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Age Differences in Short-Term Memory Binding Are Related to Working Memory Performance Across the Lifespan

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Memory performance increases during childhood and adolescence, and decreases in old age. Among younger adults, better ability to bind items to the context in which they were experienced is associated with higher working memory performance (Oberauer, 2005). Here, we examined the extent to which age differences in binding contribute to life span age differences in short-term memory (STM). Younger children ($N = 85$; 10 to 12 years), teenagers ($N = 41$; 13 to 15 years), younger adults ($N = 84$; 20 to 25 years), and older adults ($N = 86$; 70 to 75 years) worked on global and local short-term recognition tasks that are assumed to measure item and item-context memory, respectively. Structural equation models showed that item-context bindings are functioning less well in children and older adults compared with younger adults and teenagers. This result suggests protracted development of the ability to form and recollect detailed short-term memories, and decline of this ability in aging. Across all age groups, better item-context binding was associated with higher working memory performance, indicating that developmental differences in binding mechanisms are closely related to working memory development in childhood and old age.

Keywords: STM, working memory, child development, aging, binding

Across the human life span, memory performance shows large variation, with a substantial increase in performance across childhood and adolescence, a peak in young adulthood, and accelerated decline with advancing adult age. This pattern applies to short-term memory (STM; e.g., Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Sander, Werkle-Bergner, & Lindenberger, 2011) as well as to episodic memory (e.g., Fandakova, Shing, & Lindenberger, 2012; Shing, Werkle-Bergner, Li, & Lindenberger, 2008). STM refers to the temporary storage of information (Baddeley, 2012), whereas episodic memory refers to the long-term storage of events that are bound to particular times and places in the past (Tulving, 1972). The formation of complex memory representations, ranging from perceptual feature binding to the formation of higher order memories, concepts, and ideas, critically depends on binding processes (Murre, Wolters, & Raffone, 2005). In this context, *binding* refers to the process of encoding, consolidating, and retrieving the relations among co-occurring features of a given memory representation (Cohen & Eichenbaum, 1993; Treisman, 1996; Zimmer, Mecklinger, & Lindenberger, 2006). At the neural level, the mediotemporal lobe (MTL), and the hippocampus in particular, is important for the establishment of associations among features of mnemonic entities in episodic (Eichenbaum, 2006; Squire, 2004) and STM (Axmacher, Elger, & Fell, 2009; Axmacher, Schmitz, Weinreich, Elger, & Fell, 2008; Hannula, Tranel, & Cohen, 2006; Ranganath & D'Esposito, 2001, but see Jeneson & Squire, 2012, for a different point of view). Although the critical contribution of life span age differences in binding mechanisms to long-term memory are relatively well established (Old & Naveh-Benjamin, 2008; Shing et al., 2010; Sluzenski, Newcombe, & Kovacs, 2006), their contributions to STM have not received the same attention in the literature (Sander, Lindenberger, & Werkle-Bergner, 2012).

Within a recently proposed two-component framework of memory development across the life span (Sander et al., 2012; Shing et al., 2010), binding mechanisms underlying the associative component of memory are assumed to be relatively mature by middle childhood, and undergo senescent decline in late adulthood and old age. In addition, age-related differences in the functionality of strategic operations, probably dependent on prefrontal cortex (PFC) regions, contribute to developmental changes in memory performance. Here, children, due to protracted PFC maturation (e.g., Sowell et al., 2003; Toga, Thompson, & Sowell, 2006), as well as older adults, due to senescent PFC impairments (e.g., Raz et al., 2005; Raz & Rodrigue, 2006), are assumed to show lower levels of attentional, organizational, and control functions related to mnemonic processing. However, both associative and strategic components are suggested to work interdependently in any given mnemonic act to variable degrees, depending on the task and the person's age.

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Focusing on the binding aspects of memory processing, for the aging part, there has been growing evidence supporting the notion of an associative deficit in older adults (see a meta-analysis by Old & Naveh-Benjamin, 2008), particularly in the episodic memory domain. Less is known about age-related differences in binding in STM, but the available evidence supports the associative binding deficit in older adults (Chen & Naveh-Benjamin, 2012; Cowan et al., 2006; Sander et al., 2012). In contrast, the empirical evidence from child development is mixed. On the one hand, studies involving episodic (e.g., Shing et al., 2008; Sluzenski et al., 2006) and visual STM (e.g., Cowan et al., 2006; Sander et al., 2012) tasks showed that binding undergoes early maturation and is relatively functional by middle childhood. However, the evidence from neuroimaging studies of long-term memory is mixed. Whereas one study (Ofen et al., 2007) found no evidence for increase in MTL activation during the encoding of vividly recollected scenes in participants between 8 and 24 years, another study (Ghetti, DeMaster, Yonelinas, & Bunge, 2010) observed developmental differences in MTL activation profiles during encoding of pictures that were later remembered with specific contextual details, suggesting that there may be ongoing change in binding abilities and the functional organization of the MTL network well into middle childhood.

Given the sparse evidence with regard to age-related changes and the mixed evidence for childhood development, the main goal of the present study was to investigate the extent to which age differences in binding are related to differences in short-term recognition performance in childhood and old age. Toward this end, we used a *global–local recognition paradigm* (Oberauer, 2003, 2005) to investigate changes in component processes supporting STM performance across the life span. Participants learned and were tested on letters that were presented in different spatial locations. Although the perceptual layout was the same during encoding, the test format varied across experimental conditions: In the *global recognition task*, subjects judged whether they have previously studied the item (i.e., whether they have seen the presented letter during learning). In the *local recognition task*, subjects judged whether they have previously studied a given association (i.e., whether the letter has been presented at a particular location before). Hence, in the global condition, participants could solve the task either by relying on memory for the letter (i.e., item memory) or by also remembering its location (i.e., item-context memory), whereas in the local condition they could solve the task only by remembering the item-context-association.

