Input, Retention, and Output Factors Affecting Adult Age Differences in Visuospatial Short-Term Memory

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Objectives. The sources of age differences in short-term memory for spatial locations were explored in 2 experiments that examined factors related to input, to maintenance, and to output**.**

Method. In each experiment, 4 dots were presented briefly, followed after a retention interval by a probe dot, which was judged to either match or not match one of the 4 memory-set dots.

Results and Discussion. Results showed that poorer performance by older adults could be attributed independently to reduced visual acuity, to less effective use of rehearsal strategies, and to differences in response biases**.**

Key Words: Response criterion—Retention processes—Visual acuity—Visual short-term memory—Visual working memory.

AGE differences in verbal short-term or working memory have been studied extensively (for reviews, see Hoyer & Verhaeghen, 2006 and Zacks, Hasher, & Li, 2000). Age differences in visuospatial working memory have received less attention, although some studies have attempted to determine whether age differences are greater or lesser in one than the other (Allen, 1991; Allen, Kaufman, Smith, & Propper, 1998a; Jenkins, Myerson, Joerding, & Hale, 2000; Myerson, Emery, White, & Hale, 2003; Salthouse, 1995; Schear & Nebes, 1980; Shelton, Parsons, & Leber, 1982; Tubi & Calev, 1989; but also see Cattaneo, Bhatt, Merabet, Pece, & Vecchi, 2008). Other questions, too, have been asked and answered. Hartley, Speer, Jonides, Reuter-Lorenz, and Smith (2001) demonstrated that verbal and visual working memory, which are dissociated in younger adults, also appear to be largely dissociated in older adults. Rowe, Hasher, and Turcotte (2008) demonstrated that proactive interference in visual short-term memory was greater in older than in younger adults as had been found previously for verbal working memory (Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999). What have not been fully addressed are the origins of age-related differences in visual short-term memory. Why do older adults perform less well than younger adults? We can identify at least three possible loci of age differences, corresponding to differences at the stages of input, retention, and recall. First, at input, one possibility is that the perceptual registration of the stimulus may be less precise. Second, during retention, older adults may lose precise information through simple decay or through failure to use maintenance mechanisms or operations employed by younger adults. Third and finally, at recall, older adults may have a different decision criterion for

how close a probed location must be to a remembered location for a match response to be given. The three reasons are not mutually exclusive.

Visual short-term or working memory has been studied extensively in younger adults (for recent summaries, see Luck, 2007 and Luck & Hollingworth, 2008). One of the most commonly used procedures involves sequential comparison (e.g., Luck & Vogel, 1997). A to-be-remembered visual display is presented, and then, after a retention interval (RI), a new display is presented and the individual is asked to determine whether the new display matches the original display in some particular way. Allen and colleagues (1998b) reported the results of one sequential comparison experiment that explored whether age-related differences in spatial memory reflected primarily early stimulus-encoding stages or later processing stages. In their Experiment 2, they manipulated the number of locations in which a stimulus whose location was to be remembered could appear. Older adults were more affected by an increase in the number of locations than younger adults, consistent with an age difference in the precision of initial encoding. This interaction was not qualified by higher order interactions with other manipulations, so the authors concluded that there were also age differences in later stages. Allen (1991) had previously reported that younger and older adults did not differ in response biases that would have been suggestive of age differences in output processes.

In an attempt to provide a more systematic and definitive examination of the contributions of input, retention, and output factors, we revisited the question raised by Allen and colleagues (1998b). In the experiments reported here, we briefly displayed four dots simultaneously as a memory set; after a RI, we presented a probe that either matched one of

Table 1. Participant Characteristics: Number and Mean Age, Education, Self-Rated Health, and Snellen Visual Acuity (*SD*s in parentheses)

	n	Age (years)	Education (years)	Rated health (1–10)	Visual acuity (/20)[a]
Experiment 1					
Younger	24	19.67 (0.96)	13.46 (0.83)	8.54 (1.22)	21.25 (5.57)
Old	24	76.11 (6.72)[b]	16.82 (2.86)	7.98 (1.70)	31.88 (12.75)[b]
Experiment 2					
Younger	24	19.93 (2.15)	13.67 (1.63)	7.04 (1.43)	20.42 (3.88)
Older	22	75.34 (6.17)[b]	15.50 (1.92)	8.36 (0.95)	30.45 (8.99)[b]

[a] Visual acuity was determined by obtaining the individual's complete contrast sensitivity function (Vision Contrast Test System, Vistech Consultants, Dayton, OH) and then converting to conventional Snellen units.

