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Life-Span Development of Visual Working Memory: When Is Feature Binding Difficult?

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We asked whether the ability to keep in working memory the binding between a visual object and its spatial location changes with development across the life span more than memory for item information. Paired arrays of colored squares were identical or differed in the color of one square, and in the latter case, the changed color was unique on that trial (item change) or was duplicated elsewhere in the array (color-location binding change). Children (8–10 and 11–12 years old) and older adults (65–85 years old) showed deficits relative to young adults. These were only partly simulated by dividing attention in young adults. The older adults had an additional deficiency, specifically in binding information, which was evident only when item- and binding-change trials were mixed together. In that situation, the older adults often overlooked the more subtle, binding-type changes. Some working memory processes related to binding undergo life-span development in an inverted-U shape, whereas other, bias- and salience-related processes that influence the use of binding information seem to develop monotonically.

Keywords: working memory, life-span development, binding, visual attention, change detection

Older adults have a memory deficiency compared with young adults, specifically in the retention of binding information. When items are presented in pairs, the items can be remembered normally, but there is difficulty in remembering which ones were paired with which others. This appreciable decline occurs for the binding of focal items to contextual elements (Bayen, Phelps, & Spaniol, 2000; Chalfonte & Johnson, 1996; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Naveh-Benjamin, 2000; Naveh-Benjamin & Craik, 1995) or the binding of different focal elements to each other (Naveh-Benjamin, 2000; Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003). Naveh-Benjamin (2000), extending the work by Chalfonte and Johnson (1996), suggested an associative deficit hypothesis, which focuses on the distinction between memory for single units and memory for associations among units. The present study examined the generality of the associative deficit hypothesis for children as well as for older adults and for a task examining working memory rather than long-term memory. In this task, two arrays of colored squares must be compared, with the arrays sometimes identical and sometimes differing in the color of a single square. This task has been extensively researched in young adults (Luck & Vogel, 1997; Morey & Cowan, 2004, 2005; Todd & Marois, 2004; Vogel & Machizawa, 2004; Vogel, Woodman, & Luck, 2001) and has been examined in infants (Ross-Sheehy, Oakes, & Luck, 2003) and children (Cowan et al., 2005).

In our version of the task, haphazardly placed squares of different colors form a sample array that is soon replaced by a blank interval and then by a test array identical to the sample array or differing in the color of a single square. A circle surrounding one square in the test array indicates which square changed color, if any square did, and the required response is a judgment as to whether a color change occurred. Inasmuch as colors are selected for the sample array from a small set, randomly with replacement, a given color can appear more than once in each array. For that reason, a changed color may be unique in the array (an item change) or may be duplicated at some other location in the array (a binding change). These types of changes are illustrated in Figure 1. In the case of item changes, the response would be correct if the participant noticed that a new color had been introduced, whereas in the case of binding changes, the response could be correct only if the participant noticed that an already-present color was now also present at the cued location. In other words, the change in binding between colors and locations would have to be noticed. The task requires brief but vivid retention of the sample array in memory, to be compared with the test array. Performance levels in young adults are excellent with up to about four squares per array and quickly drop as a function of array set sizes beyond four. We have found that it is possible to examine performance on this task in participants from the early years of elementary school through old age; children younger than the elementary school years often do not use the response keys consistently or do not tolerate the relatively large number of trials needed.

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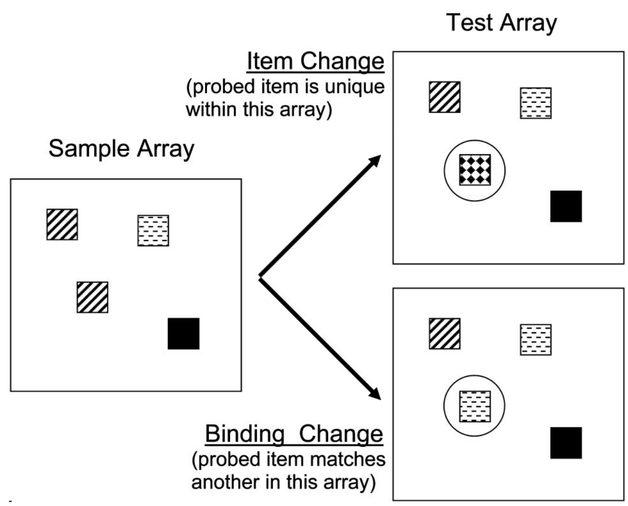

Figure 1. An illustration of two types of stimulus change. Patterns represent colors. In item changes, a new color appears in the test array in the encircled location, whereas in binding changes, the color that appears in the encircled location matches a color already present elsewhere in the array. The drawing is not to scale.

We investigate four key questions about performance in this task: (a) whether there are age-group deficits in binding in this working memory task, (b) whether the development of binding is shaped as an inverted U across the life span or is monotonic, (c) whether developmental deficits in binding can be mimicked by dividing attention in young adults, and (d) how associative deficits in binding should be described according to a signal-detection analysis. The rationale for these questions follows.

Deficits in Binding in a Working Memory Task

Can an associative deficit in the older adults be found in this visual working memory task, which involves only a short (1-s) retention interval between the two arrays to be compared? We expected that it could, given that working memory presumably underlies long-term learning (Baddeley, 2000; Baddeley, Gathercole, & Papagno, 1998; Cowan, 1995, 2001). In older adults, there are few studies of the development of immediate memory for objects in an array and, to our knowledge, none using Luck and Vogel's (1997) procedure. This procedure may provide a direct method of examining the basic capacity of visual working memory, which should change across ages according to Cowan's (2001) suggestions. Mitchell et al. (2000) found a deficit in older adults in both items and locations in a spatiotemporal array.

Olson et al. (2004, Experiment 1) found no such effect in memory for spatial configuration of up to six objects, but then it may have been possible to combine the items into a single spatial design, removing the load from working memory. Specifically, their stimuli were pairs of arrays with three or six identical squares in each array, with a cued item in the second array. This second array was identical to the first or differed in the location of the cued item (which should lead to a "different" response) and/or differed in the locations of all of the other items in the array. Both younger and older adults found it easier to determine the location of the cued item when the other items remained fixed between the two arrays. Given that each array forms a spatial design that might be remembered in terms of multi-item patterns, it is understandable that no age difference resulted.

In light of the existing literature, the present direct test is still necessary.

Life-Span Developmental Course of Binding

Is the associative deficit symmetrical across the life span, such that aging reverses the course of child development, as J. Hughlings Jackson expected (Jackson, 1860, reprinted in Taylor, 1958), or is binding only a problem for older adults? When one develops tasks that can be used across a wide age range, from elementary school children through older adults, it is possible to assess the form of the life-span development of psychological processes (e.g., Cepeda, Kramer, & De Sather, 2001; Gulya et al., 2002; Massaro, Thompson, Barron, & Laren, 1986; Williams, Ponesse, Schachar, Logan, & Tannock, 1999; Zelazo, Craik, & Booth, 2004)?

We have found little recent research specifically on item versus binding memory in children. Most of the relevant recent work has focused on children too young to be tested with the same methods as adults (e.g., see Bauer, Burch, & Kleinknecht, 2002; Moore & Lemmon, 2001). There were some studies in an earlier era with more comparable methods in children and adults (e.g., Goulet, 1968; Keppel, 1964; Lynch & Rohwer, 1972). In general, the research has suggested that relatively young children have a deficit in richly encoding pictorial stimuli using covert verbalization. However, the question of whether children have a more basic deficit in binding items to their context, which could be observed in an array-comparison task, remains open.

