

Binding and Strategic Selection in Working Memory: A Lifespan Dissociation

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Working memory (WM) shows a gradual increase during childhood, followed by accelerating decline from adulthood to old age. To examine these lifespan differences more closely, we asked 34 children (10–12 years), 40 younger adults (20–25 years), and 39 older adults (70–75 years) to perform a color change detection task. Load levels and encoding durations were varied for displays including targets only (Experiment 1) or targets plus distracters (Experiment 2, investigating a subsample of Experiment 1). WM performance was lower in older adults and children than in younger adults. Longer presentation times were associated with better performance in all age groups, presumably reflecting increasing effects of strategic selection mechanisms on WM performance. Children outperformed older adults when encoding times were short, and distracter effects were larger in children and older adults than in younger adults. We conclude that strategic selection in WM develops more slowly during childhood than basic binding operations, presumably reflecting the delay in maturation of frontal versus medio-temporal brain networks. In old age, both sets of mechanisms decline, reflecting senescent change in both networks. We discuss similarities to episodic memory development and address open questions for future research.

Keywords: aging, binding, change detection, cognitive control, development, visual working memory

A primary function of visual working memory (WM) is to maintain information of perceptual input from the environment for a short period of time so that the information can be used for goal-directed behavior (D'Esposito, 2007). A critical feature of WM is its limited capacity, which is usually estimated to include about three or four items (Luck & Vogel, 1997; G. A. Miller, 1956). Because WM capacity has been shown to be predictive for a wide range of cognitive functions (Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Oberauer, Subeta, Wilhelm, & Wittmann, 2008), the determination of the individual WM limit has been of great scientific interest.

One paradigm to measure visual WM capacity is the change detection task (Luck & Vogel, 1997). In its standard version the

observer is briefly presented with a memory array followed by a one-second retention interval and then compares the representation maintained in WM to a probe array in which one item might have changed. Based on the correct and incorrect answers to displays with increasing WM load, a person-specific capacity measure (k score) can be calculated (Cowan, 2001). In the past, the change detection paradigm has been applied in a whole range of behavioral (Eng, Chen, & Jiang, 2005; Jiang, Olson, & Chun, 2000; Olson & Jiang, 2004; Vogel, Woodman, & Luck, 2001, 2006; Wheeler & Treisman, 2002; Woodman & Vogel, 2005), electrophysiological (McCollough, Machizawa, & Vogel, 2007; Sauseng et al., 2009; Vogel & Machizawa, 2004; Vogel, McCollough, & Machizawa, 2005), and neuroimaging (Todd & Marois, 2004, 2005; Xu, 2007; Xu & Chun, 2006; Yeh, Kuo, & Liu, 2007) studies, with slight variations. Most of these studies were restricted to younger adults, but one study investigated a lifespan sample (Cowan, Naveh-Benjamin, Kilb, & Sauls, 2006), and four studies investigated children and younger adults (Cowan et al., 2005; Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010; Riggs, McTaggart, Simpson, & Freeman, 2006; Simmering-Best, 2008). In all behavioral age-comparative investigations, lower capacity estimates were found for both children and older adults in comparison with younger adults. However, the underlying cognitive and neuronal mechanisms for this lifespan trajectory of increasing performance across childhood and decreasing performance across senescence are not well understood.

Lifespan Changes in Components Contributing to Working Memory Performance

Models of WM inspired by neuroscientific findings define WM as processes operating on representations in a distributed neural network (D'Esposito, 2007; Postle, 2006; Zimmer, 2008). On a

