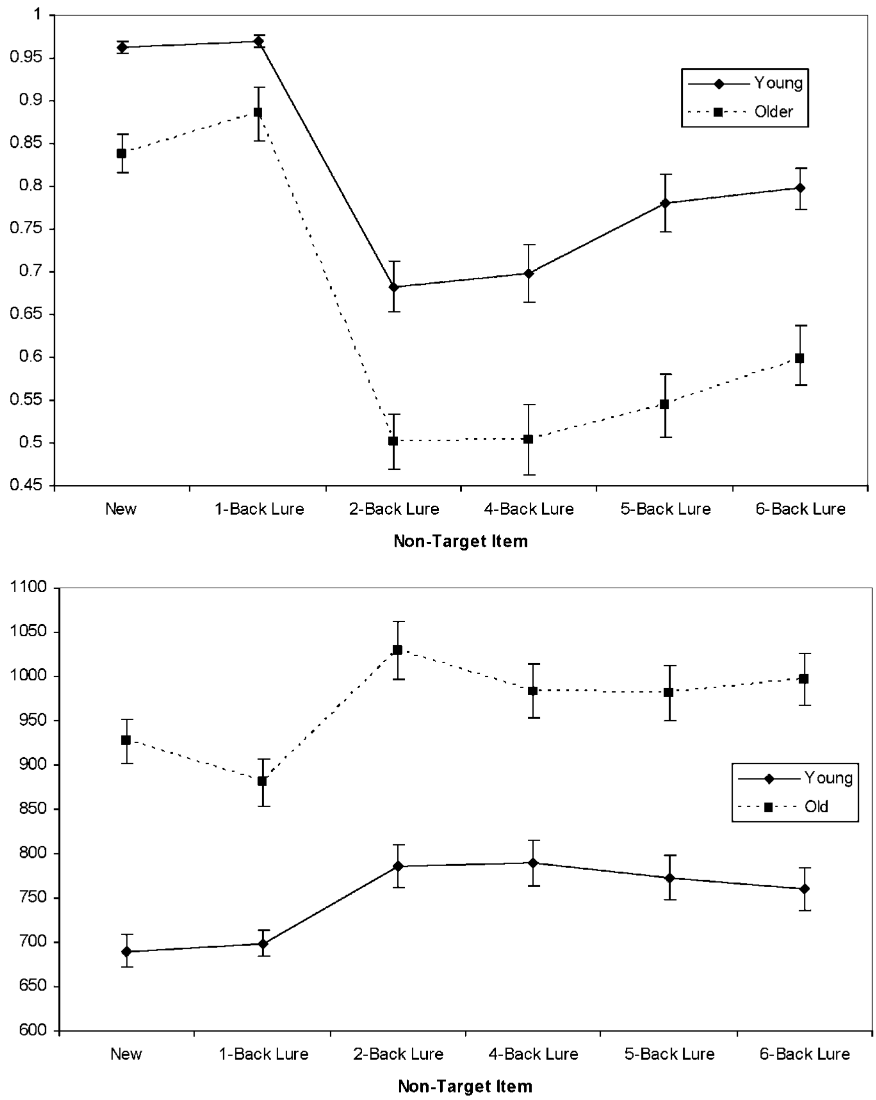


Non-Target Items for *n* Level 3

Accuracy

A 2 (Age) × 6 (Non-target item type: new, 1-back lure, 2-back lure, 4-back lure, 5-back lure, 6-back lure) ANOVA showed main effects of both age, $F(1, 70) = 29.16$, $MSE = 0.11$, $p < .001$, partial $\eta^2 = .29$, and item type,

FIGURE 4. Performance on non-targets for *n* level 3 in Experiment 2: (a) accuracy; (b) response times. Error bars represent standard errors.