An expectation of inverted-U-shaped developmental growth comes from the general notion that nervous system decline in old age is a mirror image of nervous system development in childhood. However, specific rates of decline may not mirror the rates of development exactly. For example, the hippocampal system, which is necessary for the storage of episodic memories in a way that allows subsequent explicit recall, declines noticeably in old age but seems to be relatively intact even in elementary school children. In contrast, the frontal lobes, which largely account for the role of attention in creating rich, explicit memories (for reviews, see Cowan, 1995; Kane & Engle, 2002), appear to function more similarly in elementary school children and older adults, below young adults in both cases (for young children, Nelson, 2002; Rabinowicz, 1980; Saitoh, Karns, & Courchesne, 2001; M. L. Smith, Kates, & Vriezen, 1992; for older adults, Raz, 2000; Raz, Rodrigue, Head, Kennedy, & Acker, 2004). If this is so, different profiles of abilities would be predicted in children versus older adults. Children would be less likely than older adults to have memory deficits that are independent of attention (caused by hippocampal deficits) but no less likely to have deficits in the mnemonic use of attention (caused by frontal lobe deficits).

The Role of Attention in Developmental Deficits in Binding

A rationale for this question about the role of attention has been established in the preceding section. To the extent that a difference from the performance of young adults is due to poorer attention in some other group, the performance of that group should be mimicked by dividing attention in adults. The different states of neural development in childhood versus aging could lead to an especially informative pattern in which divided attention resembles some aspects of binding (or, perhaps, binding in some age groups) and not others. Indeed, some researchers have proposed that older adults have depleted attentional resources, and they have used divided-attention conditions in young adults to simulate the effects of that attentional depletion (e.g., Craik, 1983, 1986; Craik & Byrd, 1982; Rabinowitz, Craik, & Ackerman, 1982).

In the domain of long-term episodic memory, dividing attention in young adults between a tone discrimination task and a long-term memory task has not produced deficits in binding compared with item memory (Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2004; Naveh-Benjamin, Guez, & Marom, 2003; Naveh-Benjamin, Guez, & Shulman, 2004). Instead, dividing attention has caused roughly equal deficits in item and associative recognition. According to some theoretical considerations, though, insufficient attention might be expected to hinder the detection of binding changes more than item changes in working memory procedures. Treisman and Gelade's (1980) view suggests that the construction of a mental representation with features bound together into objects should require attention. The basis for this statement is that searches for conjunctions of features take much longer than searches for individual features, with a much higher search slope as a function of the array set size in the search for conjunctions. On the other hand, for the sake of working memory it may be that one can remember only objects, not features per se, in which case a test of feature memory versus memory for bindings between those features should produce similar results. In one recent study on visual working memory for arrays, Wheeler and Treisman (2002) obtained ambiguous results, including a disadvantage for binding trials in some circumstances but not in others.

Given the evidence on brain development cited above, one might expect that the pattern found in children would resemble the divided-attention pattern. It might not be expected in older adults, for whom an associative deficit has been observed (e.g., Naveh-Benjamin, 2000; Naveh-Benjamin, Guez, & Marom, 2003; Naveh-Benjamin, Hussain, et al., 2003). A deficit in binding within long-term memory may be linked to the use of hippocampal regions of the brain that are not dependent on attention beyond what is needed for adequate stimulus encoding (e.g., Cohen & Eichenbaum, 1993; Johnson, 1994; Rolls, 1996). The question of what aspects of performance in children or older adults resemble divided-attention conditions in young adults is addressed in Experiments 1b and 2b.

A Signal-Detection Analysis of Binding Deficits

How should the associative deficit be described according to a signal-detection analysis (e.g., Green & Swets, 1966)? That analysis includes the concept of sensitivity—or, in our study, how well a participant could distinguish between trials in which the two arrays changed versus stayed the same—and bias—or, in our study, a participant's proclivity, when in doubt, to indicate that a change occurred. It is of interest whether sensitivity, bias, or both change with age, as it sheds light on the psychological processes involved.

Interpretation of signal-detection results depends on the test procedure. In the ideal case for a signal-detection analysis, a trial block includes only one kind of trial in which a signal is present (or in this case, one kind of change) and a kind of trial in which the signal is absent (i.e., no change occurs). On every trial, the participant presumably perceives a particular signal strength, or in this case the sense that a change has occurred. This signal strength comes from a summation of the actual signal, if one was present, plus the contribution of various sources of internal and external noise. Given that the participant has no way to know for sure whether that perceived signal strength comes from the distribution of signal trials or no-signal trials, the decision can only be made by setting a criterion and responding accordingly; that is, by indicating that a change has occurred only if the signal strength is higher than the criterion. In many actual experiments, however, there are several types of signal trials mixed together in a trial block. In this situation, the criterion setting can be of considerable interest.

To illustrate the latter case, Figure 2 depicts the situation in which item-change, binding-change, and no-change trials are mixed together in the same trial block. The horizontal axis represents the amount of change sensed, and the vertical axis represents the proportion of trials for each amount of change. The top and bottom of the figure depict two theoretical situations with identical sensitivities but different criterion settings. In the top, a liberal bias results in correct responses for most trials of all types. In the bottom, a conservative bias results in correct responses for most no-change and item-change trials, but incorrect responses for most binding-change trials. In this panel, a small improvement in performance on no-change trials has been obtained at a much larger cost on binding-change trials. Therefore, criterion setting can be of considerable practical importance. To explore the consequences of

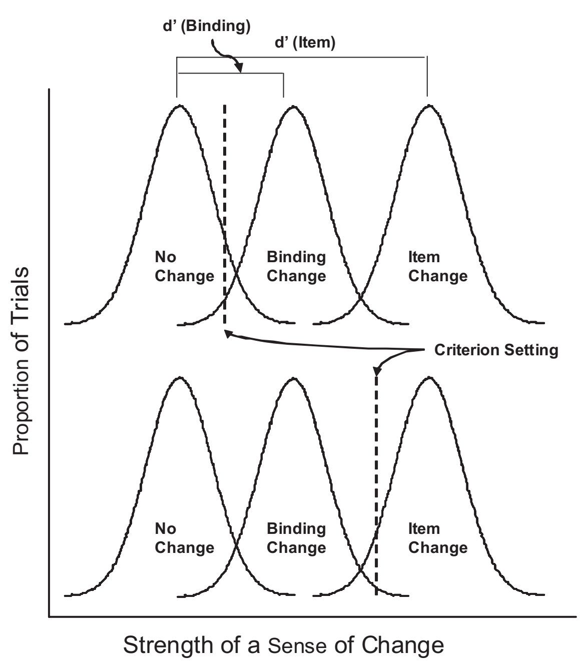

Figure 2. An illustration of the effect of criterion bias on performance in a situation with item-change, binding-change, and no-change trials mixed together. Top: A conservative bias allows detection of most item changes and few binding changes. Bottom: A liberal bias allows detection of most item changes and also most binding changes.

task demands, we used stimuli with item and binding changes mixed together in the same blocks in Experiments 1a and 1b and in separate blocks in Experiments 2a and 2b.

At first glance, one might suppose that performance deficits in older adults in mixed trial blocks could be obtained as a result of deficits in task switching (e.g., Kramer, Sowon, & Gopher, 1999; Smith et al., 2001). However, participants were not informed whether item or binding changes might occur. Therefore, from the participant's point of view, even in the mixed-block situation there was only one task, which was to determine if the probed item in the second array had changed color compared with the first array. On every trial, the participant had to assume that both item and binding information could be relevant until the second array arrived and the comparison could be made. Given that the participant had no way to know which type of trial was in process during the retention interval, we assume that task switching could not play a role.

All plausible theoretical frameworks are likely to make the prediction that children and older adults will display lower levels of sensitivity than young adults. Where theoretical views might diverge is in whether any of the age groups differ from others in the difference in sensitivity between item and binding trials.

In the mixed-block design of Experiments 1a and 1b, any difference between item and binding trials must, in principle at least, produce both sensitivity differences and bias differences. That is because the performance level on no-change trials is the same in the evaluation of both item and binding changes. (Subdividing no-change trials into two sets cannot alter the situation, inasmuch as they are all the same from the participant's point of view.) Lower performance on binding changes than on item changes, with a common no-change trial type, would result in both lower d' values for binding and a lower relative tendency to say that there was a change in the evaluation of binding trials. In contrast, in the separate-block design of Experiments 2a and 2b, there is the opportunity to do better on no-change trials in item blocks than in binding blocks if participants happen to learn implicitly that all of the changes in the item blocks are more salient than the ones encountered in the binding blocks. That would allow an easier decision in item-change blocks for both change and no-change trials (even though the instructions did not include a discussion of the different types of changes that were possible, in any experiment). Thus, sensitivity and bias can be considered independent of one another in Experiments 2a and 2b.

