BRIEF REPORTS

Interference and Facilitation in Spatial Working Memory: Age-Associated Differences in Lure Effects in the *N*-Back Paradigm

Florian Schmiedek
Max Planck Institute for Human Development
and Humboldt-Universität zu Berlin

Shu-Chen Li and Ulman Lindenberger
Max Planck Institute for Human Development

Working memory (WM) declines prominently during normal aging. The mechanisms underlying this decline are not fully understood. The authors analyzed performance on 2 versions of a 2-back spatial WM task to assess younger and older adults' responses to lures (i.e., nontarget items that match an item earlier in the sequence but not at the current target lag). Results demonstrate lure interference effects that are particularly pronounced among older adults. At the same time, however, older adults showed facilitation for targets. Taken together, these findings suggest that the contribution of familiarity signals to WM performance increases during normal aging.

Keywords: working memory, interference, *n*-back task, lure effects, familiarity

Working memory (WM) is a well-established theoretical concept (see Baddeley, 2007; Miyake & Shah, 1999) that is relevant for a wide range of behaviors (e.g., reading comprehension, complex skill learning, fluid intelligence) that involve simultaneous storage and processing of information (Feldman Barrett, Tugade, & Engle, 2004). WM is also critical for understanding cognitive deficits associated with attention disorders (e.g., Barkley, 1997), schizophrenia (e.g., Carter et al., 1998), and aging (e.g., Craik, Anderson, Kerr, & Li, 1995; Mayr & Kliegl, 1993; Salthouse, 1994). A prominent experimental paradigm used in WM research is the *n*-back task (e.g., Cohen et al., 1997). The participants' goal in this task is to evaluate whether each stimulus, presented one by one in a sequence, matches another stimulus presented earlier in the sequence, at a given lag. For example, in a visually presented letter 3-back task, participants see a series of letters one by one and have to decide whether each letter matches the one seen three steps before in the sequence. The *n*-back task is commonly used in cognitive neuroscience research of WM (see Owen, McMillan, Laird, & Bullmore, 2005, for a meta-analysis), schizophrenia research (see Glahn et al., 2005, for a meta-analysis), and cognitive

aging research. Half a century ago, Kirchner (1958) investigated age differences in an early variant of the spatial *n*-back paradigm and observed that older participants' performance on this task was impaired. Dobbs and Rule (1989) systematically compared age differences in a variant of the verbal *n*-back task in a sample ranging in age from 20 to 80 years and showed that memory performance decreased monotonically with advancing age for lags one and two.

Although *n*-back tasks are used frequently, little is known about the mechanisms underlying *n*-back performance. Given the complexity of such tasks, it is likely that a range of WM processes are involved, among them, processes of information maintenance and manipulation as well as updating of temporal order and other context information (Marshuetz, 2005; Miller & Cohen, 2001). In particular, spatial *n*-back tasks require continuous updating operations of spatial position and temporal order that are relevant for the critical response lag. The nature of mechanisms relevant for such online updating is largely unknown and may differ across variants of the *n*-back paradigm. Some proposals have been made. For instance, inhibitory mechanisms suppressing no-longer-relevant stimuli (i.e., stimuli with a lag greater than the critical target lag, *n*) might play an important role for successful performance. Thus, age differences in *n*-back performance may reflect, to some extent, senescent impairments in inhibitory processing (e.g., Hasher, Zacks, & May, 1999).

When one conceives of the *n*-back task as a short-term recognition memory task, additional aging-associated mechanisms come to the fore. Theoretical considerations and empirical evidence suggest that WM capacity and aging-related differences therein reflect general limitations in establishing, maintaining, dissolving, and updating arbitrary bindings. For instance, Oberauer (2005) has argued that correct recognition of items seen *n* steps prior requires the successful coordination of binding and unbinding processes. Hence, the mechanisms of familiarity and recollection, which are generally examined by using other forms recognition memory

(Yonelinas, 2002), may also affect performance in the *n*-back task. In the case of the *n*-back task, "familiarity" does not refer to whether a stimulus is an old item (i.e., has been formerly presented) or is not, as the whole series of stimuli in a given trial of the *n*-back task would have been seen before, at least after a couple of trials, so that all items would be familiar by definition. Instead, the term *familiarity* is used, as in Oberauer (2005), to denote an automatic source of information about how much the present item matches activated representations in long-term memory.