Similar to Oberauer (2005), a structural equation modeling (SEM) approach was used to disentangle the contribution of binding mechanisms to STM performance across the life span. In this context, SEM provides a particularly suitable framework for examining age differences in memory components on the level of constructs rather than manifest variables. The advantage of using latent factors for the description of life span age differences in recognition memory is that they are free of measurement errors and test-specific variance, and allow to test for differences in variances and covariances across age groups directly (Kline, 2005; McArdle, 2009).

In the original model, Oberauer (2005) found two latent factors that contributed to short-term recognition in young adults,[1] namely, one represented single-item memory and the other represented item-context binding. In his model, the factor representing memory for item-context bindings (but not the factor representing single-item memory) was related to working memory (WM) capacity, highlighting the importance of binding processes for WM performance.[2] In the present study, we followed up on these results by examining the extent to which (a) a two-factor model can adequately describe the structure of short-term recognition memory across different age groups, (b) binding processes are important for STM differences across the life span, and (c) relations between STM for item-context representations and a WM measure differ across age groups. WM refers to the ability to briefly maintain and concurrently manipulate a limited amount of information in mind (cf. Baddeley, 2012; D'Esposito, 2007). Hence, while the initial study by Oberauer (2005) was based on young adults' data only, we extend the paradigm to both middle childhood and old age.

We expected that a two-factor model is necessary to capture the structure of the global and local recognition tasks in all age groups. In line with predictions of the two-component framework (Sander et al., 2012; Shing et al., 2010), children were expected to show similar or only slightly lower performance in STM for single items and item-context representations compared with younger adults. Older adults, on the other hand, were expected to show a unique age difference in memory for item-context representations compared with younger adults. In addition, we assumed that item-context binding mechanisms would be similarly important to explain interindividual differences in WM across all age groups (cf. Sander et al., 2012). The latter observation would support notions of binding mechanisms as major constituent processes for successful memory performance in general (Zimmer et al., 2006).

Method

Participants

Participants were sampled from two different studies (Sander et al., 2011; Shing et al., 2008) and were tested on the present task during a separate session of the respective study, in which several different measures were assessed, including those described in the present manuscript. The sample for the present analyses includes 85 children (10 to 12 years, $M_{\text{age}} = 11.10$, $SD_{\text{age}} = 0.56$; 40 female), 41 teenagers (13 to 15 years, $M_{\text{age}} = 14.41$, $SD_{\text{age}} = 0.41$; 21 female), 84 younger adults (20 to 25 years, $M_{\text{age}} = 23.16$, $SD_{\text{age}} = 1.51$; 43 female), and 86 older adults (70 to 75 years, $M_{\text{age}} = 72.19$, $SD_{\text{age}} = 2.10$; 44 female). The sample size of the teenager group was smaller than the other age groups because this age group was only investigated in the study by Shing et al. (2008). All participants were

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[1] Oberauer (2005) called these factors familiarity and recollection. Given that the differentiation in these two processes is widely used in episodic memory research, but less in STM research, we prefer to stick to a more literal description of the two factors and refer to the two factors as memory for items and item-context bindings.

[2] Oberauer (2005) used several tasks as indicators for WM performance, whereas we only used one task. Our digit-sorting task (Kray, 2000; see the Method section for details) followed the WM definition as the ability to briefly maintain and concurrently manipulate a limited amount of information in mind (Baddeley, 2012).

residents of Berlin, Germany. The older adults lived independently in the community. All participants were assessed on marker tests of crystallized intelligence (spot-a-word; cf. Lehrl, 1977; Lindenberger, Mayr, & Kliegl, 1993) and processing speed (digit symbol substitution test; cf. Lindenberger et al., 1993; Wechsler, 1955). Performance on these marker tests is presented in Table 1. The age groups differed reliably in both spot-a-word performance, $F(3, 292) = 284.77$, $p < .001$, $\eta_p^2 = .75$, and digit symbol performance, $F(3, 292) = 72.64$, $p < .001$, $\eta_p^2 = .43$. For spot-a-word, age differences between all investigated groups were significant (all $ps < .001$). Processing speed was higher in younger adults than in children, $t(141.84) = 14.42$, $p < .001$, $d = 2.27$, teenagers, $t(123) = 4.54$, $p < .001$, $d = 0.89$, and older adults, $t(141.84) = 14.42$, $p < .001$, $d = 1.64$. Teenagers also showed reliably higher processing speed than children, $t(124) = 7.69$, $p < .001$, $d = 1.4$, and older adults, $t(125) = 4.70$, $p < .001$, $d = 0.95$, who did not differ from each other ($p > .05$). The studies were approved by the ethics committee of the Max Planck Institute for Human Development, Berlin, Germany.