There are several lines of research leading to different expectations regarding the development of response bias. Young children have a tendency to respond "yes" regardless of the nature of the question, but that trend typically disappears by 3 or 4 years of age (Fritzley & Lee, 2003). In the medical decision literature, older adults have a tendency to avoid risk by deciding in favor of treatment quickly or, if possible, deferring to a physician's judgment (Curley, Eraker, & Yates, 1984; Leventhal, Leventhal, Schaefer, & Easterling, 1993). However, no difference between young and older adults was obtained in a study in which the decisions were of much smaller practical consequence (Dror, Katona, & Mungur, 1996). In any case, it is difficult to know how to apply the concept of risk to the present task, in which there is no difference in the consequence of incorrect responses on change versus no-change trials.

A concept that seems more relevant is false recognition, the tendency to recognize as old the items that are new but share some features with old items (e.g., Kausler, 1994; Rankin & Kausler, 1979). Related to this tendency is the notion that two varieties of memory contribute to responses: familiarity and recollection (cf. Jacoby, 1991). Items that share only some of the features of an old item may still seem familiar, which can result in a positive recognition response even though they cannot be completely recollected. The research literature has suggested that older adults rely on familiarity rather than recollection more than do younger adults (Hay & Jacoby, 1999; Jennings & Jacoby, 1997). That is true of young children as well (Anooshian, 1999), with an inverted-U-shaped change in recollection across the life span (Zelazo et al., 2004). The notion of false recognition could apply to the present procedure if a participant thought that the changed item in the second array looked familiar and therefore judged it to be unchanged. This would be expected to occur most frequently on binding-change trials because the color of the cued item is familiar in that it was present elsewhere in the first array. Reliance on familiarity cues in older adults therefore would be expected to increase the tendency to miss binding changes. That tendency theoretically could affect the sensitivity, the bias, or both, depending on how no-change trial performance was affected.

Finally, some of the literature has suggested that bias does not change independently with age but that it may be a by-product of age differences in sensitivity, with sensitivity and bias being correlated (Danziger, 1980; Harkins, Chapman, & Eisdorfer; 1979; LeBreck & Baron, 1987). Children can be of use in evaluating that hypothesis if, as expected, they perform at levels comparable to older adults. If bias is a by-product of sensitivity, then the bias should be similar in groups with similar sensitivities. If, on the other hand, older adults have a specific tendency to engage in false recognition, they could show large differences in bias from children with levels of sensitivity similar to theirs.

In sum, we used the array-comparison task to examine the life-span development of binding in visual working memory with particular scrutiny of the potential roles of attention, sensitivity, and criterion setting. In Experiment 1a, we examine the life-span development of binding, and in Experiment 2a we used a modification that allowed sensitivity and criterion bias to be examined separately. Experiments 1b and 2b examine the effects of dividing attention in adults, in tasks comparable to those of Experiments 1a and 2a, respectively.

Experiment 1a: Developmental Study Using Mixed Blocks of Conditions

In this first experiment, we assessed detection of both item changes (i.e., trials in which the color changed to a new color that was not present in the sample array) and binding changes (i.e., trials in which the color changed to a color already present elsewhere in the sample array, so that a new binding of color and location had to be detected) against a common set of no-change control trials. The relative rate of occurrence of item and binding changes was left up to chance, and about 46% of all changes were item changes. We included children in two age groups for the sake of a life-span comparison because, on the basis of past research related to perceptual memory across the life span (e.g., Gulya et al., 2002; Zelazo et al., 2004), we expected that performance in older adults would be at a level bracketed by these two age groups.

Method

Participants. The participants were 41 third-grade children (19 boys, 22 girls; mean age: 8.82 years, $SD = 0.40$), 43 fifth-grade children (17 boys, 26 girls; mean age: 10.75 years, $SD = 0.48$), 53 young adults (29 men, 24 women; mean age: 20.43 years, $SD = 2.03$), and 33 older adults. Child data in only this first experiment came from a larger study (see the author note). Five older women failed to follow instructions, sometimes advancing to the next trial without making a forced response, an option permitted because of a programming mistake corrected in later experiments. The remaining 28 older adults (4 men, 24 women) had a mean age of 71.11 years ($SD = 4.56$). The younger and older adults were equated on the number of years of formal education (*M*s = 13.92 and 14.39 years, respectively; *SD*s = 1.74 and 1.59).

The children and the older adults were residents of Columbia, Missouri, whereas the young adults were students at the University of Missouri. The older adults lived independently in the community, reported having good health, and were able to come to the laboratory. They passed a screening questionnaire to eliminate those with memory or thinking problems, stroke, and any degenerative chronic disease (Parkinson's, Alzheimer's, multiple sclerosis, etc.) and were readily able to follow the instructions. All participants reported having good hearing and normal or corrected-to-normal vision. The children were 85% White, 4% Hispanic, 4% Black, 4% Asian, and 3% other or unknown. Information about family structure or siblings is unavailable and was assumed to be unimportant for this study. The young adults were 88% White, 4% Hispanic, 4% Black, and 4% Asian. Exact figures are unavailable for the older adults but were approximately comparable to those of the other groups.

Stimuli, apparatus, and procedure. Testing took place 1 participant at a time in a sound-attenuated booth equipped with a computer. As in Luck and Vogel's (1997) study, an array of colored squares was presented on a gray screen on each trial, followed by a second array identical to the first or differing in the color of one square. One square was cued (encircled) in the second array, and either the two arrays were alike or they differed in the color of the cued square. A single keypress response was to indicate whether there was a change.

Each trial began with a fixation cross that appeared after the participant pressed a key to indicate that the trial should begin. The fixation cross lasted 1 s and was replaced by the first array for 250 ms. At an estimated viewing distance of 50 cm, the array encompassed 9.8° horizontal × 7.3° vertical visual viewing angle, and each colored square within it took up 0.75° × 0.75°. Spatial locations of the squares in the array were random except that the minimum separation between their centers was 2.0°, and no square appeared within 2.0° of the center of the viewing area.

The square colors—red, blue, violet, green, yellow, black, and white—were assigned randomly with replacement so that the same color could appear more than once in an array. Interpolated between arrays was a 1-s gray screen, the same shade as the background behind the color squares. The cue was a 1-pixel-thick black circle 1.5° in diameter, surrounding one square in the second array. The required response was a computer keypress indicating whether the color changed between arrays (the "/" and "z" keys, respectively). The second array persisted on the screen until a response was made. Eight practice trials were presented, followed by 128 test trials. These included equal numbers of trials with 4, 6, 8, or 10 squares per array. Half of the trials at each array size were change trials. Array sizes were randomly ordered across trials. Each trial ended with response feedback (to keep motivation up and provide an index of maximal performance), and breaks between trials were offered and allowed as needed.

Results and Discussion

Proportion correct. A 4 × 3 × 4 analysis of variance (ANOVA) was carried out with age group (third grade, fifth grade, young adults, and older adults) as the between-subject factor and two within-subject factors: change condition (item change, binding change, or no change) and the number of items in the array or the array size (4, 6, 8, or 10). Predictably, there were main effects of the age group, $F(3, 161) = 24.23$, $MSE = 0.10$, $p < .001$; change condition, $F(2, 322) = 43.77$, $MSE = 0.07$, $p < .001$; and array size, $F(3, 483) = 92.92$, $MSE = 0.03$, $p < .001$. The age-group trend was curvilinear as expected, with means (and standard errors of the mean) for third graders, fifth graders, young adults, and older adults of .70 (.01), .73 (.01), .83 (.01), and .69 (.02), respectively. Newman-Keuls post hoc tests showed that the young adults differed from all other groups, which did not differ significantly from one another. Performance in the item-change, binding-change, and no-change trials averaged .78, .65, and .78, respectively ($SEM = .01$ in each case), so that the effect of change condition was due to the relatively poor performance on binding trials. Performance generally decreased with increasing array set sizes as expected ($M = .85$, .71, .73, and .66 for Set Sizes 4, 6, 8, and 10, respectively; $SEM = .01$ in each case). All pairwise differences were significant by Newman-Keuls tests except for the reversal between Set Sizes 6 and 8.