[b] Younger and older adults differed significantly, $p < .05$.

the memory-set dots or mismatched by a manipulated distance. The stimuli were small dots that could appear over a wide area of the visual display rather than characters or symbols appearing in only seven possible locations as Allen had used (Allen, 1991; Allen et al., 1998a, 1998b). We selected a single set size of four, as did Allen, because it was a nontrivial memory load but also was likely to be within the short-term span of most younger and older adults. Our intention was to select a task load that would result neither in floor effects for older adults nor in ceiling effects for young adults. In our first experiment, we probed for age differences in input or output; in the second experiment, we probed for age differences during the retention period.

The broader theoretical question we intended to address was whether any age differences we observed could be accounted for by a change in a single mechanism or whether changes in independent mechanisms seem more plausible. We will return to this issue in the *Discussion*.

EXPERIMENT 1

The first possible reason for age differences in performance is that there may be differences in perceptual registration. Probably, the most important determinant of registration accuracy is visual acuity. Lowered visual acuity (and, more broadly, contrast sensitivity) is ubiquitous in old age (e.g., Ivers, Mitchell, & Cumming, 2000; Klein, Klein, Lee, & Cruickshanks, 1999; Klein, Klein, Lee, Cruickshanks, & Gangnon, 2006). With lower acuity, the location of a stimulus dot will be less precisely registered. We could say then that the parcellation of the visual field is coarser in older adults or that their perceptual receptive fields are larger by loose analogy with the receptive fields defined by the number of retinal cells that map to a single ganglion cell in the optic nerve. There may be other input-related factors beyond acuity that could affect the registration of the stimulus. To determine whether those were present, we computed the signal detection measure of *sensitivity* (d') and asked whether age differences in sensitivity remained after visual acuity had been removed as a covariate.

The third of the possible reasons for age differences in visual short-term memory performance is that there may be differences at the time of recall. The primary source of such a difference would be a more lenient decision criterion for how close a probed location must be to a remembered

location for a match response to be given. This would result in reduced accuracy, resembling that produced by perceptual factors but for a very different reason. To explore age differences in decision criteria, we calculated the signal-detection theory measure, *beta* (β). At the point where the criterion is set to discriminate between matching and nonmatching stimuli, β is the ratio of the likelihood of a matching stimulus to a nonmatching stimulus. An ideal decision maker would set the criterion such that β was 1.0, that is, the stimulus was equally likely to be a match or a mismatch. A β less than 1.0 would indicate that the criterion was set so that there was a response bias toward giving a "match" response; a β greater than 1.0 would indicate a bias toward a "mismatch" response.

METHOD

Participants

The older participants in all these studies were volunteers from the local community; the younger participants were undergraduate student volunteers. Volunteers were paid $10 for their participation. The characteristics of those participating in Experiment 1 as well Experiment 2 are given in Table 1.

Procedure

The procedure was a sequential recognition task for visuospatial location. Each trial began with a "READY" message for 1 s. A blue fixation dot was present alone for 1 s and then four yellow memory-set dots were added, presented around the circumference of an imaginary circle 13 cm (or 16° with an approximate viewing distance of 46 cm [No chin rest was used. Participants positioned their chair so that their abdomen touched the table holding the monitor while they were sitting upright. Distance from the eye to the center of the screen was measured for five individuals and averaged 46 cm.]) in diameter. The fixation point, the memory-set dots, and the probe dot all measured 2 pixels square (approximately 1.5 mm or .2°). Each dot was presented at a randomly chosen location within the central 40 degrees of one of the four quadrants. (To avoid confusion, the symbol, °, is used to indicate degrees of visual angle subtended by a stimulus, whereas the word, "degrees," is used to indicate the relative location of stimuli on the imaginary 360 degree circle around which stimulus dots were presented; of the
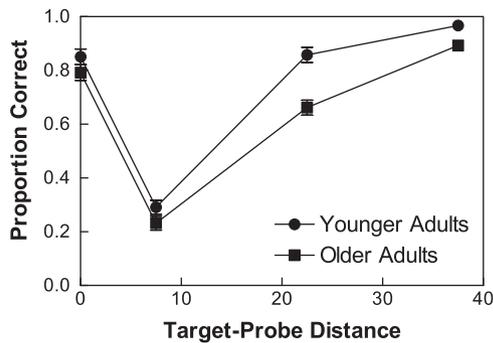
Figure 1. Mean proportion correct in Experiment 1 for younger and older adults as a function of mismatch (in degrees around the imaginary circle on which targets were displayed) between memory-set item and probe (bars show standard error).