$F(5, 350) = 87.66$, $MSE = 0.02$, $p < .001$, partial $\eta^2 = .56$ (see figure 4a). Follow-up contrasts for the item type effect revealed that new and 1-back lure items were similar and had the highest accuracy levels, with a significant drop in performance from the 1- to 2-back lures ($p < .001$) that remained constant for the 4- and 5-back lure positions. Although there was no significant increase from the 5- to 6-back positions, the increase in accuracy from the 4- to the 6-back position was significant ($p < .001$). Neither age group showed a return to baseline levels of performance. There was also a significant interaction between age and item type, $F(5, 350) = 3.14$, $MSE = 0.02$, $p = .009$, partial $\eta^2 = .04$. This was characterized by similar, significant, age effects for new items and 1-back lures, and a significantly larger effect for the other lures (all p values < .05), which all showed similar age differences.[2]

Response Times

An identical ANOVA using RTs revealed that older adults were slower overall, $F(1, 70) = 44.25$, $MSE = 114158.31$, $p < .001$, partial $\eta^2 = .39$, and that RTs differed across item types, $F(5, 350) = 24.03$, $MSE = 6684.51$, $p < .001$, partial $\eta^2 = .26$. There was no interaction between age group and item type (see figure 4b). Follow-up contrasts showed similar, significant RTs for new and 1-back lures, which in turn were faster than for all other lures (all p values < .05).

Discussion

The results of Experiment 2, using non-verbal stimuli, generally replicated findings from Experiment 1. Despite a few inconsistencies across experiments, none suggest qualitative differences in performance on *n*-back lures based on stimulus type.

Focusing first on the lure position subject to the least decay (i.e., 1-back), results were again consistent with predictions about the relatively high level of activation for the 1-back lure position. In fact, in a pattern that differed from Experiment 1, accuracy was equivalent and quite high for new items and 1-back lures for both *n* levels, and RTs showed this equivalence for *n* level 3. One possible explanation for this discrepancy is the inclusion of practice trials using *n* level 1 in Experiment 2. Although these were included to familiarize participants with the line drawings, this extra practice might have affected 1-back lure performance by providing additional experience in maintaining information from immediately preceding items.

In agreement with Experiment 1, however, we again found reduced performance for the 2-back lure for *n* level 3 in relation to 1-back lures. Also, lure positions more distant than and adjacent to the target (i.e., the 3-back lure for *n* level 2 and the 4-back lure for *n* level 3) showed no evidence for immediate inhibition of no-longer-relevant information; indeed, performance was at its lowest in these positions. These findings together provide additional support for a decay account combined with the perturbation model (Estes, 1972) and suggest faulty temporal information in the presence of activated item information, especially in adjacent-to-target positions. The more distant lure positions showed a rebound in performance in both accuracy and RTs, as in the first experiment, with the exception of RTs for *n* level 3. Performance did not return to baseline levels even for the most distant lures, again suggesting deficient temporal memory for items that still have residual activation in WM.

With respect to age effects in lures, we again found significant age differences in accuracy and RTs for all lures, but in this experiment age differences for less recent information were greater than for 1-back lures. There was also an exaggerated age effect in accuracy for the 3-back lures in *n* level 2, consistent with the hypothesis of reduced WM for temporal context information. Unlike in Experiment 1, however, this effect was not evident for the 4-back lures in *n* level 3. One possible reason for this difference is the increased difficulty of the non-verbal stimuli used in the second experiment. Indeed, an examination of older adults' lure performance for *n* level 3 shows quite low accuracy for the 2- and 4-back lures, and a *post hoc* cross-experiment analysis indicated that age differences in accuracy were overall greater in Experiment 2 than in Experiment 1 ($p = .003$). It is therefore possible that the line drawings were more difficult to process for older adults, and that a floor effect masked our ability to interpret the size of age differences for these lure positions. Nevertheless, the RT patterns for the two experiments were comparable, showing similar age effects across the lure positions.

To situate the findings in relation to the hypotheses set forth earlier, the age-related patterns of lure performance indicate further support for the temporal context WM hypothesis, at least for *n* level 2. Further, although significant age differences in new items for both *n* levels and for overall *n*-back performance suggested an item memory decline in older adults, this deficit did not provide a full explanation for lure performance (i.e., age differences did not become progressively smaller as lure distance increased).

In sum, Experiment 2 reinforced support for the importance of temporal context WM in processing information outside the FOA, but was inconsistent with Experiment 1 in regard to the role of temporal context for the most recently presented information. As in the first experiment, a combination of predictions from the perturbation model (Estes, 1972) and decay mechanisms are consistent with lure performance patterns. Similar to Experiment 1, age-related results from the current experiment generally support the hypothesis that a decline in WM for temporal context information exists above and beyond a probable item WM decline.