Most important, there was an interaction of Age Group × Change Condition, $F(6, 322) = 12.07$, $MSE = 0.07$, $p < .001$. One can see from Figure 3 that older adults had a different response profile than other participants: they displayed especially low performance on binding-change trials, combined with excellent performance on no-change trials. This same interaction was found in an ANOVA in which no-change trials were omitted, $F(3, 161) = 5.72$, $MSE = 0.07$, $p < .001$. Thus, there is evidence that older adults, but not the children, showed a binding deficit compared to the young adults. Although the item − binding difference was significant in all age groups, it was more than twice as large in older adults as in any other group, extending to working memory the associative deficits observed by Naveh-Benjamin and col-

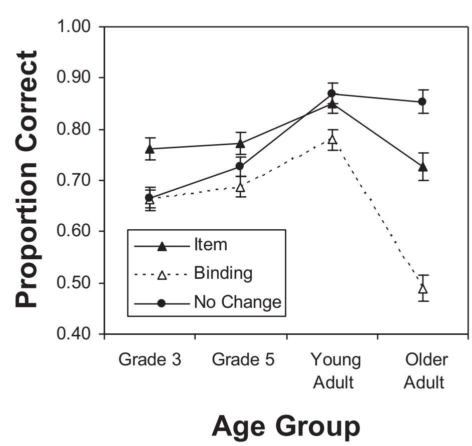

Figure 3. Proportions correct for every age group and change condition in Experiment 1a (which involved mixed trial blocks including item and binding trials), collapsed across set size. Error bars are standard errors.

leagues in long-term memory procedures (Naveh-Benjamin, 2000; Naveh-Benjamin, Guez, & Marom, 2003; Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Naveh-Benjamin, Guez, & Shulman, 2004).

Last, there was an interaction of Age Group × Array Size, $F(9, 483) = 2.30$, $MSE = 0.03$, $p < .02$, modified by a three-way Age Group × Array Size × Change Condition interaction, $F(18, 966) = 1.65$, $MSE = 0.03$, $p < .05$. The means corresponding to these interactions are shown in Figure 4. One potential basis of these interactions is particularly germane. One can see that, for the three younger age groups, performance levels at the lowest set size were uniformly high in all three change conditions. As set size increased, performance losses differed across change conditions. In older adults, however, a different pattern was observed. The binding-change trials resulted in markedly lower performance levels than the other change conditions, even at the smallest set size. Thus, the binding deficit in older adults may not be based on conditions that overwhelm capacity limits; it may be more ubiquitous.

In all of the analyses, interaction effects that do not have age group as a factor were deemed irrelevant to the aims of the research and, for the sake of simplicity, are not discussed.

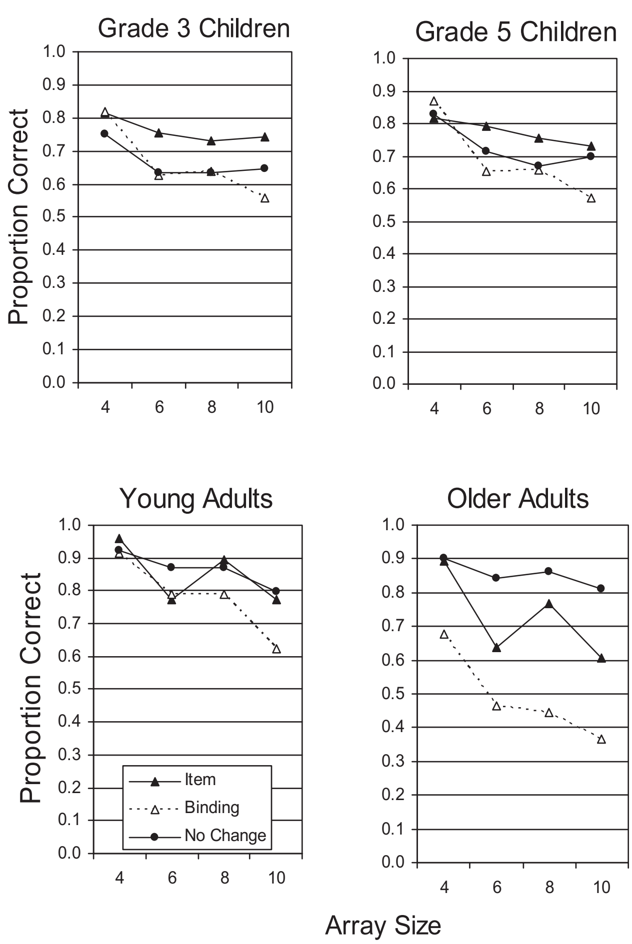

Figure 4. Proportions correct for every age group, change condition, and array set size in Experiment 1a.

We were concerned that most of the older adults in this sample were women. Therefore, we conducted the analyses again using only women in each age group. All of the same significant effects were obtained on ANOVAs and Newman-Keuls tests. This rules out gender as the basis of the age effects observed. Of course, it remains possible that a different pattern would emerge in men if we had a larger sample of them.

It is also noteworthy that there was a developmental change from children to adults in performance levels. The aging deficit in the binding condition cannot be attributed to developmental level alone because children had a similar level of performance on item-change trials (lower than the young adults by about the same amount in both cases). Yet for binding-change trials, children's deficit was similar to their deficit on item-change trials, not specifically more impaired as were the binding-change trials in older adults (see Table 1).

Signal-detection analysis. Table 2 presents d' estimates of sensitivity, or the ability to distinguish change- from no-change trials regardless of the bias to respond "change" or "no change." These estimates are calculated as z(proportion hits) − z(proportion false alarms), with a hit defined as detection of a change and a false alarm defined as a "change" response in the absence of any actual change. For the sake of the analysis, individual mean hit rates of 1.0 were lowered to 0.99 and individual mean false-alarm rates of 0.0 were raised to 0.01. The table shows that, for both item-change trials and binding-change trials, there was an inverted-U-shaped developmental change. That was born out in an ANOVA of d' scores with age group and trial type (item or binding) as factors, which yielded effects of age group, $F(3, 166) = 26.53$, $MSE = 0.99$, $p < .001$, and trial type, $F(1, 166) = 51.17$, $MSE = 0.28$, $p < .001$, but no interaction. Newman-Keuls tests indicated that the young adults were significantly above all other groups and, in addition, that older adults were above third-grade children. For all groups, sensitivity was significantly higher on item changes than on binding changes.

The criterion bias was estimated in a common way as $-.5[z$(proportion hits) + z(proportion false alarms)]. The estimates are shown in Table 2. As one can see from the table, the pattern was quite different from the sensitivities and appears more as a monotonic as opposed to an inverted-U-shaped developmental trend. An ANOVA comparable to the one conducted for sensitivities revealed an effect of age group, $F(3, 166) = 10.68$, $MSE = 0.39$, $p < .001$, and trial type, $F(1, 166) = 51.17$, $MSE = 0.17$, $p < .001$, but no interaction. Newman-Keuls tests showed that older adults had a tendency to respond "no change" significantly more than any other participant group. The difference in measured bias between item and binding trials was significant in every group except the fifth-grade children.

In the youngest age group, the bias toward responding that there was a change was manifest in better performance on item-change trials than on no-change trials, as Figure 3 shows. It is possible that these children were so concerned with detecting changes that they overlooked the importance of not producing many false positives.

In sum, this experiment suggests that although both children and older adults had poorer working memory performance than young adults, the tendency for this problem to be exaggerated for binding trials was observed only in older adults.