360 degrees of the imaginary circle). After 500 ms, the memory-set dots were erased. The blue fixation dot remained present for a RI after which a white probe dot was added. The RI was randomly chosen from 500, 1,000, 2,000, or 3,000 ms. The position of the probe dot could exactly *match* the position of one of the four memory-set dots or it could be displaced by 5–10 degrees—a *near mismatch*, 20–25 degrees—a *moderate mismatch*, or 35–40 degrees—a *far mismatch*. (The mismatches correspond, approximately, to 6–11, 23–28, and 40–45 mm on the display.) The exact displacement within the range and whether the displacement was clockwise or counterclockwise was determined at random. The probe dot remained visible for 1 s and then the entire display was replaced by a request for a decision about whether the locations had matched, with the responses given with the index and middle finger of the right hand using the period (.) and slash (/) keys of a standard keyboard. There were 16 practice trials followed by 192 experimental trials, divided into four blocks of 48 trials, with RIs and proximities of the probe to the target randomly intermixed. Stimulus generation and response collection were controlled by E-Prime (Schneider, Eschmann, & Zuccolotto, 2002) running on Intel-based PCs.

Results

Analysis of variance (ANOVA) was carried out on the proportion correct as a function of the within-subjects variables proximity (match, 5–10, 20–25, and 35–40 degree mismatch) and RI (500, 1,000, 2,000, and 3,000 ms) and the between-subjects variable age group (young or old). Preliminary analysis showed there were no significant effects involving the RI (the largest nonsignificant F was 1.74). Specifically, for younger adults, the proportion correct was 0.77 with a 500 ms RI and 0.75 with a 3,000 ms RI; for older adults, the proportion correct was 0.65 at both 500 and 3,000 ms RI. Otherwise, results involving RI are not described. There were significant main effects of age group, $F(1, 46) = 25.79$, $p < .001$, $\eta^2_{PARTIAL} = .36$, and of proximity,

$F(3, 138) = 286.35$, $p < .001$, $\eta^2_{PARTIAL} = .86$. Accuracy was lower for older adults ($M = 0.65$, $SE = 0.01$) than for younger adults ($M = 0.74$, $SE = 0.01$). It was highest for far mismatches of 35–40 degrees ($M = 0.93$, $SE = 0.01$), intermediate for matches ($M = 0.82$, $SE = 0.02$) and moderate mismatches of 20–25 degrees ($M = 0.76$, $SE = 0.02$), and lowest for near mismatches of 5–10 degrees ($M = 0.26$, $SE = 0.02$). The interaction of age group and proximity was significant, $F(3, 138) = 3.59$, $p = .015$, $\eta^2_{PARTIAL} = .07$. As can be seen in Figure 1, this occurred because accuracy was significantly different for older adults than for younger adults with moderate mismatches, $t(46) = 4.92$, $p < .001$, and with far mismatches, $t(40) = 3.21$, $p = .002$, but not for matches, $t(40) = 1.44$, $p = .155$, or near misses, $t(40) = 1.61$, $p = .115$.

The two age groups differed significantly in measured visual acuity, $F(1, 46) = 13.99$, $p = .001$, $\eta^2_{PARTIAL} = .23$. To explore the contributions of visual acuity to the observed age differences, we repeated the age comparisons at each distance, this time with variance due to visual acuity removed through analysis of covariance (ANCOVA). When this was done, visual acuity accounted for a significant proportion of the variance in accuracy for the match condition, $F(1, 46) = 6.20$, $p = .017$, $\eta^2_{PARTIAL} = .12$, the near-mismatch condition, $F(1, 46) = 5.19$, $p = .028$, $\eta^2_{PARTIAL} = .10$, the moderate-mismatch condition, $F(1, 46) = 5.84$, $p = .020$, $\eta^2_{PARTIAL} = .12$, and the far-mismatch condition, $F(1, 46) = 7.53$, $p = .009$, $\eta^2_{PARTIAL} = .14$. When acuity was removed as a covariate, the age difference in the remaining variance was nonsignificant for the matching condition, $F(1, 46) = 0.01$, $p = .895$, significant for near mismatches, $F(1, 46) = 5.20$, $p = .028$, significant for moderate mismatches, $F(1, 46) = 11.29$, $p = .002$, and nonsignificant for far mismatches, $F(1, 46) = 2.82$, $p = .10$.