Cowan (1995) distinguished between such an activated part of long-term memory and the focus of attention, which has a presumed capacity limit of four elements (Cowan, 2001). In discussing his concentric model of WM, Oberauer (2002) further elaborated this account. He distinguished the activated part of long-term memory from a narrower region of direct access, which is responsible for the building and maintenance of bindings between representations, and the focus of attention, which can likely hold just one item for ongoing processing operations (cf. McElree, 2001). Regarding the *n*-back task, the focus of attention might play a role for items within a short lag (i.e., a lag of one) and thereby provide them with a privileged status for the required decisions. The region of direct access is where continual updating of bindings between spatial and temporal positions would need to take place; thus, it is plausible to assume that the last *n* items are held accessible. As for items associated with lags larger than *n*, one could assume that they are no longer needed in the region of direct access. To the degree that passive decay or active inhibition is not sufficient to reduce the activations of items with larger than *n* lags back to baseline, all items encountered before in a trial potentially belong to the activated part of long-term memory and contribute familiarity signals to the recognition memory decision. Such familiarity information might influence the memory decision to differing degrees, depending presumably upon the efficiency of inhibition, updating, or attention-shifting mechanisms within the region of direct access.

Lure items in the *n*-back task are nontarget items that match an item earlier in the sequence but not at the current critical target lag (e.g., 1-back, 3-back, or 4-back matches in a 2-back task). Lure items provide an empirical means for observing the more or less efficient control of familiarity signals. For instance, strong reliance on familiarity information could potentially lead to interference for lures of all lags; possibly, the strength of such interference would decline as a function of the temporal lag. Lure effects have been analyzed in a few previous studies. For instance, lure effects have been shown to be particularly sensitive to the cognitive deficits present in schizophrenia (Perlstein, Carter, Noll, & Cohen, 2001) and traumatic brain injury (Perlstein et al., 2004). Furthermore, the lure effect is related to individual differences in fluid intelligence and lateral prefrontal activations (Gray, Chabris, & Braver, 2003). Recently, Kane, Conway, Miura, and Colflesh (2007) reported 1-back lure effects in verbal 2-back and 3-back tasks; these effects were interpreted as familiarity-based responding. Regarding age-associated differences, Oberauer (2005) demonstrated that proportional lure-related intrusion costs in reaction time (lures compared to nontargets) were larger in older than in younger adults.

So far, studies on lure effects with the *n*-back paradigm have primarily examined lags that were smaller than the target distance (but see McElree, 2001). Systematic analyses of lure effects for longer lags are complicated by difficulties in creating appropriate sequences, given constraints on the number of targets, nontargets, and lure items of different lags. This complexity is even greater if items with unambiguous interpretation are desired (e.g., items that are specific 4-back lures in a 3-back task and not at the same time also lures of any other lag).

The data presented here permit the investigation of lure effects with unambiguous lag status up to Lag 9. Data come from the Intra-Person Dynamics Study (for a detailed description, see Huxhold, 2007; Lindenberger, Li, Lövdén, & Schmiedek, 2007; Röcke, 2006). After an extensive pretest over 3 consecutive days, individuals participated in a microlongitudinal study phase with daily 1-hr-long assessment at a fixed time of day for over 45 days. The daily assessment included a 2-back spatial working memory task. Due to the study design, we acquired data amenable for analyzing lure effects with longer lags. Even though occurrence of lures was random on all trials, the large total number of items obtained across 45 days allowed classifying items post hoc as lures up to nine steps back in a stringent way. Furthermore, the study also allowed the investigation of another important aspect that, to our knowledge, had not previously been pursued. Two versions of the spatial 2-back task were used: the standard one, in which participants had to respond according to the actual positions at which circles appeared in a grid, and a more complex one, in which responses had to be made according to mentally shifted target positions. It was thus possible to differentiate whether intrusion effects arise primarily from the perceived locations or from mentally generated bindings of temporal and spatial positions.