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neuronal level, successful memory performance relies on the dynamic interplay between sensory-specific, multimodal association regions, and executive control regions. Most of the executive control regions involved in processes related to attention, selection and optimization of memory representations are located within the frontal lobes (Desimone & Duncan, 1995; Edin et al., 2009; Gazzaley et al., 2007; McNab & Klingberg, 2008; E. K. Miller & Cohen, 2001; Werkle-Bergner, Müller, Li, & Lindenberger, 2006). Furthermore, neuroimaging as well as electrophysiological studies identify the posterior parietal cortex (Todd & Marois, 2004, 2005; Vogel & Machizawa, 2004) as a possible locus of capacity limits in WM performance. In addition, research also indicates that medio-temporal lobe (MTL) plays an important role in memory encoding. Dynamically synchronized interactions between rhinal cortex and hippocampus seem to contribute to the binding of features into compound representations (Fell et al., 2001) and to consolidation of these representations in interaction with sensory-specific and posterior-parietal association areas (for review, see Axmacher, Mormann, Fernandez, Elger, & Fell, 2006; Werkle-Bergner et al., 2006). Taken together, neurophysiological as well as functional neuroimaging studies suggest that WM processes are achieved through a complex interplay of a widespread neuronal network (e.g., Zimmer, 2008).

Across the lifespan, brain regions contributing to memory performance undergo differential changes and can be more or less prone to effects of maturation, learning, and senescence, differentially affecting the dynamic interactions between brain regions in different age groups (Raz et al., 2005; Raz & Rodrigue, 2006; Sowell et al., 2003; Toga, Thompson, & Sowell, 2006). Behavioral findings reflect these age-related variations in memory-relevant brain regions; across the lifespan, performance on both episodic and working memory tasks shows pronounced age-related differences (Li et al., 2004). From childhood to young adulthood, marked improvements in various WM tasks are observed (Gathercole, 1999), whereas in older adults, WM performance usually declines with advancing age (Park & Payer, 2006). Findings from longitudinal studies generally support these cross-sectional results (de Frias, Lövdén, Lindenberger, & Nilsson, 2007; Schneider, Schumann-Hengsteler, & Sodian, 2005).

Only a few studies have examined both children and older adults within the same experiment to integrate findings from both ends of the lifespan. Based on a series of such studies (Brehmer, Li, Müller, von Oertzen, & Lindenberger, 2007; Brehmer et al., 2008; Shing, Werkle-Bergner, Li, & Lindenberger, 2008), Shing, Werkle-Bergner, Li, and Lindenberger (2008; see also Shing & Lindenberger, in press; Shing et al., 2010) suggested an integrative framework conceptualizing the functioning of (episodic) memory across the lifespan as two interacting components, namely the associative and the strategic components.

The *associative component* refers to binding mechanisms that form links within and between memory traces at different levels of complexity (cf. Craik, 2006). It is thought to reflect processes dependent on MTL regions that are relatively mature by late childhood and especially prone to senescent changes. The *strategic component* refers to the organization, selection, and manipulation of memory elements during encoding and maintenance as well as retrieval processes and is hypothesized to rely on the prefrontal cortex (PFC). Crucially, the PFC, in contrast to MTL and sensory-specific brain regions, undergoes profound maturational changes

well into adolescence (Dempster, 1992) and is among the first regions to show senescence-related decline (Raz et al., 2005; Raz & Rodrigue, 2006). Hence, Shing and colleagues (2008, 2010) suggest a lifespan dissociation between the associative and strategic component and assume that aspects of memory performance that primarily depend on the associative component are at similar levels in children and younger adults, but lower in older adults, whereas memory performance relying on the strategic component is lower in both children and older adults than in younger adults.

Here, we suggest that this two-component framework, introduced by Shing et al. (2008) to inform research on episodic memory development from childhood to old age, is also pertinent to WM development because the neural networks supporting episodic memory and WM show considerable structural and functional overlap (Ranganath, 2006; Ranganath & Blumenfeld, 2005; Ranganath, Cohen, & Brozinsky, 2005). In the context of the change detection task, we identify the associative component with low-level binding mechanisms that integrate perceptual inputs into a coherent representation (Craik, 2006; Zimmer, Mecklinger, & Lindenberger, 2006). Computational models and electrophysiological evidence suggest that low-level feature binding is accomplished by synchronization of neural activity (Murre, Wolters, & Raffone, 2006; von der Malsburg, 1981). The initial binding is assumed to occur rapidly and in an automatic fashion. Prefrontally mediated control processes may then interact with these basic bindings to stabilize perceptual and memory representations. Implementation of control can thus be understood as a feedback process that takes more time than the binding process itself. Here, we investigate the lifespan trajectory of the two components by exploring their relative contributions under conditions of short and longer presentation times.