Materials and Procedure

Global and local recognition tasks. The main paradigm was a version of the global and local recognition paradigm introduced by Oberauer (2003, 2005). Following the original publication (Oberauer, 2003) of this paradigm, participants in the present study first worked on the global recognition task followed by the local recognition task. The stimulus set used in both tasks consisted of 20 uppercase consonants (B, C, D, F, G, H, J, K, L, M, N, P, Q, R, S, T, V, W, X, Z). Both tasks started with three practice blocks, followed by 12 test blocks each. Each block of the global and local recognition tasks started with six letters that were randomly selected from the stimulus set and were sequentially presented in one of six frames on the screen (see Figure 1). Different letters were presented and tested in a pseudorandom order that was the same for all participants on each block of the local and global task. Frames were presented on the middle horizontal line of the display with a size of 2.3 cm × 2.3 cm, with 7 mm of space between them. Each letter was displayed for 600 ms, followed by a 600-ms interstimulus interval. The six letters presented during the encoding phase of each block are referred to as a memory set. After the presentation of the last item from the memory set, a black display was presented for 600 ms. Recognition memory for the memory set was probed immediately after that via the sequential presentation of six probes.

In the global recognition task, participants were asked to memorize only the identity of the letters from the corresponding memory set. During the recognition phase, participants were instructed to respond "old" if the presented probe was part of the memory set and "new" if the presented probe was novel (i.e., not part of the memory set). On each block, three probes were part of the memory set and three were novel.

In the local recognition task, participants were instructed to memorize both the identity as well as the frame, that is, the location of each presented letter. During the recognition phase, all six presented probes were part of the memory set. However, three letters were presented at the same spatial location as during the encoding phase and three were presented at a different spatial location. Participants were asked to respond "old" only if a letter was presented at the same location as before and "new" if the letter was presented at another location.

In both tasks, recognition probes were presented for up to 3,000 ms or until a response was given and accuracy was stressed over speed. Recognition performance was calculated as the difference between hits (i.e., correct "old" response) and false alarms (i.e., incorrect "old" response) in each block of the global and local recognition tasks (Snodgrass & Corwin, 1988).

WM task. Following the WM definition as the ability to maintain and concurrently manipulate information in mind for a short period of time (Baddeley, 2012), we assessed WM using a digit-sorting task (cf. Kray, 2000) that represents a combination of a simple digit span task with a sorting manipulation requirement (cf. Craik, 1986). Digits between 1 and 12 were used as stimuli. Lists of four to eight digits were auditorily presented to the participants (cf. memory span, Wechsler, 1987) at a rate of approximately one second per digit. Immediately after the presentation, subjects were instructed to write down the digits by sorting them according to magnitude (cf. Kray, 2000). Three lists for each span were administered. Performance was scored as number of correctly remembered items, calculated up to the maximum span in which two of the three presented lists were remembered correctly.

Table 1
Descriptive Summary of Covariates and Task Measures

Measure	Children (*n* = 85) *M* (*SD*)	Teenager (*n* = 41) *M* (*SD*)	Young adults (*n* = 84) *M* (*SD*)	Older adults (*n* = 86) *M* (*SD*)
Digit Symbol	46.33 (7.06)	57.76 (9.20)	66.74 (10.91)	47.51 (12.43)
Vocabulary	15.00 (3.23)	17.88 (3.54)	24.02 (3.39)	28.86 (3.13)
Digit Sorting	8.58 (2.82)	9.93 (2.33)	10.34 (2.61)	7.67 (2.54)
Global recognition	.60 (.21)	.76 (.12)	.80 (.12)	.67 (.17)
Composite score 1	.59 (.24)	.76 (.14)	.80 (.14)	.67 (.18)
Composite score 2	.60 (.23)	.75 (.14)	.80 (.15)	.67 (.21)
Local recognition	.27 (.19)	.40 (.18)	.54 (.22)	.29 (22)
Composite score 1	.26 (.21)	.38 (.23)	.53 (.24)	.27 (.24)
Composite score 2	.26 (.24)	.39 (.20)	.54 (.25)	.27 (.25)