Method

Participants

Eighteen younger adults (20–30 years of age, $M = 25.5$ years, $SD = 2.7$) and 18 older adults (70–80 years of age, $M = 74.2$ years, $SD = 2.8$) were included in the present analyses. Cognitive functioning was examined with marker tasks of perceptual speed and crystallized abilities. Selectivity analyses showed that, compared with a sample from a larger representative study (Li et al., 2004), the present sample did not exhibit significant selectivity effects regarding cognitive status (Huxhold, 2007). Thirty participants completed all 45 daily sessions, whereas the other 6 (2 younger and 4 older participants) completed between 42 and 44 sessions (overall participation rate = 99.4%).

Materials and Experimental Procedure

In each session, participants first worked on four trials of a spatial 2-back task in a regular condition and then worked on four trials of a version that required mental shifting. In the regular condition, a sequence of black circles appeared in the eight outer squares of a three-by-three grid (the middle square was not used). In the shifting condition, circles appeared in the same manner as in the regular condition, but here, participants had to mentally shift the presented position one step clockwise and memorize the shifted positions (see Figure 1).

In both conditions, sequences in each trial consisted of 22 items, which were randomly drawn with the constraint that two circles in consecutive steps could not be in the same position; this constraint excluded the occurrence of 1-back lures in the regular version. The
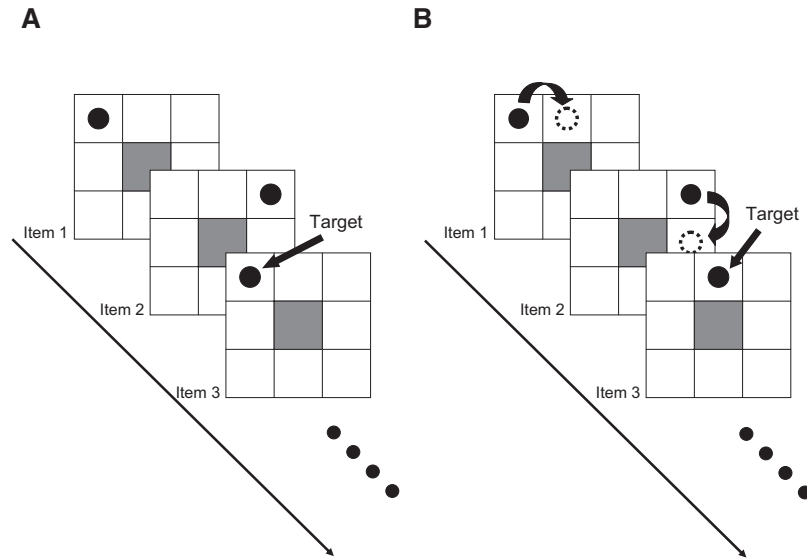
A **B**

Figure 1. Illustration of the two task versions of the spatial 2-back task. In the regular version (A), black circles appeared in the eight outer squares of a three-by-three grid. In the example shown here, the third item would be a target because the position of the circle matches those two steps back. In the shifting version of the task (B), circles had to be mentally shifted one position clockwise (denoted by the arrows) and the shifted position had to be stored (denoted by the circles with dashed lines). In this example, the third item would be a target because it matches the shifted position of the item two steps back.

random sequences of the trials of each session were identical for all participants. The presentation time was 500 ms for each circle, with interstimulus intervals of 2,500 ms. For targets, participants had to respond with their right index finger on a keyboard key marked green; for nontargets, they had to respond with their left index finger on a key marked red.