ANOVA was also carried out on the signal detection sensitivity measure, d'. The measure was obtained for each of the mismatch conditions (which can be thought of as no-signal conditions) relative to the match (or signal) condition. As a result, there were three levels of the within-subjects variable, proximity (near, moderate, and far mismatch). There were significant main effects of age group, $F(1, 46) = 16.73$, $p < .001$, $\eta^2_{PARTIAL} = .27$, and of proximity, $F(2, 92) = 396.16$, $p < .001$, $\eta^2_{PARTIAL} = .90$. Sensitivity was lower for older adults ($M = 1.31$, $SE = 0.14$) than for younger adults ($M = 2.11$, $SE = 0.14$). It was highest for far mismatches of 35–40 degrees ($M = 2.80$, $SE = 0.06$), intermediate for moderate matches ($M = 1.92$, $SE = 0.12$), and lowest for near mismatches of 5–10 degrees ($M = 0.40$, $SE = 0.06$). The interaction of age group and proximity was significant, $F(3, 138) = 3.59$, $p = .015$, $\eta^2_{PARTIAL} = .07$. As seen in Figure 2, the interaction occurred because the significant superiority of younger adults over older adults was smaller for the near mismatches than for the farther mismatches.

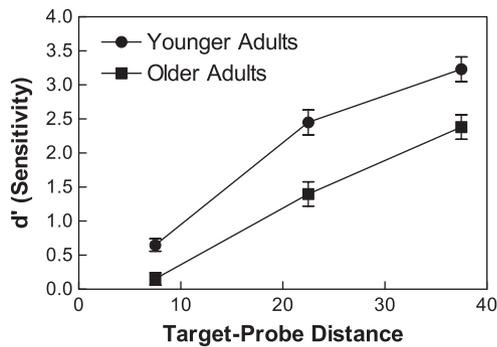To determine whether there were age differences in sensitivity after accounting for visual acuity, we again carried

Figure 2. Sensitivity (*d′*) from Experiment 1 for near-miss, moderate-miss, and far-miss conditions relative to match condition for younger and older adults (bars show standard error).

Figure 3. Decision criteria (β) from Experiment 1 for near-miss, moderate-miss, and far-miss conditions relative to match condition for younger and older adults. Values less than 1.0 indicate a bias toward a "match" response; values greater than 1.0 toward a "mismatch" response (bars show standard error).

out ANCOVAs. These showed that the age differences remained significant in the near-mismatch condition, $F(1, 46) = 8.28$, $p = .006$, and the moderate-mismatch condition, $F(1, 46) = 4.20$, $p = .011$, but not in the far-mismatch condition, $F(1, 46) = 3.22$, $p = .079$.

We also computed β for the each of the mismatch conditions relative to the match condition to determine whether there were differences in criterion setting. To permit the calculations for all cases, for those with perfect accuracy, the proportion correct was arbitrarily set at 0.99; when accuracy was zero, the proportion correct was set at 0.01. There was a significant main effect of proximity, $F(2, 92) = 71.35$, $p < .001$, $\eta^2_{PARTIAL} = .61$, with a bias toward the "match" response for near misses ($M = 0.73$, $SE = 0.04$), relatively little bias for moderate misses ($M = 1.04$, $SE = 0.12$), and a bias toward "mismatch" for far mismatches ($M = 2.42$, $SE = 0.19$). There was no effect of age group, $F(1, 46) = 2.42$, $p = .127$, $\eta^2_{PARTIAL} = .05$. The interaction of age group and proximity was significant, $F(2, 92) = 5.85$, $p = .004$, $\eta^2_{PARTIAL} = .11$. The results are shown in Figure 3. Tests of the simple main effect of proximity for each age group showed that, for older adults, there was no significant change from near mismatch to moderate mismatch, with a small bias toward the "match" response both for near misses and for moderate misses but a large increase in bias toward mismatch for far misses. Younger adults shifted from a bias toward "match" for near misses ($M = 0.59$, $SE = 0.06$) to a slight bias toward "mismatch" for moderate misses ($M = 1.27$, $SE = 0.24$) and, as with older adults, showed a large increase in bias toward "mismatch" for far misses. Another approach to these data is to use one-sample *t* tests to ask whether the response bias for each group differed significantly from 1.0 (no bias). For near mismatches, both younger and older adults were significantly below 1.0, favoring a "match" response, $t(46) = -6.55$, $p < .001$, and $t(46) = -2.55$, $p = .018$, respectively. For moderate mismatches, older adults were significantly below 1, $t(46) = -2.33$, $p = .029$, whereas younger adults did not differ, $t(46) = 1.14$, $p = .264$. For far mismatches, both younger and older adults
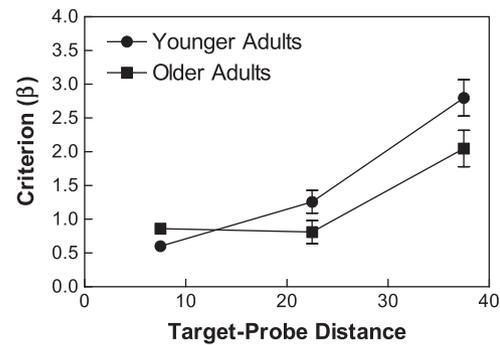
were significantly above 1.0, favoring a "mismatch" response, $t(46) = 6.22$, $p < .001$ and $t(46) = 4.27$, $p < .001$, respectively. From either perspective, the results are clear. The decision-criterion settings for older adults produced more errors for moderate and far mismatches but fewer errors for near mismatches.