GENERAL DISCUSSION

The *n*-back lure paradigm was utilized in two experiments to examine general and age-related mechanisms of item and temporal context activation in WM, as framed by Cowan's (1988, 1999) WM model. Results converged on three main findings: (1) recently presented information with the least time to decay has a processing advantage, but is still susceptible to temporal context errors and age effects; (2) most lure errors were made in positions adjacent to target positions for both age groups; and (3) age differences in temporal context WM appear to contribute to task performance above and beyond a probable decline in item WM.

First, confirming the hypothesis of high activation of recently presented items, 1-back lures were consistently more accurate than the intermediate lure positions, across both experiments. Consistent with Estes (1972), however, these lures were at times confused with their temporally close neighbors. Assuming that item information (i.e., recognition memory) is intact, this indicates difficulty with temporal context information even for items with relatively high activation. In regard to the 2-back lures for *n* level 3, which had more time to decay than 1-back lures, both experiments showed quite low performance compared to all other items, except for equivalent performance in relation to the 4-back lures, which were also adjacent to the target position and subject to perturbation. This pattern supports the view that item information in these intermediate positions is activated enough to support recognition, but temporal context information is not sufficiently activated to support accurate responding.

For lure positions containing information not needed for later responses, activation of both item and temporal information appears to decrease. An examination of the lures matching items adjacent to and more distant than the target positions (i.e., 3-back lures for *n* level 2 and 4-back lures for *n* level 3) allows for a comparison of predictions from the decay and inhibition mechanisms. If inhibition is able to completely dampen all task-irrelevant items, then we should find a substantial increase in performance for those lures. As predicted, our data indicate no such immediate rebound, showing quite low performance for these adjacent-to-target, 'non-relevant' lure positions. A role for inhibition cannot be ruled out, but the incremental nature of improved lure performance for the more distant positions suggests a mechanism that works gradually. In our opinion, the pattern is instead more consistent with a decay mechanism that may work faster for temporal information and/or a gradual increase in the temporal discriminability of target and lure positions, the maximum of which was not detected in the current experiments. Items as far back as six positions retained enough residual item information (along with faulty temporal information) to cause confusion with the target position.

Additional support for these conclusions is found in the analyses of RTs across lure positions, which showed similar patterns to those of accuracy. The slowing of responses for the adjacent-to-target lure positions suggests that processing of item and temporal information about these lures required additional time. The exception to this general pattern was for *n* level 3 in Experiment 2, which failed to show a rebound for the most distant lure positions.

With respect to age differences, the results confirmed the general hypothesis of age differences in non-FOA processing, consistent with previous research (Verhaeghen & Basak, 2005; Verhaeghen et al., 2005). Our findings also address age-related hypotheses based on activation levels of item and temporal information outside the FOA. Data from both experiments support the hypothesis of an age-related reduction in temporal context WM. This is consistent with prior demonstrations of age effects in contextual information processing and item-to-context binding (e.g., Braver & Barch, 2002; Naveh-Benjamin, 2000; Oberauer, 2005), and specifically in memory for temporal context (e.g., Hartman & Warren, 2005; Howard et al., 2006). Because temporal memory should be most critical at positions adjacent to the target, where position information is easily confused, we predicted an increased age effect in these positions. Indeed, age differences in accuracy were significantly larger for the position just beyond the target (i.e., the 3-back lure position for *n* level 2 and the 4-back lure position for *n* level 3), compared to the other lure positions. The failure to demonstrate this pattern in Experiment 2 for the 4-back lure position in *n* level 3 may have been influenced by floor effects.

It is worthwhile to note that for both experiments, the RT data indicated similar age effects for all the non-FOA lure positions, including the adjacent-to-target positions that showed exaggerated age effects in the accuracy data. These discrepancies between accuracy and RTs in the measurement of age effects may suggest the measurement of qualitatively different processes (i.e., availability vs. accessibility, e.g., Verhaeghen & Basak, 2005) or, more likely, reflect the fact that the timing for the tasks was experimenter-determined and may not have allowed for a depiction of the full range of age-related RT effects.