Data-Analytic Procedure

By definition, the first two items in a sequence had to be nontargets. Participants were instructed to respond negatively (i.e., no target) to these stimuli, but these responses were excluded from the analyses. Therefore, a total of 3,600 items (45 occasions × 4 trials × 20 items) was available for each of the two task versions. In each trial, six or seven items were targets. Lures and targets were defined as items that matched the item *n* steps back but that did not match any other items in their shifted or original (i.e., unshifted) positions for all remaining steps between 1-back and 9-back. In the regular condition, lures were items that matched the presented positions, whereas in the shifting condition lures were items that matched the shifted positions. In the shifting condition, we also defined and analyzed "perceptual lures" (i.e., items that matched the originally seen positions). The remaining items, which were neither targets nor lures of any kind, were defined as "pure nontargets." For these pure nontargets, familiarity effects due to earlier presentation of the same position in a sequence were strongly reduced. In a very few cases, positions of pure nontargets might have been presented before in a sequence, but there was a lag of at least 10 steps. This categorization of items resulted in 258 targets and 504 nontargets for the regular version. Numbers of lures for each lag ranged from 29 to 58 for this task. For the version involving shifting, 339 targets and 401 nontargets were

available, and the numbers of lures for each lag ranged from 21 to 70. Numbers of perceptual lures in the shifting condition ranged from 27 to 102. All remaining items were excluded because they had ambiguous status (e.g., 3-back lures that were also 6-back lures).

Reaction times (RTs) faster than 150 ms were excluded, and only RTs for correct responses were used in the analyses. Before analysis of RTs, we accounted for improvements due to practice across occasions by detrending individual data using a nonparametric loess-curve-fitting procedure with span $s = .20$ (Fox, 2000). Results for raw RTs are shown in Appendix A. Analyses of pretest and posttest data, which were available for 16 younger and 18 older participants, indicate substantial practice effects for both groups.[1] Additional information on practice effects is reported in Li et al. (in press).

Results

Regular Condition

For all results reported here, alpha level was set to .05, and values for partial eta square (η_p^2) are reported as indicators of effects size. Accuracies in the regular condition were comparable across age groups for all item types but 3-back and 4-back lures, on which older participants performed significantly worse (see Table 1). This was indicated by a significant interaction of age and

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[1] Pre–posttest results for the regular version (younger adults: $M_{RT, pretest} = 696$ ms; $M_{RT, posttest} = 354$ ms; $M_{accuracy, pretest} = .92$; $M_{accuracy, posttest} = .98$; older adults: $M_{RT, pretest} = 1,047$ ms; $M_{RT, posttest} = 559$ ms; $M_{accuracy, pretest} = .87$; $M_{accuracy, posttest} = .98$) and the shifting version (younger adults: $M_{RT, pretest} = 747$ ms; $M_{RT, posttest} = 348$ ms; $M_{accuracy, pretest} = .87$; $M_{accuracy, posttest} = .96$; older adults: $M_{RT, pretest} = 1,432$ ms; $M_{RT, posttest} = 654$ ms; $M_{accuracy, pretest} = .62$; $M_{accuracy, posttest} = .92$).

Table 1
Accuracies for Younger and Older Participants for the Different Task Versions and for Different Item Types

| | Regular condition | | Shifting condition | | | |
| | | | Shifted lures | | Perceptual lures | |
Accuracy	Younger	Older	Younger	Older	Younger	Older
Backward match						
1	n.a.	n.a.	0.98	0.89	n.a.	n.a.
2	0.93	0.95	0.94	0.88	n.a.	n.a.
3	0.95	0.84	0.93	0.71	1.00	0.95
4	0.97	0.91	0.97	0.90	0.99	0.96
5	0.99	0.97	0.99	0.96	0.99	0.95
6	1.00	0.99	0.99	0.97	0.99	0.95
7	0.99	0.98	0.99	0.94	0.99	0.96
8	1.00	1.00	0.99	0.96	1.00	0.96
9	1.00	0.99	1.00	0.95	0.99	0.97
No match (nontarget)	0.99	0.99	0.99	0.97	n.a.	n.a.