The final question we asked was whether there were age differences in accuracy beyond those accounted for by the input factor, visual acuity, together with the output factor, decision bias. We tested for this by comparing younger and older adults for each of the mismatches with both acuity and β removed as covariates. (Recall that β is defined for each mismatch condition relative to the match condition, so the comparison cannot be made for matches.) When this was done, we found that the age differences in proportion correct remained significant for near mismatches, $F(1, 46) = 8.29$, $p = .006$, and moderate mismatches, $F(1, 46) = 6.92$, $p = .012$, but not for far mismatches, $F(1, 46) = 0.52$, $p = .400$.

Discussion

The results of Experiment 1 confirmed earlier findings that visual short-term memory accuracy was lower in older adults than in younger adults. The age differences in proportion correct were, however, significant only for the moderate- and far-mismatch conditions. Furthermore, the results showed that both input factors, perceptual registration, and output factors, response bias, contributed significantly to the observed age differences. The results allow the possibility of age differences in processing that occurred during the RI, but this is not certain as we will explain.

Poorer visual acuity in older adults was hypothesized to be an important input factor that could in theory contribute to age differences. The results showed that acuity was in fact lower in older adults and that acuity accounted for a significant proportion of the variance in accuracy in all four of the proximity conditions. When acuity was removed as a covariate, the age differences were significant in the near-mismatch and moderate-mismatch conditions. The results show that

acuity differences were not important for exact matches and that the poorer performance by older adults with far mismatches was completely accounted for by acuity differences. For the more difficult mismatch conditions, near and moderate, age-related variance in the proportion correct remained after the effects of acuity were removed. For the near mismatch, the formerly nonsignificant age difference in accuracy became significant, indicating that acuity effects had in fact masked other age differences. Thus, the proportion correct was affected by input processes. To isolate factors not related to output, we also calculated the measure of sensitivity, d'. Despite the label, sensitivity does not reflect only early perceptual processes. Rather it reflects the operation of all factors except for decision processes, which would operate at the time of output. Such factors could include both input and retention factors but not output factors. When the effects of visual acuity were removed from d' as a covariate, significant age-related variance remained for the near- and moderate-mismatch conditions. This means either that there are other perceptual processes beyond visual acuity contributing to the age differences in accuracy or that there are processes operating during retention or both.

Analysis of the measure of decision criterion, β, showed that differences in decision bias operating at the time of responding also contributed to the age differences in accuracy. For probes that were 5–10 degrees from the target location, both younger and older adults showed a bias toward an incorrect "match" response. When the probe was 10–20 degrees further displaced, younger adults adjusted their bias so that it was in favor of a "mismatch" response, whereas the older adults did not. With probes at 35–40 degrees, both younger and older adults had adjusted their decision criterion to strongly favor a "mismatch" response, albeit more so for the younger adults. These results show that, independent of the precision of the perceptual representation, older adults had a larger field in which they were biased to judge a mismatch as actually matching. If there are factors affecting the RI, their effects must be seen in the near- and moderate-mismatch conditions because only in those conditions was there significant age-related variance after both acuity and β had been removed as covariates.

We found no loss of information in either group with an increasing RI. Allen (1991) found a greater loss from a 100 ms RI to a 10,100 ms RI in older than in younger adults, although both conditions had a 100 ms pattern mask, and the latter condition had a 10 s distractor task, whereas our RI was unfilled. It is highly likely that the absence of either a mask or a distracting task in Experiment 1 allowed additional processing during the RI that was not possible in Allen's experiment.

EXPERIMENT 2

The results of Experiment 1 allowed the possibility that age differences in visual short-term memory may also be due to differences in processes operating during the early portion of the RI. It is well established that rehearsal, either overt or covert, plays an important role in the retention of verbal material (e.g., Rundus, 1971). Baddeley (1986) proposed that the eye movement or visual attention control systems may play a similar role in maintaining visuospatial information in active memory. More recently, Awh has provided empirical evidence in support of this proposal (Awh & Jonides, 1998; Awh, Jonides, & Reuter-Lorenz, 1998; Awh et al., 1999). Awh and colleagues (1999) developed a procedure specifically designed to interfere with retention strategies involving maintaining the focus of attention. During the RI, they presented a reversing black and white annular checkerboard, reasoning that this would disrupt attentional maintenance. We adopted this procedure in Experiment 2; otherwise, the procedures were substantially similar to those of Experiment 1. If maintenance of the focus of visual attention is critical to maintaining the location of the to-be-remembered location, then the appearance of the reversing annular checkerboard should disrupt it.