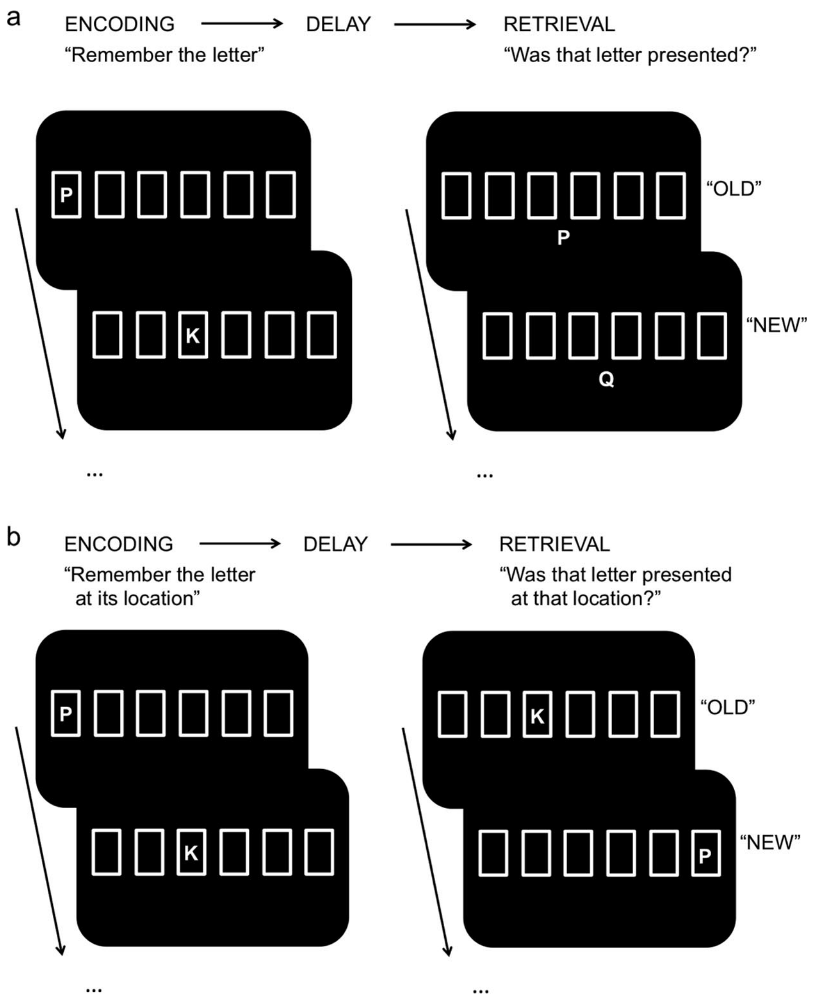

Figure 1. Graphical representation of the experimental paradigm. (a) Global recognition task. (b) Local recognition task.

Analysis

To investigate the life span development of item and item-context representations in STM, we followed the approach initially proposed by Oberauer (2005), using SEM to extract latent means and variances of item and item-context memory and relate them to the WM measure (cf. Oberauer, 2005). In our version of the global and local recognition tasks, the number of letters presented in a given block was fixed to six across both tasks and did not vary as in the original application of the model (Oberauer, 2005). Given this difference in procedure, we took the following steps to build latent factors of item and item-context memory. First, we rank-ordered the 12 blocks of the global and local recognition tasks according to mean recognition performance in the respective task. The rank-ordering of the blocks within each task was necessary due to variations in performance across the 12 blocks, probably reflecting fluctuations in attention, fatigue, or other factors. In addition, all participants had a break after the sixth block that may have affected their performance on the seventh block. To account for these effects without affecting the age groups differentially, we rank-ordered the blocks of each task within each age group before assigning them to the indicator variables. Following, each block was assigned to one of two indicator variables (the assignment was the same for all participants), resulting in two composite scores per task that represent mean performance on six pseudorandomly chosen blocks of the corresponding task. This procedure ensured the two composite measures of each task to be equal at the mean level. Accordingly, there was no difference between the two composite measures for global (all $ps > .40$) and local recognition (all $ps > .60$) in any of the age groups (see Table 1).

A graphical representation of the structural equation model implemented in the present study is depicted in Figure 2. The two composite scores for the global task were allowed to load on both the Item and Item-Context factors, as performance in this task might result from both remembering the single item as well as the spatial location at which it is presented (Oberauer, 2005). Given the specific way of building the composite scores described, we did not expect the two composite scores to differentially contribute to the latent Item factor. Therefore, the

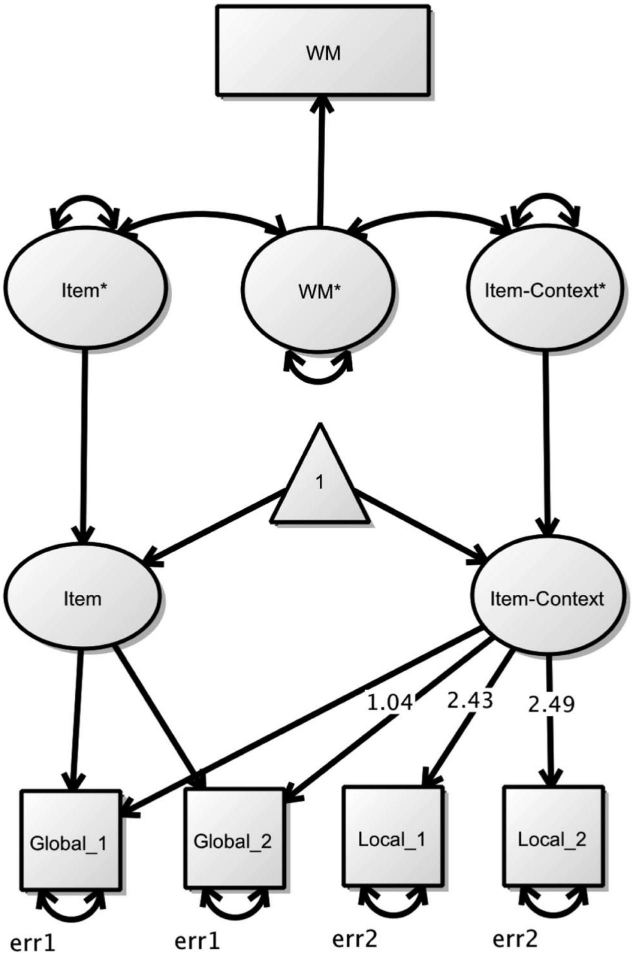

Figure 2. Graphical representation of the multigroup structural equation model for the global and local recognition tasks. Manifest variables from the tasks are composite scores of recognition performance in the global recognition task (termed Global_1 and Global_2) and the local recognition task (termed Local_1 and Local_2). Loading numbers represent unstandardized estimated factor loadings that are equal across age groups (see Table 2 for standardized loadings). The graphical representation for this model was created with Ωnyx (von Oertzen, Brandmaier, & Tsang, 2013). err = error term; WM = working memory measured by the Digit Sorting Task.