Note. n.a. = not applicable.

item type, $F(8, 272) = 6.4, p < .05, \eta_p^2 = .16$, which was due to the lower accuracies for the older group on 3-back lures, $F(1, 34) = 6.8, p < .05, \eta_p^2 = .17$, and 4-back lures, $F(1, 34) = 5.6, p < .05, \eta_p^2 = .14$.

Intrusion costs were also observed in terms of prolonged RTs. This result was achieved by analyzing the differences between RTs on targets and lures and RTs on pure nontargets. The effect of age group was not reliable, $F(1, 34) = .03, p = .86, \eta_p^2 = .00$, but significant effects were found for lag, $F(7, 238) = 9.5, p < .05, \eta_p^2 = .22$, and the interaction of age group and lag, $F(7, 238) = 7.5, p < .05, \eta_p^2 = .18$. The interaction was due to opposite age-related differences for lures and targets. On 3-back lures, the age group difference was reliable, $F(1, 34) = 6.8, p < .05, \eta_p^2 = .17$, whereas for all longer lags, comparison between age groups did not yield reliable effects. On target items, however, the age group difference was reliable, $F(1, 34) = 9.0, p < .05, \eta_p^2 = .21$,

because older participants responded reliably faster to targets than to nontargets, whereas younger participants did not (see Figure 2).

Shifting Condition

In the shifting condition, age group differences on accuracies were also significant, $F(1, 34) = 23.0, p < .05, \eta_p^2 = .40$, as was the effect of lag, $F(9, 306) = 29.1, p < .05, \eta_p^2 = .46$, and the interaction, $F(9, 306) = 9.4, p < .05, \eta_p^2 = .22$. As evident from Table 1, the age group difference on accuracies was largest for 3-back lures, $F(1, 34) = 26.0, p < .05, \eta_p^2 = .43$, but was also significant for 1-back lures, $F(1, 34) = 8.2, p < .05, \eta_p^2 = .19$, and 4-back lures, $F(1, 34) = 7.5, p < .05, \eta_p^2 = .18$. A slightly different picture was found for the RT contrasts. Here, the strongest age difference was present for 1-back lures. Overall, the age group difference was not reliable, $F(1, 34) = 1.3, p = .27, \eta_p^2 =$
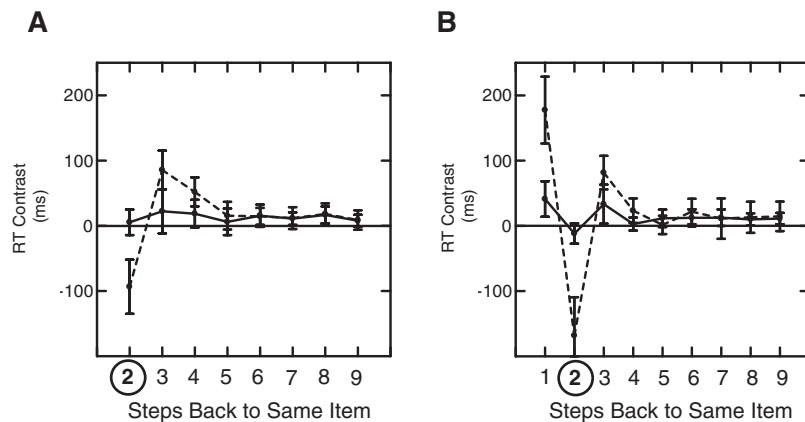

Figure 2. Reaction time (RT) contrasts of target and lure items versus nontarget and nonlure items in the regular version (A) and the version involving mental shifting of the stimuli (B). The circled "2" denotes the targets. The RT contrast on the *y*-axis results from the difference of target RTs minus pure nontarget RTs or lure RTs minus pure nontarget RTs, depending on item type. Error bars denote standard errors. Solid lines = younger adults; broken lines = older adults.