Overview of the Present Study

In two experiments, we examined mechanisms that contribute to age-related differences in WM performance between children, younger adults, and older adults.

Each participant was tested in three sessions involving groups of four to five individuals within a two-week period. In Session 1, covariate measures were assessed. In Session 2, participants completed three blocks of a color change detection task without distracters (= Experiment 1). In Session 3, the same participants completed three blocks of the same change detection task but with distracters (= Experiment 2).

Experiment 1: Contributions of Associative and Strategic Components to WM Performance

Experiment 1 examined the relative contributions of associative and strategic components to WM performance of three age groups. We assumed that the building of representations heavily relies on the functionality of binding mechanisms. Given that binding mechanisms operate rapidly and in a relatively automatic fashion (Zimmer, Mecklinger, & Lindenberger, 2006), we hypothesized that with short presentation times, the possibility to exert strategic control would be rather limited. Thus, age differences in this condition should mainly reflect the efficiency of the associative component in the different age groups. Based on our earlier proposition that the associative component is relatively mature in

children, but compromised in older adults (Shing et al., 2008, 2010), we expected older adults to achieve generally lower WM performances than children and younger adults when presentation times are fast, and children to perform at a level more similar to younger adults.

Furthermore, we expected that the consolidation and stabilization of WM representations would depend on interactions of associative binding mechanisms with strategic control operations, the latter presumably being established through PFC operations. We assumed that prefrontal control and the establishment of connectivity between different brain regions is a more time-consuming process that selectively profits from longer presentation times. We therefore hypothesized that WM performance would improve with longer presentation times because of increasing reliance on control processes to consolidate and stabilize early representations, while the basic binding operations are required at all presentation times. Because brain regions related to control mechanisms, and here specifically prefrontal regions, undergo profound changes until young adulthood and are heavily compromised in old age, we predicted that, even with longer presentation times, both children and older adults would show deficits in WM performance in comparison to younger adults.

Method

Participants. The original sample included 40 children, 40 younger adults, and 40 older adults. Six children and one older adult were excluded from the study because their data involved more than 5% of trials with no or anticipatory responses. Thus, the effective sample in Experiment 1 consisted of 34 children (aged 9–12 years, $M = 10.99$, $SD = 0.44$, female $n = 12$), 40 younger adults (aged 20–26 years, $M = 23.07$, $SD = 1.38$, female $n = 20$), and 39 older adults (aged 69–76 years, $M = 71.8$, $SD = 1.53$, female $n = 20$). All participants were residents of Berlin, Germany. The older adults lived independently in the community. The children were fifth graders in academic upper secondary schools. The ethics board of the Max Planck Institute for Human Development, Berlin, Germany, approved the study. Participants gave written informed consent according to institutional guidelines.

All participants were assessed on tests of crystallized intelligence (spot-a-word; cf. Lehrl, 1977) and fluid intelligence (digit symbol substitution test; cf. Wechsler, 1955) as well as on a test of attention (d2; Brickenkamp, 1994). Visual acuity was measured in Snellen decimal units at two different distances using Landolt rings (Geigy, 1977). Close vision was measured separately for the left and the right eye at a distance of 30 cm, far vision was assessed binocularly at a distance of 5 meters. All measures were taken with the best optical correction available to participants.