With respect to age differences in item WM, which are often smaller in magnitude than those related to context memory (e.g., Spencer & Raz, 1995; Verhaeghen et al., 1993), certain aspects of our data support this type of memory decline. New item performance was examined, with the hypothesis that if older adults have intact item memory, they should be as proficient as younger adults in rejecting items presented for the first time in a sequence. Although there were no age differences for new items for *n* level 2 in Experiment 1, each of the other analyses showed small but significant age effects. The item WM hypothesis was not supported, however, in relation to lures. Older adults exhibited substantial difficulty with all lure items, indicating active item information but faulty temporal information. If they had completely lost item activation, then lures would presumably be easy to reject, especially those matching the most distant positions. Further, the qualitative similarity of the rebound pattern for younger and older adults in the more distant lure positions suggests similar rates of item information decay outside the FOA (e.g., Hartman et al., 2001). Although it is probable that older adults have a lower level of activation for item information than younger adults, the age effects for the more distant lures indicate that item information has not exited WM entirely. Thus, the data provide little support for item WM decline as the sole explanation for reduced *n*-back performance.

In sum, our findings in relation to cognitive aging suggest an item memory deficit, but also a more substantial decline in WM for temporal context information. Based on prior research, this decline, as inferred from *n*-back lure performance, is likely attributable at least in part to content-context binding mechanisms at the encoding stage (e.g., Naveh-Benjamin, 2000; Oberaurer, 2005), which subsequently affect activation levels for temporal information held outside the FOA. Our results suggest that these binding processes make temporal context information more vulnerable than item WM, at least when item memory depends primarily on recognition, as in the *n*-back task (e.g., Oberauer, 2005). When residual item information is combined with inadequate temporal context information, performance suffers for both younger and older adults. This was apparent in perturbation errors for lures that were adjacent to target positions. Older adults utilized the same WM mechanisms as young, but showed differential deficits across mechanisms, specifically those related to temporal context WM.

The consistency of general and age-related results across the two experiments suggests that the theoretical conclusions from this project are replicable and also generalizable across verbal and non-verbal stimulus domains. A comparison of performance patterns between younger and older adults allows for an increased understanding of cognitive aging processes, but also a method to learn more about mechanisms of WM common across the lifespan.

The issues investigated here are also broader than just the study of the *n*-back task. Our results have implications for studies in cognitive psychology, cognitive aging, and cognitive neuroscience that use not only the *n*-back task to measure WM processes, but other tasks as well. Many studies of WM focus solely on the measurement of item information. However, context memory may be of greater importance in WM than previously recognized (e.g., Braver & Barch, 2002; Burgess & Hitch, 2005; Hartman & Warren, 2005; Oberauer, 2005). Most WM tasks require context memory, whether it be the ordering or reordering or stimuli (i.e., alphabet span task, Letter-Number Sequencing Task) or selecting relevant information (i.e., complex span tasks). Thus, we support the continued examination of theoretical and empirical distinctions between content and context WM, and a more detailed understanding of patterns of age differences in each.

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REFERENCES

Anderson, J. R., & Matessa, M. (1997). A production system theory of serial memory. *Psychological Review, 104,* 728–748.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. A. Bower (Ed.), *The psychology of learning and motivation, Volume 8* (pp. 47–89). New York: Academic Press.

Baddeley, A. D., & Hitch, G. J. (1994). Developments in the concept of working memory. *Neuropsychology, 8,* 485–493.

Balota, D. A., Duchek, J. M., & Paullin, R. (1989). Age-related differences in the impact of spacing, lag, and retention interval. *Psychology and Aging, 4,* 3–9.

Bayen, U. J., Phelps, M. P., & Spaniol, J. (2000). Age-related differences in the use of contextual information in recognition memory: A global matching approach. *Journals of Gerontology: Psychological Sciences and Social Sciences, 55B,* 131–141.

Beck, A. T., & Steer, R. A. (1990). *Manual for the Beck Anxiety Inventory*. San Antonio, TX: Psychological Corporation.

Beck, A. T., Steer, R. A., & Brown, G. K. (1996). *Manual for the Beck Depression Inventory – Second Edition*. San Antonio, TX: Psychological Corporation.

Bjork, E. L., & Healy, A. F. (1974). Short-term order and item retention. *Journal of Verbal Learning and Verbal Behavior, 13,* 80–97.

Braver, T. S., & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience and Biobehavioral Reviews, 26,* 809–817.

Braver, T. S., Barch, D. M., Keys, B. A., Carter, C. S., Cohen, J. D., Kaye, J. A., et al. (2001). Context processing in older adults: Evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology: General, 130*, 746–763.

Braver, T. S., Satpute, A. B., Rush, B. K., Racine, C. A., & Barch, D. M. (2005). Context processing and context maintenance in healthy aging and early stage dementia of the Alzheimer's type. *Psychology and Aging, 20,* 33–46.