.04, but sizable reliable effects were found for lag, $F(8, 272) = 19.2$, $p < .05$, $\eta_p^2 = .36$, and the Lag × Age Group interaction, $F(8, 272) = 10.8$, $p < .05$, $\eta_p^2 = .24$. Age-related differences in lure effects were reliable for 1-back lures, $F(1, 34) = 10.5$, $p < .05$, $\eta_p^2 = .24$, and 3-back lures, $F(1, 34) = 5.1$, $p < .05$, $\eta_p^2 = .13$, but not for lures with longer lags. Looking only at targets, the facilitation effect for the older group (see Figure 2) led to a substantial age-related effect, $F(1, 34) = 13.9$, $p < .05$, $\eta_p^2 = .29$. A direct comparison of the interference and facilitation effect sizes of the regular versus shifting conditions is hampered by the fact that the shifting task was always done after the regular one, as this task order potentially produced order effects.

In addition, we investigated "perceptual lures" (i.e., lure items that matched the originally presented positions in the shifting condition). Although accuracies on perceptual lures were significantly lower for the older group, $F(1, 34) = 13.8$, $p < .05$, $\eta_p^2 = .29$, there was no reliable effect of temporal lure position, $F(6, 204) = 0.5$, $p = .77$, and no interaction, $F(6, 204) = 0.4$, $p = .88$. For the RT contrasts, however, the overall effect of age group, $F(1, 34) = 8.4$, $p < .05$, $\eta_p^2 = .20$, as well as the effect of lag, $F(7, 238) = 3.7$, $p < .05$, $\eta_p^2 = .10$, were reliable, whereas the interaction was not, $F(7, 238) = 1.7$, $p = .12$. Separate analyses with linear trends for the two age groups showed that the RT contrast decreased linearly over lag for older adults, $F(1, 17) = 10.1$, $p < .05$, $\eta_p^2 = .37$, but not for younger adults, $F(1, 17) = 1.9$, $p = .19$.

There was no indication that the two kinds of lure effects (i.e., for originally seen vs. for shifted positions) were produced by different subgroups of participants. Correlations of both kinds of interference effects across participants were positive (e.g., for 3-back lures, $r = .61$, $p < .05$, for the younger adults; $r = .37$, $p = .13$, for the older adults). Therefore, there was a tendency for participants with comparably stronger interference effects of one kind to show more interference of the other kind as well. This relation at least partially excluded the possibility that the group effect of perceptual lures was due to a subgroup of participants not being able to successfully perform mental shifting in the first place, as such inability should have produced negative correlations between the two kinds of interference effects.

Discussion

To our knowledge, this is the first investigation of lure effects in an n-back task with systematic variation of lures across a wide range of temporal lags. Interference effects were observed for lures up to Lag 4. These effects were present for actually seen positions as well as for positions that were generated by mental shifting. The wide range of lags considered allows us to draw the conclusion that lure effects decrease quickly. Even with higher statistical power, lure effects with lags greater than four are unlikely to be detected (see Figure 2). Comparisons of age groups showed stronger interference effects for lure items in the older group, with a clear temporal decay, paired with facilitation for targets. These results are in line with those of earlier studies that demonstrated interference effects on accuracy for lures with relatively short lags (Gray et al., 2003; Kane et al., 2007; Oberauer, 2005; Perlstein et al., 2004). Furthermore, our n-back data also show, for the first time, facilitation for targets relative to nontargets among older adults.

The findings of the present study have several methodological and substantive implications. With respect to the n-back paradigm, the strength of the interference effects observed in this study underscores the importance of carefully controlling the occurrence of lures in applications of n-back tasks. This control could be achieved either by avoiding presenting lure items as thoroughly as possible or, preferably, by including their occurrence as a factor in the experimental design. On the basis of more recent work, our attempts at creating stimulus sets with controlled numbers of lures for different lags suggest that such control is possible to a considerable but not unlimited degree, due to combinatorial constraints.