Performance on these background variables is summarized in Table 1. Univariate analysis of variance (ANOVA) with age group as between-subject factor indicated significant age differences on all background variables. Post hoc comparisons (Bonferroni corrected) revealed that in both the digit symbol substitution test and d2 attention test, younger adults reached the highest scores and differed from older adults, $t(77) = 8.28$, $p < .05$, $d = 1.66$, and $t(77) = 10.53$, $p < .05$, $d = 2.11$, and children, $t(72) = 9.26$, $p < .05$, $d = 2.71$, and $t(72) = 12.29$, $p < .05$, $d = 2.93$, respectively. The scores of children and older adults did not differ reliably from each other, $t(71) = 1.26$, $p > .05$ and $t(72) = 2.12$,

Table 1
Descriptive Summary of Covariate Measures

Measure	Children ($n = 34$) M (SD)	Younger adults ($n = 40$) M (SD)	Older adults ($n = 39$) M (SD)
Age	10.99 (.44)	23.07 (1.38)	71.80 (1.53)
Digit symbol	47.70 (6.75)	70.83 (9.81)	50.87 (13.92)
Vocabulary	15.41 (3.21)	24.70 (3.1)	28.49 (2.68)
Close vision	0.92 (0.17)	0.91 (0.13)	0.46 (0.19)
Far vision	1.80 (0.41)	1.60 (0.44)	0.84 (0.23)
d2	329.50 (41.01)	516.00 (77.82)	361.82 (67.67)

$p > .05$, respectively. With regard to the spot-a-word test, older adults reached the highest scores, followed by younger adults, and then children. Contrasts showed that differences between all age groups were significant (all $t > 5.61$ and all $p < .05$). With regard to measures of vision acuity, the effects of age for both close and far vision, $F(2, 110) = 102.664$, $p < .05$, and $F(2, 110) = 68.775$, $p < .05$, were driven by the older adults that had lower close and far vision accuracy than children, $t(71) = 12.16$, $p < .05$, $d = 2.58$, and $t(71) = 10.95$, $p < .05$, $d = 2.93$, and younger adults, $t(77) = 12.53$, $p < .05$, $d = 2.86$, and $t(77) = 8.98$, $p < .05$, $d = 2.12$, whereas the latter two groups did not differ, $t(72) = .14$, $p > .05$, and $t(72) = 2.35$, $p > .05$. These results confirm the age typicality of our samples.

Experimental paradigm. In Experiment 1, a standard version of the change detection task (Luck & Vogel, 1997) was used to test the hypotheses (see Figure 1a). Memory arrays of colored squares were presented to the participants in three blocks for 100 ms, 500 ms, and 1000 ms. The order of the blocks was pseudo-randomized and counterbalanced across participants. To allow for large inter-individual differences in performance, we presented memory arrays of 2, 4, 6, 8, or 10 items. Presentation of the different set sizes was randomized. After a retention interval of 1000 ms after the offset of the memory array, a probe array of colored squares was shown. Participants had to indicate whether all of the colors of the presented squares were identical to the memory array or whether one of the squares had changed in color. Subjects answered via button press labeled as “same” (in German: “gleich”) and “different” (“ungleich”). Response hands were counterbalanced across individuals. Note that unlike Cowan et al. (2006) we did not experimentally control for the nature of color changes, thus whether the changed item introduced a unique new color in the probe array or repeated a color of the memory array. Participants were encouraged to respond as accurately as possible and to guess if they were not sure of their response. After each response participants had to rate the confidence in their response on a three-point Likert scale ranging from unsure to sure. Each block began with 20 practice trials to allow participants to get used to the presentation time of the memory array. Afterwards, each participant completed 140 trials of varying set size per presentation time. Set size and change condition were equally distributed within each block.