loadings of the two scored on the latent factor were fixed to 1.[3] The two composite scores for the local task were allowed to load on the Item-Context factor only, as successful performance in this task specifically requires memory for the binding between the letter and the location at which it appeared (Cowan et al., 2006; Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Oberauer, 2005).[4] Our starting model was an unrestricted model with all loadings, means, and factor and residual variances estimated independently for each age group. Following this, we tested several nested models by imposing additional restrictions on this unrestricted model. All models were analyzed with Mplus 6.1 (Muthén & Muthén, 1998–2006) using maximum likelihood estimation (Bollen & Curran, 2006; Meredith & Tisak, 1990). To evaluate model fit, chi-square statistics, the comparative fit index (CFI), and the root mean square error of approximation (RMSEA) were examined. The chi-square statistic is a common index of fit. However, it cannot be interpreted in a standardized way and is particularly sensitive to sample size. To reduce its sensitivity, a division by the degrees of freedom (*df*) is recommended. The CFI (Bentler, 1990) relates the difference ($\chi^2 - df$) for the hypothesized model to the same difference for the null model of independent variables. It can vary between 0 and 1, with 1 representing ideal fit and CFI $>$0.9 indicating acceptable fit (Bollen & Curran, 2006). The RMSEA (Steiger & Lind, 1980) represents the lack of model fit of the estimated model compared with a perfect (saturated) model. It has a minimum of zero and no upper limit. Generally, values of RMSEA less than .08, including .05 within its 90% confidence interval, indicate good fit, and those greater than 0.1 reflect poor fit (Browne & Cudeck, 1993; Steiger, 1990).

Age comparisons were assessed by fixing parameters of interest (i.e., means, variances, covariances) to be equal in particular age groups. The difference between the chi square for these nested models is chi-square distributed, with *df* equal to the difference in the number of free parameters between the two models. The significance level for all tests was set to $p < .05$. All pairwise comparisons among the four age groups were carried out for each measure of interest. Bonferroni correction was used to account for multiple comparisons resulting from running all six pairwise age group comparisons with an adjusted significance level of $p < .008$.

Results

Summary of Single-Task Performance

Global recognition task. The age groups differed with respect to performance on the global recognition task, $F(3, 292) = 24.56$, $p < .001$, $\eta_p^2 = .20$. Children showed lower performance than teenagers, $t(118.6) = 5.45$, $p < .001$, $d = 0.97$, younger adults, $t(136.8) = 7.92$, $p < .001$, $d = 1.21$, and older adults, $t(169) = 2.52$, $p = .024$, $d = 0.37$. In addition, older adults' performance was lower than both teenagers, $t(106.9) = 3.25$, $p = .036$, $d = 0.62$, and younger adults, $t(153.1) = 5.80$, $p < .001$, $d = 0.90$. Teenagers and younger adults did not differ from each other ($p > .05$).

Local recognition task. There were age differences in performance on the local recognition task, $F(3, 292) = 32.64$, $p < .001$, $\eta_p^2 = .25$. Younger adults outperformed the remaining age groups, including children, $t(161.6) = 8.70$, $p < .001$, $d = 1.32$, teenagers, $t(99) = 4.13$, $p = .001$, $d = 0.70$, and older adults, $t(168) = 7.74$, $p < .001$, $d = 1.14$. In addition, teenagers showed significantly higher performance than children, $t(124) = 3.58$, $p = .008$, $d =$

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[3] If only one of the score loadings is fixed to 1 in order to define a scale for the latent factor, the estimated loading of the second composite score also approaches 1, and the same pattern of results is obtained.

[4] We examined whether one latent factor can also model performance in the global and local recognition tasks. To this end, we tested a model with all four composite scores loading on a common latent factor with free parameters across age groups. In contrast to the two-factor model, this model did not provide good fit to the data, $\chi^2 = 163.33$, $df = 29$, CFI $= 0.43$, and RMSEA $= 0.25$, 90% CI [.22, .29]. A direct comparison of the one-factor and two-factor models confirmed that they differed significantly in fit, $\Delta\chi^2 = 135.42$, $df = 8$, $p = .00$.

0.70, and older adults, $t(125) = 2.82$, $p = .036$, $d = 0.55$, who did not differ from each other ($p > .05$).

Performance on the local and global tasks was positively correlated in children, $r = .46$ $p < .001$, younger adults, $r = .51$, $p < .001$, and older adults, $r = .33$, $p = .002$, but not in teenagers, $r = .17$, $p = .29$. Same patterns of age differences were observed with each of the local and global composite scores.

WM task. WM performance, as measured by the digit sorting task, differed reliably across the age groups, $F(3, 292) = 16.96$, $p < .001$, $\eta_p^2 = .15$. Younger adults demonstrated higher WM performance than children, $t(167) = 4.23$, $p < .001$, $d = 0.65$, and older adults, $t(168) = 6.71$, $p < .001$, $d = 1.04$, but did not differ from teenagers ($p > .05$). Teenagers also showed higher WM performance than children, $t(124) = 2.66$, $p = .042$, $d = 0.52$, and older adults, $t(125) = 4.75$, $p < .001$, $d = 0.93$. In contrast, children and older adults did not differ from each other ($p > .05$).