Furthermore, these results point to the relative importance of mechanisms that potentially contribute to adult age differences in WM. The interference effects on accuracy and on RT for lures, on the one hand, and the facilitation effects for RT on targets being present only for the older group, on the other, strongly suggest that familiarity signals contribute more to the n-back task performance of older adults than to that of younger adults. This pattern of results is difficult to explain by a general slowing account (e.g., Cerella, 1985; Salthouse, 1991) because age differences are characterized by relative decreases as well as increases in speed, depending on whether lures or targets were compared to pure nontargets. Furthermore, the age group ratio of RT interference effects was 4.3 for lures with Lag 3 in the regular condition and was 6.1 and 3.4, respectively, for lures with Lags 1 and 3 in the shifting condition. The ratio of mean raw RTs for pure nontargets was 2.0 (358 ms for younger vs. 707 ms for older adults). At least descriptively, then, interference effects were larger than predicted by proportional slowing at baseline.

The pattern of results is difficult to reconcile with a view that rests entirely on age differences in inhibition. Problems with inhibiting no-longer-relevant stimuli may explain interference effects for lures with lags of 3 and more. The facilitation for targets present in the older group, however, requires a different mechanism. On the basis of an inhibition account, RTs for targets and for nontargets should not differ, because for both item types, no inhibition is required. However, the observed RT differences between the two types of items are easily explained by positing a greater influence of familiarity on task performance in the older group. According to this account, familiarity creates a fast signal that influences accuracy by heightening the likelihood of false alarms for lure items. If familiarity information is in conflict with the correct response, the decision process is slowed (see Oberauer, 2005, for an explanation based on a diffusion model account; cf. Ratcliff, 1978). These effects were especially pronounced in the older group, and this fact points to an increased reliance on familiarity signals. This interpretation is strongly supported by the fact that older participants' responses to target items were faster than those to pure nontarget items.

Our interpretation that familiarity information is weighted more heavily in the older group is consistent with recent neuroimaging findings on a recognition task (Daselaar, Fleck, Dobbins, Madden, & Cabeza, 2006). These findings indicate relatively greater familiarity-based activation among older adults in rhinal cortex, an area that shows later and less pronounced age-related volume reductions than does the recollection-supporting hippocampus (Raz et al., 2005). It is unclear whether the increased reliance on familiarity information is a strategic adaptation to the losses in hippocampus-based recollection processes or a more automatic

consequence of the relative increase in the salience of familiarity, which itself might be due to deficient inhibition of irrelevant information (cf. Gazzaley, Cooney, Rissman, & D'Esposito, 2005).

We found that 1-back lures produced stronger effects than 3-back lures on RT in the shifting condition, whereas 3-back lures produced stronger effects than 1-back lures on accuracy. This result supports strong claims made by Oberauer (2002) and McElree (2001), who stated that the focus of attention can include only one memorized item at a time. If the most recent item is still directly in the focus of attention, 1-back lures can be rejected without the need of an error-prone retrieval (McElree, 2001) or attention shifting process (Oberauer, 2002). The assumption that the focus of attention is on the most recent item is straightforward, because before a new item appears, the most recently seen item has to be shifted clockwise mentally. This processing step requires the focus of attention.

Given their decay function, familiarity signals are probably strongest for 1-back items, however (cf. Yonelinas, 2002). The necessity to overcome these familiarity signals might prolong RT, in particular for older adults, if they tend to rely more strongly on familiarity information. For 3-back lures, by comparison, the necessary retrieval process or shift of the focus of attention within the region of direct access might produce a larger amount of errors, whereas the decreasing strength of the familiarity signal might lead to relatively smaller interference effects in RT.

We also note that responses to lures were not observed for lags greater than 4. This result may indicate that the focus of attention (in Cowan's terms) or the region of direct access (in Oberauer's terms) has a capacity limit of about four items (Cowan, 2001). If approximately the last four items have a privileged status for processing in a continuous updating task, such as the *n*-back, no matter how many items are actually needed for successful task performance (two in our tasks), the observed pattern of interference could result even if familiarity information played little or no role. Instead, this pattern would indicate that bindings of items to earlier temporal positions have not yet been sufficiently released (or inhibited). The observed facilitation for targets, however, requires the additional assumption of familiarity-based response tendencies.