Table 1
Mean Proportions Correct on Trials in Which the Sample and Test Arrays Differed

Group (& attention condition)	Test condition: Item	Binding	Difference
Experiment 1a (mixed item and binding blocks)			
Grade 3	0.76	0.66	0.10*
Grade 5	0.77	0.69	0.09*
Young adults	0.85	0.78	0.07*
Older adults	0.73	0.49	0.24**
Experiment 1b (mixed blocks as in Experiment 1a)			
Young adults (full attention)	0.84	0.70	0.14**
Young adults (divided attention)	0.68	0.61	0.08*
Experiment 2a (separate item and binding blocks)			
Grade 3	0.71	0.65	0.06*
Grade 5	0.83	0.77	0.06*
Young adults	0.84	0.88	−0.04
Older adults	0.65	0.59	0.06*
Experiment 2b (separate blocks as in Experiment 2a)			
Young adults (full attention)	0.86	0.87	−0.01
Young adults (divided attention)	0.71	0.71	0.00

Note. Standard errors (for both item and binding conditions except where otherwise noted) are, in Experiment 1a, 0.02 for Grades 3 and 5, 0.01 for young adults, and 0.03 for older adults; in Experiment 1b, 0.03 for the full-attention condition and, for the divided-attention condition, 0.06 (item) and 0.04 (binding); in Experiment 2a, 0.03 for Grade 2 and Grade 5 children and young adults and 0.02 for older adults; and in Experiment 2b, 0.02 for full attention and, for the divided attention condition, 0.03 (item) and 0.02 (binding).
* $p < .05$, post hoc Newman-Keuls test; ** $p < .01$.

Experiment 1b: Attention Manipulation Using the Mixed-Blocks Design

A second experiment was conducted with young adults to determine whether their performance under divided attention could simulate the results obtained in children, older adults, or both. This should be the case if the only difference between age groups was in the ability to use attention in visual working memory.

Method

The participants were 24 college students (10 men, 14 women) with a mean age of 22.1 years ($SD = 2.7$) and an average level of education of 14.8 years ($SD = 0.9$) who did not participate in Experiment 1a. The exact ethnic distribution of participants is unavailable but is approximately comparable to that of the young adults in Experiment 1a. The procedure was identical to that of Experiment 1a, except that participants completed two similar blocks of the visual array task, one under full attention and one under divided attention, each consisting of 72 trials. Between these blocks, they also completed two baseline trials for the secondary task alone. The secondary task, carried out throughout the block, was a continuous three-choice reaction time task that involved a sequential presentation of auditory tones by the computer, one at a time, and a manual response on a computer keyboard to each tone. One of three tones, which differed from each other in frequency, was presented at random, and the participants' task was to press a predesignated corresponding key on the keyboard. A response to a tone caused the immediate presentation of any of the three tones at random. The order of the visual array blocks and of the attention condition was counterbalanced.

Results and Discussion

The results for all conditions are shown in Figure 5. It can be seen from the figure that dividing attention lowered the proportion correct but did not do so differentially for the item, binding, and no-change trials or for the different array sizes. A 2 × 3 × 4 ANOVA with the attention condition, change condition, and set size as within-subject variables produced only an effect of attention condition, $F(1, 27) = 136.27$, $MSE = 0.04$, $p < .001$, and array size, $F(3, 81) = 71.02$, $MSE = 0.02$, $p < .001$. Thus, the differential deficit in binding trials seen in older adults in Experiment 1a (Table 1) cannot be explained on the basis of poor attention. However, the general pattern with divided attention is similar to what is seen in children (cf. Figures 4 and 5).

Analyses of signal-detection results (Table 2) showed that attention had an effect on sensitivity, $F(1, 23) = 30.33$, $MSE = 0.84$, $p < .001$, but not on bias, $F(1, 23) = 1.27$, $MSE = 0.29$. The

Table 2
d′ Estimates of Sensitivity and Beta Estimates of Bias

Group (& attention condition)	Condition and measure: Item d'	Item β	Binding d'	Binding β
Experiment 1a (mixed item and binding blocks)				
Grade 3	1.21	−0.15	0.89	0.01
Grade 5	1.46	−0.08	1.17	0.07
Young adults	2.44	0.01	2.07	0.19
Older adults	1.79	0.30	1.08	0.65
Experiment 1b (mixed blocks as in Experiment 1a)				
Young adults (full attention)	2.29	−0.08	1.63	0.25
Young adults (divided attention)	1.11	−0.13	0.75	0.05
Experiment 2a (separate item and binding blocks)				
Grade 3	1.19	−0.01	1.10	0.12
Grade 5	1.96	−0.10	1.87	0.14
Young adults	2.56	0.18	2.62	0.03
Older adults	1.63	0.38	1.60	0.54
Experiment 2b (separate blocks as in Experiment 2a)				
Young adults (full attention)	2.40	0.04	2.55	0.04
Young adults (divided attention)	1.33	0.07	1.25	0.05

Note. Higher d' means better discrimination and higher beta means a greater tendency to answer "no change." Standard errors for d' ranged from 0.10 to 0.16 in Grade 3 children, 0.09 to 0.17 in Grade 5 children, 0.11 to 0.19 in young adults, and 0.11 to 0.24 in older adults. For the full-versus divided-attention groups, they ranged from 0.11 to 0.17 with full attention and from 0.12 to 0.21 with divided attention. Standard errors for beta ranged from 0.04 to 0.07 in Grade 3 children, from 0.04 to 0.08 in Grade 5 children, from 0.04 to 0.05 in young adults, and from 0.06 to 0.17 in older adults. For the full- versus divided-attention groups, they ranged from 0.05 to 0.08 with full attention and from 0.07 to 0.13 with divided attention.

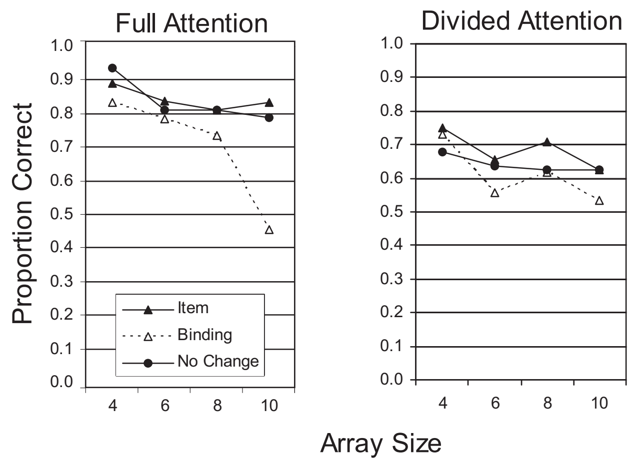

Figure 5. Proportions correct for the full and divided attention conditions in Experiment 1b. Standard errors for individual means in the figure were always below 0.08 for the full-attention condition and 0.10 for the divided-attention condition.

difference between item and binding trials did not interact with attention.

It can be observed that dividing attention in young adults appears to provide a reasonable facsimile of children's task deficits. In particular, dividing attention lowered the sensitivity for both item and binding trials. However, dividing attention in young adults did not provide a close model of performance in older adults, who displayed not only an overall decrease in sensitivity but also a strong bias detrimental to the detection of changes, and especially binding changes.

Experiment 2a: Developmental Study Using Separate Blocks of Item and Binding Trials

In this experiment, we continued to pursue the question of what the life-span developmental differences observed in Experiment 1a mean. In that experiment, item and binding changes were mixed with no-change control trials in common trial blocks. The advantage for detecting item changes as compared with binding changes, especially in older adults, could reflect a deficit in sensitivity to binding changes. However, it could also reflect a judgment issue in which older adults more conservatively respond "no change" to a possible change that is not very salient. In Experiment 2a, item and binding changes occurred in separate trial blocks, each with its own set of no-change control trials. That way, the sensitivity and bias for both kinds of changes could be assessed independently.