SEM Analysis of Age Differences in Item and Item-Context Memory

The unrestricted two-factor model was estimated as a multi-group SEM model. This model showed acceptable fit to the data, $\chi^2 = 18.79$, $df = 12$, CFI = 0.97, RMSEA = 0.09, 90% CI [.00, .16]. Next, we tested whether fixing the (unstandardized) loadings on the Item-Context factor to be the same across all age groups would lead to significant differences in model fit. This model provided acceptable fit to the data, $\chi^2 = 27.93$, $df = 21$, CFI = 0.97, RMSEA = 0.07, 90% CI [.00, .13], and did not differ significantly from the starting model, $\Delta\chi^2 = 8.96$, $df = 9$, $p = .44$. An additional restriction of equal residual variance for the two global and the two local composite scores within each age group did not lead to a significant difference in fit from the starting model, $\Delta\chi^2 = 6.49$, $df = 8$, $p = .59$, and the model showed excellent fit to the data, $\chi^2 = 34.42$, $df = 29$, CFI = 0.98, RMSEA = 0.05 90% CI [.00, .11]. However, restricting the residual variances to be the same across age groups led to significant decrease in model fit, $\Delta\chi^2 = 17.98$, $df = 6$, $p = .006$, and this model was not considered any further.

The WM covariate measure was added to this final model (factor WM in Figure 2) to examine the relationship between WM performance and individual differences in STM binding. The resulting model showed excellent fit to the data, $\chi^2 = 42.62$, $df = 37$, CFI = 0.98, RMSEA = 0.05, 90% CI [.00, .10]. This model represents the final model used to test mean age differences in the latent factors and their relationships to WM. In this final model (see Figure 2), the loadings of the composite scores on the Item-Context factor are estimated to be the same across age groups (see Table 2 for standardized factor loadings), and residual variances for each of the two composite scores belonging to the same task were equal within age groups.

Age Differences in Item and Item-Context Factors Across the Life Span

The estimated means and variances of the Item and Item-Context latent factors are presented in Table 3. Children showed reliably lower estimates of the Item factor than teenagers, $\Delta\chi^2 = 12.05$, $df = 1$, $p = .0005$, $d = 0.86$, younger adults, $\Delta\chi^2 = 9.01$, $df = 1$, $p = .003$, $d = 0.80$, and older adults, $\Delta\chi^2 = 6.91$, $df = 1$, $p = .008$, $d = 0.52$. The remaining age groups did not differ among each other (all $ps > .05$). In contrast, younger adults' estimated means on the Item-Context factor were reliably higher than children, $\Delta\chi^2 = 62.27$, $df = 1$, $p < .0001$, $d = 1.58$, teenagers, $\Delta\chi^2 = 15.70$, $df = 1$, $p = .0001$, $d = 0.95$, and older adults, $\Delta\chi^2 = 56.03$, $df = 1$, $p < .0001$, $d = 1.47$. Interestingly, teenagers also showed significantly higher performance than both children, $\Delta\chi^2 = 13.10$, $df = 1$, $p < .001$, $d = 0.95$, and older adults, $\Delta\chi^2 = 11.07$, $df = 1$, $p = .001$, $d = 0.83$. Finally, children and older adults did not differ in their mean estimates for the Item-Context factor, $\Delta\chi^2 = 0.06$, $df = 1$, $p = .80$, $d = 0.04$.

Table 2
Standardized Factors Loadings Across Age Groups

	Children	Teenagers	Young adults	Older adults
Item				
Global_1	0.66*	0.62*	0.43*	0.65*
Global_2	0.66*	0.62*	0.43*	0.65*
Item-Context				
Global_1	0.28*	0.33*	0.52*	0.37*
Global_2	0.29*	0.34*	0.54*	0.38*
Local_1	0.69*	0.54*	0.78*	0.73*
Local_1	0.69*	0.54*	0.78*	0.73*

* $p < .05$.

To summarize, although age differences on the Item factor were minimal, younger adults outperformed the remaining age groups on the Item-Context factor, followed by teenagers. Children and older adults showed the lowest performance and did not differ from each other.

Relationship of Item and Item-Context Factors With WM

The correlations between the latent factors and the covariate measure are presented in Table 3. In line with previously reported relationships between WM capacity and binding in short-term recognition (Oberauer, 2005), better Item-Context memory was positively related to higher WM performance in younger adults, $r = .55$, $p < .001$. Importantly, higher Item-Context estimates were also associated with higher WM performance in children, $r = .35$, $p = .01$, teenagers, $r = .62$, $p = .001$, and older adults, $r = .66$, $p < .001$. To confirm these results, a model with correlations fixed to zero in all age groups was compared with an unconstrained model, resulting in a significant drop in model fit, $\Delta\chi^2 = 68.35$, $df = 4$, $p < .001$. Importantly, constraining the Item-Context–WM correlation to be equal across age groups did not lead to a significant difference from the unrestricted model, $\Delta\chi^2 = 5.29$, $df = 3$, $p = .15$, suggesting that this relationship was similar across the life span.

Item memory was not reliably related to WM performance in children, $r = .24$, $p = .08$, teenagers, $r = -.18$, $p = .36$, younger adults, $r = -.18$, $p = .26$, and older adults, $r = -.11$, $p = .36$. Moreover, fixing the correlation to zero in all age groups did not result in a significant change in model fit, $\Delta\chi^2 = 5.39$, $df = 4$, $p = .25$, confirming that variation in item memory did not contribute to individual differences in WM. Here, too, constraining the Item–WM correlation to be equal across age groups revealed no

Table 3
Estimates of Latent Means, Variances, Residual Variances, and Correlations Across Age Groups

	Children	Teenagers	Young adults	Older adults
Mean				
Item	0.49*	0.59*	0.58*	0.56*
Item-Context	0.11*	0.16*	0.22*	0.11*
Variance				
Item	0.022*	0.008*	0.004*	0.016*
Item-Context	0.004*	0.002*	0.006*	0.005*
Residual variance				
Global	0.024*	0.010*	0.011*	0.016*
Local	0.026*	0.029*	0.023*	0.028*
Correlations with WM				
Item	.24	−.18	−.18	−.11
Item-Context	.35*	.62*	.55*	.66*

* $p < .05$.

significant differences across the age groups, $\Delta\chi^2 = 6.28$, $df = 3$, $p = .10$.