In sum, the present findings indicate increased reliance on familiarity information in older adults in one WM paradigm. An increased influence of familiarity alone, however, is not sufficient to explain the observed patterns of age differences. In addition, the mechanisms for overcoming familiarity-based responding appear to be less efficient in later adulthood. Such reduced efficiency could result from less reliable updating processes, reduced inhibition, or both. Interpretation of these findings as indicative about age-related decreases in WM capacity in general hinges on the validity of our spatial *n*-back tasks as a measure of WM (cf. Kane et al., 2007). Unpublished data from our lab indicate that a very similar spatial *n*-back task is as good an indicator of WM as is a well-established complex span task (Schmiedek, Hildebrandt, Lövdén, Wilhelm, & Lindenberger, 2008).

Processing theories of working memory also need to integrate the prominent role of neuromodulatory mechanisms. A relevant theory that relates aging-related decline in dopaminergic modulation to impaired item identity (e.g., spatial location in our case) and the binding of item information with temporal order information is the theory of deficient dopaminergic neuromodulation in normal cognitive aging (Li, Lindenberger, & Sikström, 2001). This theory models suboptimal dopaminergic modulation as less effective stochastic gain tuning of neural network's activations, which leads to increasing random activation noise and less distinctive stimulus representations. The extent of interference between the representations of target items and lure items at different temporal lags is greater in systems with less distinctive item representations. The greater interference would then result in higher misleading familiarity of lure items and illusory bindings between items and their temporal orders. Thus, suboptimally modulated systems with less distinctive representations of items presented at different temporal lags increase the chances of lure items being mistaken for targets. This sequence of effects accounted for adult age differences in a simulated spatial *n*-back WM task similar to the one tested here (Li & Sikström, 2002) as well as in associative memory binding (Li, Naveh-Benjamin, & Lindenberger, 2005). In addition, related theorizing has formally explored the interaction between dopaminergic and GABAergic systems for binding and unbinding information in WM (Durstewitz, Kelc, & Güntürkün, 1999). Further progress in explicating links across behavioral and neuronal levels of analysis, with particular attention to dual-process models of recollection versus familiarity, is needed so we can better understand WM: its processing dynamics, its links to other forms of memory, and its age-associated changes.

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Appendix

Results for Raw Reaction Times

A   **B**
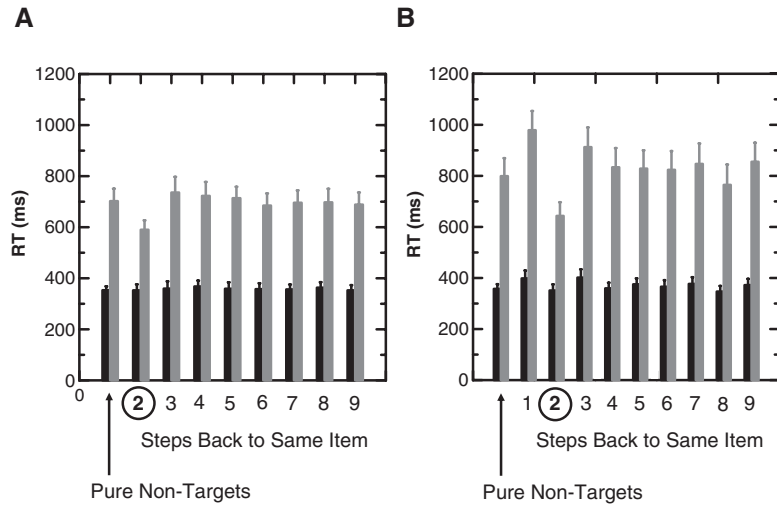
Raw reaction time (RT) contrasts of pure nontarget, target, and lure items in the regular version (A) and the version involving mental shifting of the stimuli (B). The circled "2" denotes the targets. Error bars denote standard errors. Black bars = younger adults; gray bars = older adults.