Stimuli. Colored squares ($0.65^\circ \times 0.65^\circ$ of visual angle) were presented on grey background (RGB values: 200, 200, 200) within an area of $4^\circ \times 7.3^\circ$ of visual angle right and left of the fixation cross (distance to the fixation cross was 1.5°). Spatial

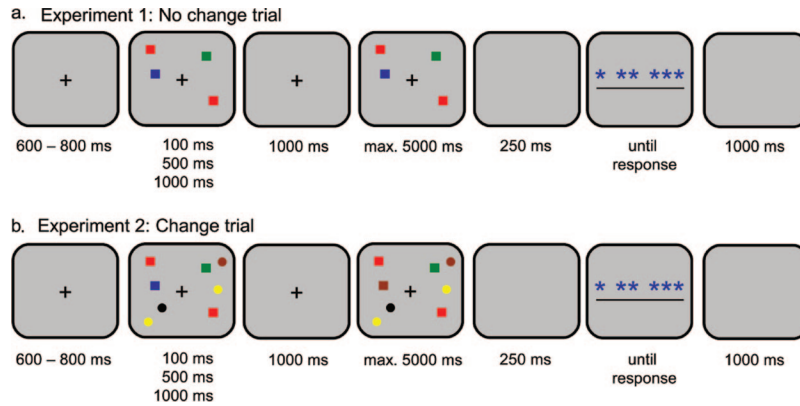


Figure 1. Experimental paradigm. Examples for (a) a change trial in Experiment 1 and (b) a no-change trial in Experiment 2.

locations of the squares were random but with a minimum distance of 2° between the centers of the squares. Participants sat at a viewing distance of 70 cm. Items were always presented in equal numbers across both visual fields. Colors were randomly selected from a set of 11 highly discriminable values [black (RGB values: 0,0,0), white (255, 255, 255), gray (126,123,126), blue (0, 0, 255), green (0, 255, 0), red (255, 0, 0), cyan (0, 255, 255), violet (255, 0, 255), brown (153, 102, 51), orange (255, 112, 1), yellow (255, 255, 0)]. The same color was not repeated more than twice per array. Because pilot testing indicated that some color changes were especially difficult to detect for older adults, we excluded changes from black to blue or grey, from blue to black or grey, from red to orange, brown, or magenta, from magenta to red, from brown to red or orange, from orange to red or brown, and from grey to black or blue.

Data analysis. In line with the literature, we first calculated individual memory capacity for each presentation time according to Cowan (2001) as $k = (\text{hit rate} - \text{false alarm rate}) \times \text{set size}$. Generally, k is assumed to increase with increasing set size and to reach an asymptote at the individual maximum performance level. In line with recent reports (Cowan et al., 2010; Cusack, Lehmann, Veldsman, & Mitchell, 2009), we observed that performance for set sizes above the respective individual capacity is not as stable as often assumed and that performance for the same set size was difficult to compare between age groups. Therefore, we decided to fit the data on the individual level using a procedure recently suggested by Rouder and colleagues (2008). This capacity estimate is closely related to Cowan's k but encompasses two more parameters to describe the distribution of hit rates and false alarm rates at the individual level based on the performance in all load conditions. WM capacity is estimated with the k score. It is computed according to Cowan's formula based on the modeled hit and false alarm rates and indicates how many items a subject is able to maintain. The maximum possible k score in our study was 10, given by the largest tested set size. The second parameter a reflects trial-to-trial fluctuation in attention and accounts for imperfect performance in set sizes below the capacity limit. The third parameter, g , is a guessing parameter, indicating a general response bias. The guessing parameter reflects the tendency of a given participant to respond with a "change" or "no change" response in a situation of uncertainty, that is, when the sensory evidence does

not support one or the other decision. A guessing parameter of 0.5 would indicate no preferential guessing, whereas a guessing parameter in the range from 0 to 0.5 indicates a conservative bias (i.e., a preference to guess "no change"). By contrast, a guessing parameter in the range from 0.5 to 1 indicates a liberal bias (i.e., a tendency to assume "change"). The distribution of hit rates and false alarm rates are modeled as follows:

$$h = a[d_i + (1 - d_i) \times g] + (1 - a) \times g$$

$$fa = a(1 - d_i) \times g + (1 - a) \times g$$

with d_i corresponding to the probability to remember an item given the individual capacity and the set size i . The parameters are estimated by a multinomial negative log-likelihood procedure with a standard optimization algorithm (Nelder & Mead, 1965; for further details, see Rouder et al., 2008).