The critical prediction for Experiment 2 concerns the differences between younger and older adults. One theoretically plausible account is that younger adults routinely make use of attention-based visuospatial encoding–rehearsal processes but that older adults either do not do so or do not do so as well. If this were the case and if the appearance of the reversing annular checkerboard during the RI interfered with these processes, then we would expect the performance of younger adults to drop toward the level of older adults when the reversing stimulus interferes. If older adults are not employing these processes, the presence of the reversing stimulus should have little effect on them.

METHOD

Participants

Twenty-four younger adults and 22 older adults from the same populations as Experiment 1 participated in Experiment 2.

Procedure

The procedure was generally similar to that of Experiment 1 but with several differences. On each trial, four white dots (subtending 0.8° at a viewing distance of 46 cm) were presented on a black background, arrayed on the circumference of an imaginary circle (22.0° in diameter), and then removed. The dots were placed randomly around the entire circumference with the restriction that no dot could be nearer than 20° to another dot. The dots were displayed for 500 ms. After a 2,500 ms RI, a white probe circle (1.2° in diameter) appeared. Either the circle surrounded the position of one of the dots (a match) or it missed the nearest target dot by 15–25 degrees (similar to the moderate-miss condition in Experiment 1) or it missed the nearest target

Table 2. Means and Standard Errors (in parentheses) for Accuracy, d', and β for Younger and Older Participants in Experiment 2 as a Function of Interference (absent or present during retention) and Target-Probe Proximity

Interference condition	Age group	Younger participants			Older participants		
	Proximity	Match	Moderate mismatch	Far mismatch	Match	Moderate mismatch	Far mismatch
No interference	Proportion correct	0.77 (0.03)	0.65 (0.04)	0.90 (0.02)	0.75 (0.03)	0.52 (0.04)	0.84 (0.02)
	d'	a	1.30 (0.17)	2.29 (0.20)	a	0.82 (0.18)	1.88 (0.20)
	β	a	0.80 (0.14)	1.96 (0.16)	a	0.55 (0.14)	1.49 (0.32)
Interference	Proportion correct	0.57 (0.03)	0.60 (0.02)	0.77 (0.03)	0.65 (0.03)	0.54 (0.03)	0.75 (0.03)
	d'	a	0.46 (0.09)	1.04 (0.15)	a	0.54 (0.09)	1.17 (0.15)
	β	a	0.72 (0.09)	1.62 (0.20)	a	0.68 (0.09)	0.92 (0.20)

[a]Not defined for match condition; computed relative to match condition in mismatch conditions.

dot by 40–50 degrees (similar to the far-miss condition). Matches, moderate mismatches, and far mismatches were equally likely. The participant's task was to indicate with a right-hand key press whether the probe matched or did not match one of the target dot positions. The instructions emphasized the accuracy of the response. There were two blocks of trials, each consisting of 24 practice trials and 144 experimental trials. In one of the blocks, the RI was unfilled; in the other, a black and white annular grid 26.6° in height and 30.3° in width appeared during the RI, identical to that used by Awh and colleagues (1999). The annular grid reversed eight times per second, with black blocks becoming white and white, black. The order of the two blocks was counterbalanced across participants.

Results

The descriptive statistics for Experiment 2 are given in Table 2. Only those analyses that directly address the hypotheses are described here. For the no-interference control condition, there were significant effects of age group, $F(1, 44) = 5.00$, $p = .030$, $\eta^2_{PARTIAL} = .10$, proximity, $F(2, 88) = 76.30$, $p < .001$, $\eta^2_{PARTIAL} = .63$, and of the interaction of age group and proximity, $F(1, 44) = 3.27$, $p = .042$, $\eta^2_{PARTIAL} = .07$. A test of the simple main effect of age group for the moderate-mismatch condition showed that accuracy for younger adults was higher than for older adults, $F(1, 44) = 8.40$, $p = .006$, and this remained true even after visual acuity was removed as a covariate, $F(1, 44) = 4.96$, $p = .031$. The two groups did not differ significantly for the match and far-mismatch conditions. The analysis central to the prediction was the interaction of interference—dot present or dot absent—with age group. This interaction was significant, $F(1, 44) = 5.68$, $p = .022$. Without interference, younger adults ($M = 0.77$, $SE = .02$) were significantly more accurate than older adults ($M = 0.71$, $SE = .02$), whereas when interference was present, younger ($M = 0.65$, $SE = .02$) and older adults ($M = 0.65$, $SE = .01$) were indistinguishable.