Finally, imposing an equality constraint on the Item–WM and the Item-Context–WM correlations across age groups significantly reduced model fit, $\Delta\chi^2 = 47.93$, $df = 1$, $p < .001$, suggesting that the two correlations are in fact not equal.

To summarize, in all age groups, higher item-context memory was associated with higher WM performance relative to the corresponding age peers, and the magnitude of this effect was similar across the life span. In contrast, item memory did not explain considerable portions of interindividual differences in WM performance in any of the age groups.

Discussion

We investigated age differences in STM binding across the life span. Using a global–local recognition paradigm that has been previously shown to capture individual differences in the ability to build and retrieve item-context associations in younger adults (Oberauer, 2005), we replicated those previous results and extended them to several novel findings regarding the life span development of item-context binding.

First, short term-recognition performance was adequately captured using a two-factor model across all age groups. The present results suggest that the general structure of short-term recognition memory is similar in children, teenagers, and older adults, and is comparable with the factor structure observed in younger adults. Hence, the SEM analysis lends support for the idea that from middle childhood to old age, two different sources of variance, defined by the need to learn and retrieve item versus bound item-context memory representations, contribute to STM recognition (e.g., Craik & Bialystok, 2006; Sander et al., 2012; Shing et al., 2010).

Second, STM for single items and item-context bindings showed age-differential trajectories across the life span. Older adults' estimates for single item recognition did not differ from teenagers and younger adults, suggesting that the ability to hold and retrieve item information in mind over a brief period of time may be relatively preserved in old age (cf. Naveh-Benjamin et al., 2004). In contrast, young children showed lower performance for single-item representations than the remaining age groups. One possible explanation for this surprising finding could be age differences in trial-by-trial variation in attention across blocks of the task (e.g., Betts, McKay, Maruff, & Anderson, 2006; Klenberg, Korkman, & Lahti-Nuuttila, 2001). In a recent study with a change-detection WM paradigm, Sander et al. (2011) found that WM capacity was lower in children and older adults compared with younger adults. Importantly, statistical modeling of hit and false-alarm rates in the change detection paradigm on an individual level (Rouder et al., 2008) indicated that children (10 to 12 years) showed reduced sustained attention compared with both younger and older adults. After controlling for age differences in attention by applying appropriate statistical modeling techniques, estimates for WM capacity were even higher in children compared with older adults (Sander et al., 2011, Figure 2).

Alternatively, lower single-item memory in the younger children may be related to the specific stimulus material used in the present study. As part of the pragmatics of cognition (Baltes, 1987), vocabulary knowledge increases across child developmental periods and is characterized by stability or maintenance in old age (Li et al., 2004). Hence, despite their solid experience with decoding letters, fifth graders in the present study may not have been able to use vocabulary knowledge to facilitate encoding of the presented letter strings to the same degree as the remaining age groups. Future studies are needed to investigate different stimulus materials and the potential influence that they may have on age differences in STM binding (cf. Chen & Naveh-Benjamin, 2012).

The age pattern of STM performance for item-context bindings was different (Cowan et al., 2006). Here, all age groups showed lower levels of performance compared with younger adults. In addition, teenagers showed higher levels of performance compared with children and older adults. Taken together, our results indicate that the ability to learn and retrieve associations between items and the context in which they are encountered in STM undergoes prolonged development up to young adulthood as well as age-related decline in older adults (cf. Cowan et al., 2006).

Oberauer (2005) suggested that the main difference between the global and local recognition tasks is the experimental manipulation of the need for establishing associations in the local, but not the global, task. From this perspective, the lack of differences between children and older adults seems in contradiction to the two-component framework of memory development, which suggests that the ability to associate information is relatively mature by middle childhood and undergoes age-related decline (Sander et al., 2012; Shing et al., 2010; see also Ofen et al., 2007; Ofen, Chai, Schuil, Whitfield-Gabrieli, & Gabrieli, 2012). The results are more in line with recent findings pointing to the continued maturation of MTL regions until at least 12 years of age (Demaster & Ghetti, 2012; Ghetti et al., 2010), particularly for long-term memory that entails recollection of contextual information. However, it should be noted that children in the present study showed lower STM for items compared with the remaining age groups. Hence, it is plausible that factors similar to those affecting children's item memory (e.g., fatigue, fluctuations in attention) might have influenced their memory for item-context bindings. Because the present task does not allow us to distinguish between these accounts of children's performance, the results should be interpreted with caution.

Importantly, in the present study, the item-context factor estimates were positively associated with the WM capacity measure, which relied on the simultaneous maintenance and manipulation of digits. Thus, we replicated the finding of Oberauer (2005) that WM is positively related to the factor capturing item-context representations in STM for young adults. Crucially, we extended this result to childhood and old age, and demonstrated that the positive relationship between item-context binding and WM capacity was also present to a similar degree in all age groups, including children and older adults. Taken together, the results underline the importance of binding mechanisms for age differences not only in STM but also in WM.