Model fitting was performed in R (<http://www.r-project.org/>) using code provided by Jeffrey N. Rouder (<http://pcl.missouri.edu/apps>). Model fits were satisfactory for most participants as indicated by χ^2 fit statistics that correspond to p values greater than the 0.05 criterion [$\chi^2(7) = 14.067$] (see Table 2). However, note that model fits as indicated by the Bayesian Information Criterion (BIC) differed significantly between age groups and presentation time conditions¹ (see Table 3 for means, see also General Discussion).

Main analyses of age differences in the estimated parameters were conducted with the ProcMixed Procedure in SAS (SAS 9.1 for Windows). The ProcMixed model allows for heterogeneous variance and covariance structures across age groups and condi-

¹ Repeated measures ANOVA with TIME (3) as within-subjects effect and AGE (3) as between-subjects effect revealed significant main effects of TIME, $F(1.8, 202.1) = 12.477, p < .05$, and AGE, $F(2, 110) = 31.581, p < .05$, as well as a reliable interaction of TIME and AGE, $F(3.7, 202.1) = 3.266, p < .05$, (df Greenhouse-Geisser-corrected). Pairwise comparisons showed that children's and older adults' model fits were significantly worse than younger adults' model fits, but they did not differ from each other. The main TIME effect was driven by an improvement in model fit with longer presentation time. The interaction reflected an improvement in model fit for the older age group with longer presentation time that was larger than in younger adults and children.

Table 2
Percent of Participants With Sufficient Model Fit per Age Group and Presentation Time Condition

Presentation time	Children (<i>n</i> = 32) %	Younger adults (<i>n</i> = 40) %	Older adults (<i>n</i> = 39) %
100 ms	82.4	87.5	74.4
500 ms	94.1	90.0	82.1
1000 ms	88.2	90.0	87.2

tions in a repeated measures design. To constrain the data as little as possible, we fitted an unstructured covariance matrix to the data (for similar approaches in lifespan studies, see Shing et al., 2008; Werkle-Bergner, Shing, Müller, Li, & Lindenberger, 2009). We analyzed the estimated *k* score, the attention parameter *a*, and the guessing parameter *g* as separate multilevel models with age group as group effect and presentation time as within-subjects effect. The alpha level was set to $p = .05$. Effect sizes are indicated by the intraclass correlation coefficient ρ_I or Cohen's *d*.

Results

The mixed model based on individual *k* estimates yielded reliable main effects of age group, $F(2, 82.8) = 64.03, p < .05, \rho_I = .78$, and presentation time, $F(2, 87.1) = 19.96, p < .05, \rho_I = .56$. Older adults showed the lowest *k* estimates ($M = 2.7, SE = 0.06$), followed by children ($M = 3.39, SE = 0.07$) and then younger adults ($M = 4.14, SE = 0.10$). Planned contrasts revealed significant differences between children and older adults, $t(62.4) = 5.73, p < .05, d = 1.36$, and between younger adults and children, $t(71.9) = 5.17, p < .05, d = 1.19$. It follows that the difference between younger adults and older adults was also significant, $t(60.4) = 12.92, p < .05, d = 2.48$. Furthermore, contrasts between the different presentation times revealed a reliable increase in performance with increasing presentation time from 100 ms to 500 ms, $t(105) = 5.37, p < .05, d = 0.54$, but no further increase with even longer presentation times, $t(75) = 1.10, p > .32$. The interaction between age group and presentation time was not reliable, $F(4, 70.9) = 0.46, p > .76$.