Discussion

The results of the control condition in Experiment 2 replicated the findings of Experiment 1. The important additional finding was that visuospatial interference from the reversing annular checkerboard during the RI erased age differences in performance. (We carried out an additional experiment, not reported here in detail, that was identical to Experiment 2 except that a small colored dot—rather than the reversing stimulus—appeared along the circumference during the RI. This sudden onset would have attracted attention to that location and should have disrupted maintenance processes based on focal attention. This led to small decreases in performance that were equivalent in the two age groups. We can conclude, first, that maintenance strategies based on focal attention are less important than those based on attention to the whole field and, second, that they are used equivalently by younger and older adults.) The results of Experiment 2 mean that there must be some operation or mechanism employed to encode and retain visuospatial information in the absence of interference, a mechanism that younger adults use and that older adults do not. It is tempting to call this mechanism "visuospatial rehearsal," by analogy with rehearsal in verbal short-term memory. There is, however, no consciously applied strategy equivalent to the subvocal repetition that is blocked, for example, by articulatory suppression, so the term would simply be a label rather than an explanation. We can, nevertheless, reach the clear conclusion that age differences in both encoding and retention processes contribute to age differences in visuospatial short-term memory performance. From the additional experiment summarized earlier, we can conclude further that the processes responsible for age differences involve the whole field rather than movements of focused spatial attention. It is important to note that because we did not vary the RI in Experiment 2, we cannot reach any conclusions about the rate of loss from the visual short-term store when poststimulus encoding and rehearsal are prevented.

General Discussion

These two experiments confirmed that each of the three theoretically possible sources of age differences does in fact play a role in poorer visuospatial short-term memory performance in older adults than in younger adults. The first source of reduced accuracy is impaired perceptual registration in older adults at input. Experiment 1 showed that

measured visual acuity was lower in older than in younger adults and that recognition accuracy was significantly correlated with visual acuity. The second source of reduced accuracy is that, beyond perceptual contributions, younger adults must have been carrying out encoding and maintenance processes involving the whole field that older adults were not. When these processes were interfered with in Experiment 2, the performance of younger adults was indistinguishable from that of younger adults. The third source of reduced accuracy is that, beyond perceptual and maintenance contributions, younger adults showed stronger decision biases to respond correctly at output for moderate and far mismatches.

Although the results are clear, there do remain important and unanswered questions. One issue is that, although the results show a clear contribution of impaired visual acuity to poorer visuospatial memory performance in the older adults, they do not rule out the possibility that there are other perceptual processes operating at input as evidenced by the variance remaining in d' after the effects of acuity were removed. A converse possibility is that acuity is a very good index of the functioning of a variety of perceptual processes because every structure and stage in perceptual processing—from the cornea through the retina to the thalamus and on to the visual cortices—contributes to measured acuity. As a result, acuity could be a very powerful marker for the general intactness of the sensory nervous system and could well be capturing most or all the input differences. This would be consistent with the finding by Baltes and Lindenberger (1997) that basic measures of visual acuity accounted for a substantial portion of age-related variance in cognitive performance. The question this possibility raises is where in the perceptual system the age-related changes whose effect we observed are localized. A second issue concerns the finding in Experiment 2 that a reversing annular checkerboard erased age differences. The results do tell us that the maintenance processes used by younger adults must involve the visual field as a whole (or at least a large portion of it) and also that older adults either do not employ these processes or employ inferior variants. The results do not tell us whether these processes are conscious, deliberate, and strategic or, alternatively, passively activated. They do not tell us why older adults do not employ them. Is there some executive failure to activate them? Have the necessary substrates for their successful operation been lost? A final issue is that we do not know whether input, retention, and output factors interact. We do know because of the analytic approaches we used—analysis of covariance and signal-detection analysis—that there are independent contributions of visual acuity, retention processes, and decision criterion. This does not rule out the possibility of interactions involving other input and output processes that might be operating.

There are also issues concerning the generalizability of our findings. One is that both experiments used only visual stimuli composed of four dots. As we explained, we did this in an attempt—successful as it turned out—to avoid floor or ceiling effects. The obvious question is to what extent our conclusions would be modified with smaller or, more importantly, larger memory loads. Another issue is that our stimuli were patterns of dots. Although this may not seem important, locations in everyday experience are marked by objects, which may have names or, at least, be nameable. Would the use of objects instead of abstract dots change the nature of age differences, when ecologically representative situations were studied?