Brown, G. D. A. (1997). Formal models of memory for serial order: A review. In M. A. Conway (Ed.), *Cognitive models of memory* (pp. 47–77). Hove, UK: Psychology Press.

Brown, G. D., Preece, T., & Hulme, C. (2000). Oscillator-based memory for serial order. *Psychological Review, 107,* 127–181.

Burgess, N. (1995). A solvable connectionist model of immediate recall of ordered lists. In G. Treasuno, D. Touretzky, & T. K. Leen (Eds.), *Advances in neural information processing systems* (Vol. 7, pp. 51–58). Cambridge, MA: MIT Press.

Burgess, N., & Hitch, G. J. (1992). Toward a network model of the articulatory loop. *Journal of Memory and Language, 31*, 429–460.

Burgess, N., & Hitch, G. J. (2005). Computational models of working memory: Putting long-term memory into context. *Trends in Cognitive Sciences, 9,* 535–541.

Burgess, G. C., Gray, J. R., & Braver, T. S. (2002). *Differential sensitivity of items in the n-back task: 'Lures' explain variance in executive control that 'non-lures' don't.* Paper presented at the 43rd Annual Meeting of the Psychonomic Society, Kansas City, MO.

Chalfonte, B. L., & Johnson, M. K. (1996). Feature memory and binding in young and older adults. *Memory and Cognition, 24,* 403–416.

Cohen, J. (Ed.). (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104,* 163–191.

Cowan, N. (1999). An embedded-processes model of working memory. In P. Shah (Ed.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62–101). Cambridge, UK: Cambridge University Press.

Cowan, N. (2000). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24,* 87–185.

Dobbs, A. R., & Rule, B. G. (1989). Adult age differences in working memory. *Psychology and Aging, 4,* 500–503.

Estes, W. K. (1972). An associative basis for coding and organization in memory. In E. Martin (Ed.), *Coding processes in human memory* (pp. 161–190). New York: Halstead Press.

Farrell, S., & Lewandowsky, S. (2004). Modelling transposition latencies: Constraints for theories of serial order memory. *Journal of Memory and Language, 51,* 115–135.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). Mini-Mental State: A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12,* 189–198.

Garavan, H. (1998). Serial attention within working memory. *Memory and Cognition, 26*(2), 263–276.

Gray, J. R., Chabris, C. F., & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience, 6,* 316–322.

Hartley, A. A., Speer, N. K., Jonides, J., Reuter-Lorenz, P. A., & Smith, E. E. (2001). Is the dissociability of working memory systems for name identity, visual-object identity, and spatial location maintained in old age? *Neuropsychology, 15,* 3–17.

Hartman, M. (1995). Aging and interference: Evidence from indirect memory tests. *Psychology and Aging, 10,* 659–669.

Hartman, M., & Hasher, L. (1991). Aging and suppression: Memory for previously relevant information. *Psychology and Aging, 6,* 587–594.

Hartman, M., & Warren, L. H. (2005). Explaining age differences in temporal memory. *Psychology and Aging, 20,* 645–656.

Hartman, M., Dumas, J., & Nielsen, C. (2001). Age differences in updating working memory: Evidence from the Delayed-Matching-To-Sample Test. *Aging, Neuropsychology, and Cognition, 8,* 14–35.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). San Diego, CA: Academic Press.

Hasher, L., Stoltzfus, E. R., Zacks, R. T., & Rypma, B. (1991). Age and inhibition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 163–169.

Hasher, L., Quig, M. B., & May, C. P. (1997). Inhibitory control over no-longer-relevant information: Adult age differences. *Memory and Cognition, 25,* 286–295.

Healy, A. F. (1974). Separating item from order information in short-term memory. *Journal of Verbal Learning and Verbal Behavior, 13,* 644–655.

Henson, R. N. A. (1998). Short-term memory for serial order: The start-end model. *Cognitive Psychology, 36,* 73–137.

Howard, M. W., & Kahana, M. J. (2002). A distributed representation of temporal context. *Journal of Mathematical Psychology, 46,* 269–299.

Howard, M. W., Kahana, J. J., & Wingfield, A. (2006). Aging and contextual binding: Modeling recency and lag recency effects with the temporal context model. *Psychonomic Bulletin and Review, 13,* 439–445.

Johnson, G. J. (1991). A distinctiveness model of serial learning. *Psychological Review, 98,* 204–217.