Nevertheless, there are plausible alternative interpretations regarding the shared variance between item-context memory and WM. First, although similar in procedure, the global and local recognition tasks inherently differ in complexity and difficulty. For the global recognition task, only one feature (i.e., the item information) had to be maintained, whereas in the local task, two features (i.e., the item and the spatial location) had to be maintained. Given that age differences are usually larger for more complex tasks (cf. Craik, 1986; but see Hale et al., 2011), differences in task difficulty may have contributed to the observed age differences in item-context memory. In addition, previous research has shown that WM measures are more strongly correlated with complex than with simple tasks (e.g., Daneman & Carpenter, 1980; Kane, Conway, Hambrick, & Engle, 2007), highlighting the role of executive or strategic operations as an alternative explanation for the observed relation between WM and item-context memory. This idea is supported by existing evidence from the neuroimaging literature. On the neuronal level, PFC regions support a set of strategic and executive functions that operate on representations (Miller & Cohen, 2001), both in WM (cf. D'Esposito, 2007) and long-term memory (cf. Simons & Spiers, 2003). Importantly, both children (Ofen et al., 2007; Paz-Alonso, Ghetti, Donohue, Goodman, & Bunge, 2008) and older adults (Fandakova, Lindenberger, & Shing, 2013; Nagel et al., 2009) show lower PFC activations during memory tasks. Taken together, the existing behavioral and neuroimaging evidence suggests the possibility that developmental differences in the strategic processes, most likely implemented by prefrontal areas, may contribute to the observed pattern of life span age differences in item-context bindings (and its relation to WM) in the present study. Future studies should try to disentangle the effects of differences in difficulty and binding processes by varying independently task difficulty and binding demands.

Several limitations of the current study need to be taken into account. First, we investigated memory processes in a large sample of four different age groups. We made use of an extreme-group design by investigating those age groups that, according to the two-component framework (Sander et al., 2012; Shing et al., 2010), would show the largest differences in the developmental processes underlying task performance. Thus, we included children, teenagers, and older adults above 70 years in our sample, and compared their performance to younger adults. This kind of design leaves out a rather large age range between 20 and 70 years. Previous research (see, e.g., Hale et al., 2011; Park & Payer, 2006) has shown that performance decreases in complex memory tasks start in middle adulthood and show continuous decline in older age. Based on these findings, it is tempting to expect that STM for item-context bindings might already be lower in middle compared with young adulthood. This speculation needs to be investigated in future studies, preferably employing a longitudinal design (Lindenberger, Oertzen, Ghisletta, & Hertzog, 2011).

Second, our study focused on a single STM paradigm that allowed for similar procedures in the two subtasks. Although this paradigm is well suited to enhance comparability of task performance across a wider age range, it clearly limits the generalizability of our results. In particular, using spatial locations as the to-be-bound feature might have resulted in different age effects than if we had used a paradigm that requires other types of associations, for example, item-item bindings (see Zimmer et al., 2006, for a discussion of different levels of binding). However, although the evidence with respect to age differences in memory for locations is mixed (e.g., Chalfonte & Johnson, 1996; Mitchell, Johnson, Raye, & D'Esposito, 2000), the majority of the available evidence supports a specific age-related deficit in forming and retrieving *associations*, above and beyond the effects of single memory (e.g., Old & Naveh-Benjamin, 2008). In addition, we did not test memory for the location explicitly, given that all possible locations were used for presenting and testing letters, emphasizing the need to remember the specific association. We also used only one indicator task for assessing WM capacity within the verbal domain. However, the structure of WM abilities may vary across the life span as a function of domain (e.g., Hale et al., 2011; Johnson, Logie, & Brockmole, 2010). Further investigations are needed to generalize the present results to other tasks, domains, and different contextual features. Here, experimental designs examining life span age differences in binding across different STM and WM tasks in several domains would be particularly suited for SEM methods that model common variance across tasks that tap on the same latent construct.

Third, participants always performed the global recognition task *before* the local recognition task (see also Oberauer, 2005), eventually resulting in a greater amount of proactive interference in the local compared with the global recognition task. Both children and older adults are known to have greater difficulties withstanding proactive interference over the course of a task or an experimental session (Fandakova et al., 2012; Kail, 2002; Lustig & Hasher, 2002; Lustig, May, & Hasher, 2001). Thus, the observed larger age differences in item-context memory might be due, in part, to this potential confound.

Taken together, our results suggest protracted development of the ability to form and recollect bound representations from STM across childhood, as well as decline in this ability in aging. Across all age groups, better item-context binding was associated with higher WM performance, indicating that interindividual differences in binding abilities are related to differences in WM functioning regardless of age. Our results contribute evidence to the current discussion about the level of maturity of item-context binding in childhood by demonstrating that, under some conditions, these mechanisms may not be functioning optimally. To better understand life span differences in short-term and long-term memory, future research is needed to systematically investigate to what extent varying the demand on strategic processes affects age differences in binding mechanisms in various memory task settings, and vice versa. Furthermore, given that the present analysis can only focus on behavioral data, we cannot disentangle whether children and older adults are impaired with regard to the establishment, maintenance, or retrieval of bound information in STM (cf. Chen & Naveh-Benjamin, 2012), speaking for the need to investigate this question using neuroimaging methods. Our results provide initial evidence that the general mechanisms underlying STM performance are present in middle childhood and old age, but differ in their efficiency across the life span.

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