Efforts at theoretical explanations for age-related differences are often directed at single, or at least simple and parsimonious, principles that can account for the welter of diverse findings. Examples have included impairment of effortful functions and sparing of automatic functions (Hasher & Zacks, 1979), erosion of inhibitory processes (Hasher & Zacks, 1988), and decline in central nervous system transmission speed (Birren, 1974) or information processing speed (e.g., Salthouse & Madden, 2008) or some other common cause (e.g., Baltes & Lindenberger, 1997). Allen and colleagues (1998a, 1998b) proposed such an account specifically to account for age differences in visual short-term memory (also see Allen, 1991, for an earlier account). They attributed the poorer memory of older adults to greater systemic entropy reflecting higher internal noise. A measure of entropy can be extracted from accuracy. In a highly organized system, entropy is low and behavior is predictable; in a disorganized system, entropy is high and behavior is unpredictable. Because accuracy is lower in older adults than in younger adults, their behavior on any trial is less predictable, and as a result, measured entropy is higher. The reported results (Allen, 1991; Allen et al., 1998b) themselves show that the simple generalization of greater entropy in older adults is inadequate. The age differences in measured entropy were exaggerated by shortening the time for which the probe stimulus was presented and by reducing the distance between the location of the probe and target stimuli. This means that a general and uniform age difference in entropy is not sufficient to account for the results. Similarly, our results do not lend themselves readily to explanations by any single mechanism, with evidence for distinguishable age differences in registration, retention, and output processes.

For an explanation of the phenomena we observed, we turn to the neural substrates of visual short-term memory. Although this is reductionist, it does provide a principled way to build a proposed theory of age differences in visual short-term memory. The portion of variance explained by visual acuity is very likely to reflect age changes in the primary visual system. Age changes in the eye are well established, including loss of accommodative amplitude (presbyopia), decrease in pupil size (senile miosis), increased lens density, and lens yellowing (Spear, 1993). These changes could produce blurring. Retinal cells, particularly

rods, are lost (Curcio, Millican, Allen, & Kalina, 1992). Because rods predominate in the periphery where our stimuli were likely viewed, this could contribute to less precise localization. There is some loss of retinal ganglion cells (e.g., Balazsi, Rootman, Drance, Schulzer, & Douglas, 1984), which could have the same effect. Extrapolating from studies in primates, there is relatively little cell loss in the lateral geniculate nucleus of the thalamus (Ahmad & Spear, 1993), a way station along the path from retina to visual cortex, or in striate cortex (e.g., Haug, Kuhl, Mecke, Sass, & Wasner, 1984). However, there are reasons to believe that the connecting pathways may suffer impairment (Spear, Kim, Ahmad, & Tom, 1996).

Converging evidence indicates that the principal buffer for information in visual short-term memory is in the parietal lobes, specifically on the right intraparietal sulcus (IPS; Sheremata, Bettencourt, & Somers, 2010; Todd & Marois, 2004). The information about spatial locations in IPS is retinotopically mapped (Saygin & Sereno, 2008; Sheremata et al., 2010). It is likely that the information is maintained in retinotopic form during the RI by a feedforward–feedback loop involving the IPS and dorsolateral prefrontal cortex (Donner et al. 2007; also see Goldman-Rakic, 1988). The elimination of age differences by the whole-field interference in Experiment 2 strongly implicates impairment in this parietal–frontal cortico-cortical network as a principal source of impaired visual short-term memory in older adults. We think it highly likely that the poststimulus encoding that was interfered with in Experiment 2 involved the transfer of information from the visual cortex to the IPS, and we speculate that without interference, less information is lost in this transfer in younger than in older adults. The absence of a RI effect in Experiment 1 suggests that the feedforward–feedback loop that carries out the actual rehearsal was as effective in older as in younger adults.

Posterior–anterior connections from IPS to more medial frontal areas such as the anterior insula, anterior cingulate cortex, middle and inferior frontal gyrus, and frontal eye fields have been associated with perceptual decisions (Kayser, Buchsbaum, Erickson, & D'Esposito, 2010; Thielscher & Pessoa, 2007). We speculate that the differences we observed in decision criteria can be attributed to age-related impairment either of the target frontal areas or of the connecting fibers.

To summarize, we propose that age differences in visual short-term memory are the result of independent changes in three central nervous system networks: the optic tract; a maintenance system involving occipital, parietal, and lateral frontal areas; and an evaluative system involving parietal and medial frontal areas.

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