Method

Participants. The participants were 24 children about to enter third grade (13 boys, 11 girls; mean age: 8.69 years, $SD = 0.46$), 24 fifth-grade children (11 boys, 13 girls; mean age: 11.09 years, $SD = 0.37$), 24 young adults (9 men, 15 women; mean age: 18.94 years, $SD = 0.52$), and 32 older adults (9 men, 23 women; mean age: 71.4 years, $SD = 4.8$). Older adults fit the same description as in Experiment 1a. They had a mean of 13.9 years of education ($SD = 1.70$), whereas the young adults, who were drawn from an introductory psychology class, had a mean of 12.4 years of education ($SD = 0.72$); the age-related difference in number of years of education was significant, $t(54) = 4.12$, $p < .05$, so, if anything, the true aging deficit is slightly underestimated in these results. Clearly, as well, the introductory psychology students would be expected to go on to acquire a few more years of education on average, and therefore appear to be fair representatives of the same type of individual as our aging population. The children were 90% White, 1% Hispanic, 5% Black, and 4% other or unknown. Information about the family structure is not available and was assumed to be unimportant for this study. The young adults were 87% White, 9% Black, 1% Asian, and 3% other or unknown. Exact ethnic information is unavailable for the older adults, but it was approximately comparable to that of the other groups.

Apparatus, stimuli, and procedure. These aspects of the experiment were the same as in Experiment 1a except that, in separate blocks of trials, the changes were always item changes (with the encircled square changing to a color that was unique in the trial) or always binding changes (with the encircled square changing to a color already present elsewhere in the array). Additional alterations were made in the structure of the arrays to prevent participants from guessing the correct response based on the test array alone, without reference to the sample array. Given that item changes always produced a unique color, arrays in item-change blocks were constructed in such a way that the encircled square was a color that occurred nowhere else in the array, even on no-change trials. Conversely, given that binding changes always produced a nonunique color (by definition), arrays in binding-change blocks were constructed in such a way that the encircled square was a color that also occurred elsewhere in the array, even on no-change trials. The item and binding trial blocks were presented in a counterbalanced order, and there was a total of 8 practice trials and 64 trials in each kind of block, evenly divided among conditions and randomly ordered.

Results and Discussion

Proportions correct. The data are shown collapsed across array set sizes and presence versus absence of a change (Figure 6; cf. Figure 3 for Experiment 1a) and for the complete data set (Figure 7; cf. Figure 4 for Experiment 1a). Unlike Experiment 1a, there was no longer a dramatically larger binding deficit in older adults than in the children. Figure 6 suggests that there was a small deficit that now emerged in the children as well as in older adults. Figure 7 shows that, in older adults, there was also a very pronounced advantage of no-change trials from both blocks over

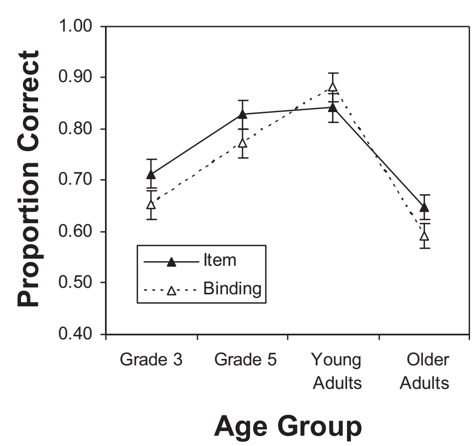

Figure 6. Proportions correct for every age group and change condition in Experiment 2a (which involved separate trial blocks for item and binding trials), collapsed across set size. Error bars are standard errors.

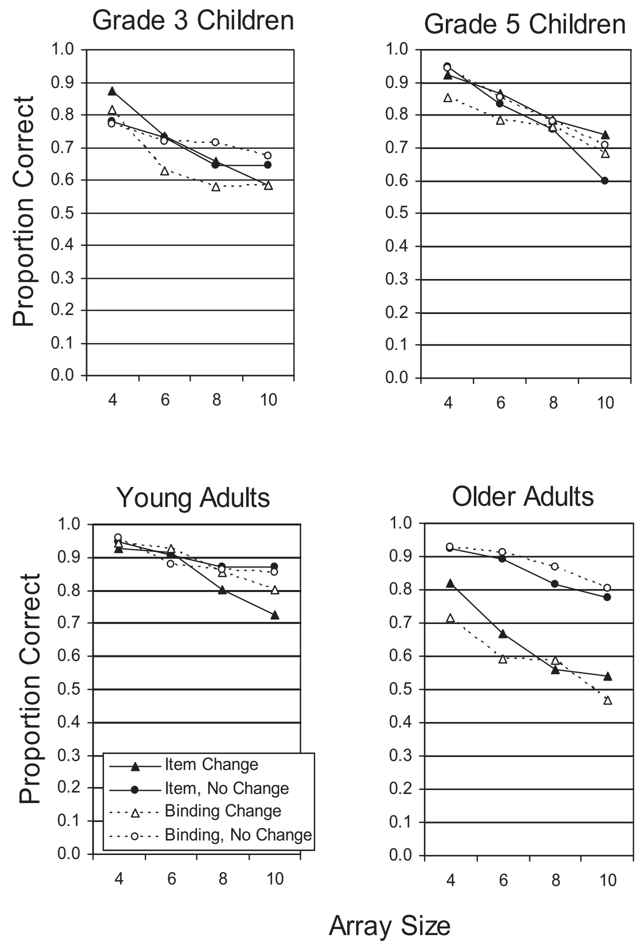

Figure 7. Proportions correct for every age group and condition in Experiment 2a (which involved separate trial blocks for item and binding trials).

change trials from both blocks, indicating a conservative response bias as in Experiment 1a.

These suggestions were supported by statistical analyses, beginning with an ANOVA in which the factors were the age group, the type of trial block (item vs. binding), the change status (change or no change), and the array size (4, 6, 8, and 10). There were significant main effects of age group, $F(3, 100) = 23.70$, $MSE = 0.10$, $p < .001$; change status, $F(1, 100) = 21.68$, $MSE = 0.11$, $p < .001$; and array set size, $F(3, 300) = 126.69$, $MSE = 0.02$, $p < .001$. The age group effect was again curvilinear, with means of .70, .80, .88, and .74 for the four age groups, respectively ($SEM = .02$ for the younger three age groups and .01 for older adults). According to Newman-Keuls post hoc tests, all group mean differences were significant. The mean performance level was not as high on change trials ($M = .74$, $SEM = .01$) as on no-change trials ($M = .82$, $SEM = .01$), and performance decreased with increasing array set size (Ms = .88, .80, .74, and .70 for sets of 4, 6, 8, and 10 items, respectively; $SEM = .01$ in each case). There was no overall item versus binding difference.

There was no interaction of Age Group × Trial Block ($F < 1$; see Figure 6). There were interactions of Age Group × Array Size, $F(9, 300) = 1.99$, $MSE = 0.02$, $p < .05$, and Age Group × Change Status, $F(3, 100) = 13.53$, $MSE = 0.11$, $p < .001$. These interactions were qualified by a three-way Age Group × Change Status × Array Size interaction, $F(9, 300) = 3.07$, $MSE = 0.03$, $p < .01$. As Figure 7 indicates, the large Age Group × Change Status interaction is clearly a result of the shift in criterion in older adults, strongly favoring no-change responses at the expense of fewer correct responses on change trials, unlike the other age groups. The basis of the other interactions may be that no-change trial performance also dropped off across set sizes more rapidly in older adults than in the other groups, as the figure shows.

Most important, there was a three-way interaction of Age Group × Trial Block × Change Status, $F(3, 100) = 3.51$, $MSE = 0.03$, $p < .05$. Separate analyses for the no-change and change trials showed that there was an Age Group × Trial Block interaction for the change trials, $F(3, 100) = 2.84$, $MSE = 0.04$, $p < .05$, but not for the no-change trials ($F < 1$). For trials in which there was a change, Table 1 shows that there was an overall disadvantage for the binding changes as compared with item changes for children and older adults, but not for the young adults.

Notice that in Experiment 1, but not in Experiment 2, even the young adults had a deficit on binding changes compared with item changes for change trials examined separately (Table 1). This suggests that the salience of binding trials may be diminished when they are mixed with item trials, as they were in Experiments 1a and 1b. This diminished salience of binding changes helps to explain why older adults were especially poor at detecting those changes, whereas in Experiment 2a they detected the changes as well as the children did.