Lee, C. L. (1992). The perturbation model of short-term memory: A review and some further developments. In S. M. Kosslyn (Ed.), *Essays in honor of William K. Estes, Vol. 2: From learning processes to cognitive processes* (pp. 119–141). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Lee, C. L., & Estes, W. K. (1977). Order and position in primary memory for letter strings. *Journal of Verbal Learning and Verbal Behavior, 16,* 395–418.

Lee, C. L., & Estes, W. K. (1981). Item and order information in short-term memory: Evidence for multilevel perturbation processes. *Journal of Experimental Psychology: Human Learning and Memory, 7,* 149–169.

Lewandowsky, S., & Murdock, B. B. (1989). Memory for serial order. *Psychological Review, 96*, 25–57.

Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. *Journal of Experimental Psychology: General, 130,* 199–207.

McCabe, J., & Hartman, M. (2003). Examining the locus of age effects on complex span tasks. *Psychology and Aging, 18,* 562–572.

McElree, B. (2001). Working memory and focal attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 817–835.

Mitchell, K. J., Johnson, M. K., Raye, C. L., Mather, M., & D'Esposito, M. (2000). Aging and reflective processes of working memory: Binding and test load deficits. *Psychology and Aging, 15*, 527–541.

Murdock, B. B. Jr. (1995). Developing TODAM: Three models for serial order information. *Memory and Cognition, 23*, 631–645.

Myerson, J., Hale, S., Rhee, S. H., & Jenkins, L. (1999). Selective interference with verbal and spatial working memory in young and older adults. *Journal of Gerontology: Psychological Sciences, 54B,* P161–P164.

Nairne, J. S., Riegler, G. L., & Serra, M. (1991). Dissociative effects of generation on item and order retention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 702–709.

Naveh-Benjamin, M. (1990). Coding of temporal order information: An automatic process? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 116*, 117–126.

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: Tests of an associative deficit hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 1170–1187.

Naveh-Benjamin, M., Hussain, Z., Guez, J., & Bar-On, M. (2003). Adult age differences in episodic memory: Further support for an associative-deficit hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 826–837.

Oberauer, K. (2001). Removing irrelevant information from working memory: A cognitive aging study with the modified Sternberg task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 948–957.

Oberauer, K. (2005). Binding and inhibition in working memory: Individual and age differences in short-term recognition. *Journal of Experimental Psychology: General, 134*, 368–387.

Olejnik, S., Li, J., Supattathum, S., & Huberty, C. J. (1997). Multiple testing and statistical power with modified Bonferroni procedures. *Journal of Educational and Behavioral Statistics, 22,* 389–406.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103,* 403–428.

Shipley, W. C. (1940). A self-administered scale for measuring intellectual impairment and deterioration. *Journal of Psychology, 9,* 371–377.

Spencer, D., & Raz, N. (1995). Differential effects of aging on memory for content and context: A meta-analysis. *Psychology and Aging, 10,* 527–539.

Stoltzfus, E. R., Hasher, L., & Zacks, R. T. (1996). Working memory and aging: Current status of the inhibitory view. In J. T. E. Richardson (Ed.), *Working memory and human cognition* (pp. 66–88). New York: Oxford University Press.

Tehan, G., Fallon, A. B., & Randall, N. (1997). The effect of item and relational processing on incidental long-term memory for order. *Memory, 5,* 457–482.

Troyer, A. K., & Craik, F. I. M. (2000). The effect of divided attention on memory for items and their context. *Canadian Journal of Experimental Psychology, 54,* 161–171.

Verhaeghen, P., & Basak, C. (2005). Ageing and switching of the focus of attention in working memory: Results from a modified N-Back task. *Quarterly Journal of Experimental Psychology, 58A,* 134–154.

Verhaeghen, P., Marcoen, A., & Goossens, L. (1993). Facts and fiction about memory aging: A quantitative integration of research findings. *Journal of Gerontology: Psychological Sciences, 48,* P157–P171.

Verhaeghen, P., Cerella, J., Bopp, K. L., & Basak, C. (2005). Aging and varieties of cognitive control: A review of meta-analyses on resistance to interference, coordination, and task switching, and an experimental exploration of age-sensitivity in the newly identified process of focus switching. In D. N. McIntosh (Ed.), *Cognitive limitations in aging and psychopathology: Attention, working memory, and executive functions* (pp. 160–189). New York: Cambridge University Press.