Signal-detection analysis. Table 2 presents d' estimates of sensitivity. It shows that, for both item-change and binding-change trials, there was an inverted-U-shaped developmental change. That was born out in an ANOVA of d' scores with age group and trial block (within subject) as factors, which yielded only an effect of age group, $F(3, 100) = 21.01$, $MSE = 0.85$, $p < .001$. Newman-Keuls tests indicated that all pairs of age groups differed significantly except for the fifth-grade children and older adults.

For beta, the criterion bias (Table 2), the pattern was quite different from the sensitivities and appears more as a monotonic as opposed to an inverted-U-shaped developmental trend. Moreover, there were differences between the patterns in the item and binding-change trial blocks. An ANOVA comparable to the one conducted for sensitivities revealed not only an effect of age group, $F(3, 100) = 13.17$, $MSE = 0.19$, $p < .001$, but also an effect of trial block, $F(1, 100) = 9.03$, $MSE = 0.05$, $p < .01$, and an Age Group × Trial Block interaction, $F(3, 100) = 7.10$, $MSE = 0.05$, $p < .001$. Newman-Keuls tests for the age group main effect showed only that the older adults differed significantly from all of the other groups. As in Experiment 1a, older adults had a much stronger tendency to respond "no change" and thus minimized both hits and false alarms. Moreover, the type of trial block tended to modulate the biases. The difference between item- and binding-trial blocks was significant in the fifth-grade children and in older adults. Whereas the children and older adults tended to respond "no change" more frequently in the binding-change than in the item-change trial blocks, for young adults there was a slight trend in the opposite direction.

Thus, overall, there is some support for a Jacksonian inverted-U function of development regarding the difficulty of remembering binding information, and it is combined with a monotonic change in the criterion bias that differentiates older adults from everyone else.

Experiment 2b: Attention Manipulation With the Separate-Blocks Design

The purpose of this final experiment was to determine whether the developmental effects observed in Experiment 2a can be modeled on the basis of poor attention in the children, older adults, or both, much as Experiment 1b did for Experiment 1a.

Method

The participants were 28 college students (10 men, 18 women) with a mean age of 19.2 years ($SD = 1.3$) and an average level of education of 12.7 years ($SD = 1.1$) who did not participate in the previous experiments. The exact ethnic distribution is unavailable but is approximately comparable to the young adults in the prior experiments. The procedure was identical to that of Experiment 2a, except that the visual array trial blocks (for item and binding) were performed under either full or divided attention. The secondary task was the continuous auditory three-choice reaction time task used in Experiment 1b. The order of trial blocks for change type and attention was counterbalanced.

Results and Discussion

Proportion correct. The results of this experiment are shown in Figure 8. An analysis was conducted with attention condition, the change-type block (item vs. binding), the change status (change or no change), and the array size (4, 6, 8, and 10) as within-subject factors. This analysis produced main effects of attention condition, $F(1, 27) = 136.27$, $MSE = 0.04$, $p < .001$, and array size, $F(3, 81) = 71.02$, $MSE = 0.02$, $p < .001$. No other effects were significant. Thus, although attention interfered with performance, it did not alter the pattern of performance. It produced no hint of an effect favoring item changes over binding changes (as was seen in both children and older adults in Experiment 2a), and it produced no hint of an advantage of no-change trials over change trials (as was seen in older adults in Experiment 2a). Poor attention thus cannot explain the pattern of responses observed in Experiment 2a, a result also found in Experiment 1.

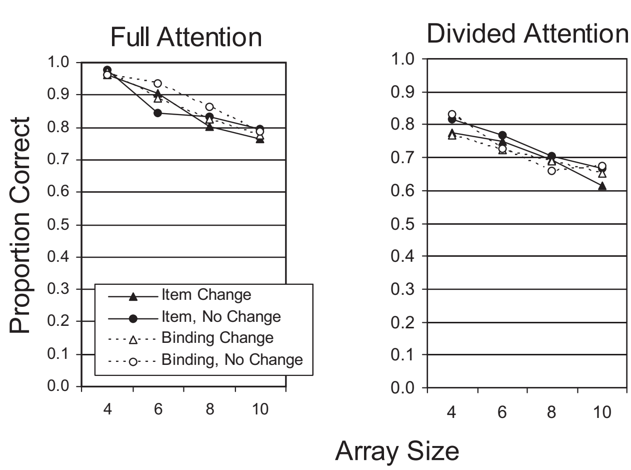

Figure 8. Proportions correct for the full- and divided-attention conditions in Experiment 2b. Standard errors for individual means in the figure were always below 0.05.

Signal-detection analysis. Table 2 shows the d' and bias scores for this experiment, as for the previous one. An ANOVA of d' with attention condition and trial blocks as factors yielded only a main effect of dividing attention, which consistently lowered d', $F(1, 27) = 145.66$, $MSE = 0.27$, $p < .001$. A comparable analysis on beta, the criterion bias, yielded no effects, however. Thus, it appears that dividing attention provides a useful model of effects of age on sensitivity, but not of effects of age on response bias.

General Discussion

The present study was designed to address several questions about the life-span development of performance on a working memory task (after Luck & Vogel, 1997) in which memory for item-color information and the binding between an item and its location in an array were both examined in two-array comparisons. The questions were (a) whether there are age-group deficits in binding in this working memory task, (b) whether the development of binding is shaped as an inverted U across the life span or is monotonic, (c) whether developmental deficits in binding can be mimicked by dividing attention in young adults, and (d) how associative deficits in binding should be described according to a signal-detection analysis.

The results were clear. Consider first Experiment 1a, in which trials with changes in item and in binding (see Figure 1) were intermixed, along with no-change trials. The results indicated that item changes were noticed more easily than binding changes in all age groups (two ages of children, young adults, and older adults). However, performance was lower in children and older adults than it was in young adults. Moreover, older adults were especially poor at detecting changes in binding. Experiment 1b showed that the particular pattern observed in older adults could not be modeled by dividing attention in young adults (Figure 4 and Table 2). It resulted in equal decrements in item and binding information, a pattern more similar to the children. This suggests that there could be an attentional basis for developmental changes in sensitivity, but that there is some additional deficit in older adults unlikely to be based on attention deficits (involving poor detection of the lower salience binding changes when intermixed with item changes).

In Experiment 2a, trials with item and binding changes were segregated into separate trial blocks, each with its own no-change control trials. This arrangement again reproduced a disadvantage of binding changes over item changes, although the pattern was now significant only in a separate analysis of change trials. This small binding deficit (shown in Table 1) was found in about equal magnitudes in children and older adults, with no effect in young adults. Moreover, older adults differed from all other groups in once more showing a large response bias advantageous for no-change trials at the expense of change trials (Figure 5 and Table 2). The difference between item and binding trials emerged as a shift in response bias in children and older adults, with a slight trend in the opposite direction in young adults. Experiment 2b, similar to 1b but with separate item and binding trial blocks, showed that the pattern of developmental differences in older adults was not mimicked when attention was divided in young adults. It mimicked the decrement in sensitivity (d'), but not the shift in bias (beta) observed in older adults or the change in bias between item and binding trials observed in both fifth-grade children and older adults (Table 2). On the basis of these results, the key questions raised here can be addressed and then the question of life-span change in binding can be considered more generally.

Key Questions

1. Are there age-group deficits in binding? The largest age-group deficits in binding could be seen for older adults. This finding was clearest in Experiment 1a, in which item- and binding-change trials were mixed together. In Experiment 2a, with item- and binding-change trials in separate blocks, there was no difference between fifth-grade children and older adults. Both groups differed from young adults in that they were less likely to notice binding changes than were the young adults. However, the binding deficits per se were not really sensitivity decrements compared with young adults, but rather bias shifts.

We cannot truly characterize the binding deficit in any group as a decrement in sensitivity. Instead, it appears that participants who have a lower sensitivity to changes in general are also reticent to respond that a stimulus has changed when that change is small in magnitude. In Experiment 2a, the magnitude of changes was essentially held constant within a trial block (given that item and binding changes were not intermixed in this experiment). This could have allowed participants to adapt to a certain magnitude of change. Yet, the difference between item and binding trials in this circumstance remained in older adults (as in Experiment 1a) and also emerged in this experiment in fifth-grade children, even though older adults had overall a much stronger bias toward not noticing changes.

2. Is the life-span development of binding shaped as an inverted U? On the basis of Experiment 2a, the answer is clearly that an inverted-U shape adequately describes development of binding. Both fifth-grade children and adults shifted in their bias toward fewer change detections in binding trial blocks, whereas young adults did not shift in that manner. That is, in terms of sensitivity and bias measured separately in this experiment, Jackson's hypothesis (Jackson, 1860, reprinted in Taylor, 1958) seems correct.

However, in Experiment 1a, in which item and binding changes were mixed together, an additional deficit in the detection of binding changes clearly showed up in older adults. It appears that the juxtaposition of two different levels of change works against detection of the more subtle, binding-type changes in that age group. One explanation for this difference is that older adults might be lulled more easily into a reliance on familiarity as opposed to recollection (cf. Hay & Jacoby, 1999; Jennings & Jacoby, 1997). In Experiment 1a, the presence of a number of item changes, which can be detected on the basis of familiarity, may allow the participant to use familiarity and still produce a reasonable distribution of "change" and "no change" responses. In contrast, in Experiment 2a, the separation of item and binding trial blocks means that recollection must be used in the binding blocks or else the participant would not produce a reasonable number of "change" responses.

In at least two ways, then, the Jacksonian hypothesis fails. First, one can see in Figure 3 that older adults do far worse than the children on binding trials in Experiment 1a. Second, in both Experiments 1a and 2a, one can see in Table 2 that the bias parameter beta gets steadily larger with age, indicating a greater tendency to say that nothing has changed. These effects could occur because older adults may be especially prone to omitting the recollection process and may therefore often answer "same" on the basis of familiarity, provided that a reasonable proportion of trials present unfamiliar stimuli to which a "different" response can be given on that same basis (i.e., in Experiment 1a and in the item-change block of Experiment 2a).

3. Can developmental deficits in binding be mimicked by dividing attention in young adults? Dividing attention did not differentially affect item and binding trials and did not affect bias, although it did lower task performance, reducing sensitivity. Therefore, although it may provide a model of some aspects of developmental change (inasmuch as children and older adults performed worse overall than young adults), it cannot serve as a model of what causes a binding deficit. In this way, it is consistent with other failures to find that dividing attention produces a binding deficit (Naveh-Benjamin, 2000; Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Naveh-Benjamin, Guez, & Shulman, 2004; Naveh-Benjamin, Hussain, et al., 2003).

4. How should associative deficits in binding be described according to a signal-detection analysis? It appears to be the response bias, rather than the sensitivity, of the memory process that produces a larger deficit for binding than for item changes in older adults in Experiment 1a (cf. Olson et al., 2004, Figure 2) and in both fifth-grade children and older adults in Experiment 2a. Life-span development produces an inverted-U shape of overall sensitivity for both item and binding changes alike. This combination of results, carefully considered, rules out the view that bias is just a correlate of sensitivity (Danziger, 1980); bias changes asymmetrically over the life span. For example, in Experiment 2a, older adults achieve almost identical sensitivity (d') levels for item and binding blocks and yet had significantly different response biases in the two types of trial blocks. A better supported view of response biases is that they depend on the extent to which the process of familiarity is used instead of recollection. Use of familiarity tends to result in false recognition of some changed items as unchanged, primarily in the case of binding changes, whereas it may improve performance on no-change trials. The tendency of older adults to often fall into this pattern of relying on familiarity when trial types are mixed may reflect their variability in the appropriateness of processing, or lack of "processing robustness" (Li et al., 2004).

Interpretation of the Life-Span Development of Binding

Given that the severe deficit in binding-change detection seen in older adults in Experiment 1a was not reproduced at all in a divided-attention experiment (Experiment 1b), it would appear that a nonattentional explanation must be found. Given the aging deficit in the encoding of contextual information (e.g., Bayen et al., 2000; Chalfonte & Johnson, 1996; Mitchell et al., 2000), a likely candidate is the degradation with aging of temporal lobe regions implicated in memory storage (e.g., Raz et al., 2004). In particular, the hippocampus and surrounding structures may be especially important in binding information about an item to the context in which it occurred (e.g., Rolls, 1996). It may be that a nonsevere deficit of temporal lobe function in aging could result in a type of participant who misses binding changes between arrays when other, more salient changes are present in the same trial block (as in Experiment 1a), but who is able to detect those binding changes when no other, more salient changes are included in the trial block (as in Experiment 2a). This type of hypothesis seems consistent with Mitchell et al.'s (2000) description of aging memory as entailing "deficits in the efficacy of reflective component processes" (p. 527).

Various studies have considered a variety of cognitive mechanisms that may change with age across the life span. These may play a role in the effects that were obtained. Some studies have pointed to an inverted-U shape of executive and inhibitory processes across the life span (e.g., Cepeda et al., 2001; Comalli, Wapner, & Werner, 1962; Dempster, 1992; Hasher, Stolzfus, Zacks, & Rypma, 1991; Williams et al., 1999; Zelazo et al., 2004). This may help to explain our sensitivity results, which did follow an inverted U.

However, aspects of the results related to bias were asymmetrical in developmental trend. (Similarly, see Gulya et al., 2002, for asymmetrical developmental change in some explicit memory processes.) It must be considered that, for trial blocks that include some binding-change trials, successful performance can occur only if familiarity cues are inhibited and answers are based instead on recollection (Jacoby, 1991). Similarly, developmental changes in attentiveness to the task (Craik & Byrd, 1982; Craik, Byrd, & Swanson, 1987; Hashtroudi, Johnson, & Chrosniak, 1990; Hess, Donley, & Vandermaas, 1989; Lane & Pearson, 1982; Plude, Enns, & Brodeur, 1994; Rabinowitz et al., 1982) could be important because it takes attention to use recollection processes consistently. Age differences in the speed of processing (Cerella & Hale, 1994; Kail & Salthouse, 1994) could be important if familiarity information is available sooner than recollection, in which case the speed of recollection processes could influence whether that information is used at all on a trial.

This is not the first study in which life-span changes can be decomposed into processes that display U-shaped change and others that change monotonically from childhood to old age. For example, the results of Hommel, Li, and Li (2004) show that pattern in a speeded task in which a circle target for which participants searched differed from nontarget objects in one feature (color) or only in the conjunction of two features (color and shape). Although there was a U-shaped trend in response times generally, elderly participants were especially slow in the conjunction search when there were many targets and when the target was absent from the display. Similar explanatory factors could apply to Hommel et al. and to the present study, including the factor of neural efficiency changing in a U shape across age groups and, in addition, factors specific to elderly people, including some deficit in detecting feature binding and a compensatory increase in cautiousness.

We found that age differences in the sensitivity to both item and binding trials appear to undergo mirror-image change in childhood and old age. There is a condition difference in response bias that also occurs in mirror image (i.e., inverted-U) form, with binding blocks producing a more positive bias than item blocks in children and older adults, versus a less positive bias in young adults (see Table 2). However, when item and binding changes occur in a common block of trials, as in Experiment 1a, older adults are particularly vulnerable to the use of a response criterion that is inappropriate for the binding trials. Thus, older adults differ from other groups in how they deal with stimuli differing in salience; the higher salience of item changes compared with binding changes in the same trial block tends to make the older adults overlook the binding changes. In both studies, also, the overall change in response biases across the life span was fairly monotonic rather than U shaped. Although we do not have the benefit of longitudinal data, we believe that large cohort effects are unlikely for basic working memory phenomena. The nature of the asymmetrical differences should be investigated in other types of procedures that have been used to test the associative deficit hypothesis in older adults. Our study emphasizes the value of life-span experimentation in improving the understanding of both maturational advances and aging deficits on the basis of comparative evidence across much of the life span.

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