The mixed model based on the attention parameter *a* only yielded a reliable main effect of age group, $F(2, 79.3) = 9.65, p < .05, \rho_I = .44$. Contrasts indicated that children had reliably lower estimates in the attention parameter than older adults, $t(66.6) = 2.24, p < .05, d = 0.53$, and younger adults, $t(43.3) = 4.24, p < .05, d = 1.05$, whereas the two adult groups did not differ, $t(54.6) = 1.80, p > .07$.

The mixed model based on the guessing parameter *g* yielded reliable main effects of age group, $F(2, 73) = 5.07, p < .05, \rho_I = .35$, presentation time, $F(2, 102) = 5.11, p < .05, \rho_I = .30$, as well as a significant interaction between age group and time condition, $F(4, 88.4) = 5.20, p < .05, \rho_I = .44$. Although all age groups adopted a conservative bias, guessing that no change had occurred rather than guessing a change, younger adults showed a stronger bias in this direction than children, $t(50.1) = 2.90, p < .05, d = 0.71$, and older adults did, $t(58.9) = 1.92, p = .0599, d = 0.43$ (marginally significant). In contrast, children and older adults adopted a similar guessing strategy, $t(70) = 0.86, p > .39$. With prolonged presentation times, participants showed a stronger ten-

dency to guess no change than change. Contrasts showed that this effect was reliable for the difference between presentation times of 100 ms and 500 ms, $t(107) = 3.02, p < .05, d = 0.20$, but not for longer presentation times, $t(97.5) = 0.58, p > .56$. The change in guessing bias from 100 ms to 500 ms presentation time was driven by the children, $t(33) = 2.09, p < .05, d = 0.23$, and the older age group, $t(38) = 2.87, p < .05, d = 0.28$. Capacity estimates, attention parameters, and guessing parameters for the three age groups under different presentation time conditions are illustrated in Figure 2. Estimated means and standard errors are reported in Table 4.

Experiment 1: Summary of results. With regard to capacity estimates, we observed the expected age pattern: Older adults showed lower performance than children, and children showed lower performance than younger adults. In all age groups, longer presentation times yielded better performance. Contrary to our hypothesis, younger adults did not show larger improvements with longer presentation times than children and older adults.

Experiment 2: Direct Assessment of Age Differences in the Strategic Component

In Experiment 2, we used the same experimental paradigm but added distracters to memory and test arrays to explicitly test for the relation between presentation time and reliance on control processes. We assumed that simultaneously presented distracters increase the need for control of the visual input and would impair performance in all age groups, especially under the condition of short presentation times, when control over stimulus perception is less efficient or complete. However, we assumed that the processing of distracters can be suppressed and that distracter effects should decrease with increasing presentation time in all age groups, reflecting the increasing influence of cognitive control operations. Because cognitive control is less mature in children and declining in older adults, we predicted that both age groups would not be able to fully inhibit irrelevant information, even with longer presentation times.

Method

Participants. For the analysis of Experiment 2, we only included a subsample of the participants of Experiment 1. Focusing on individual differences in the ability to control WM contents, we aimed to compare performance in Experiment 1 to the performance in Experiment 2. The upper limit of the *k* score is given by the largest set size tested in the experiment. Because we tested a large range of set sizes with up to 10 items in Experiment 1, we did

Table 3
Mean BIC (and Standard Errors) per Age Group and Presentation Time Condition

Presentation time	Children (<i>n</i> = 34) <i>M</i> (<i>SE</i>)	Younger adults (<i>n</i> = 40) <i>M</i> (<i>SE</i>)	Older adults (<i>n</i> = 39) <i>M</i> (<i>SE</i>)
100 ms	123.43 (4.15)	99.48 (2.85)	133.84 (3.62)
500 ms	118.76 (3.52)	92.61 (2.80)	123.58 (3.55)
1000 ms	119.58 (3.29)	95.49 (3.12)	116.51 (3.36)

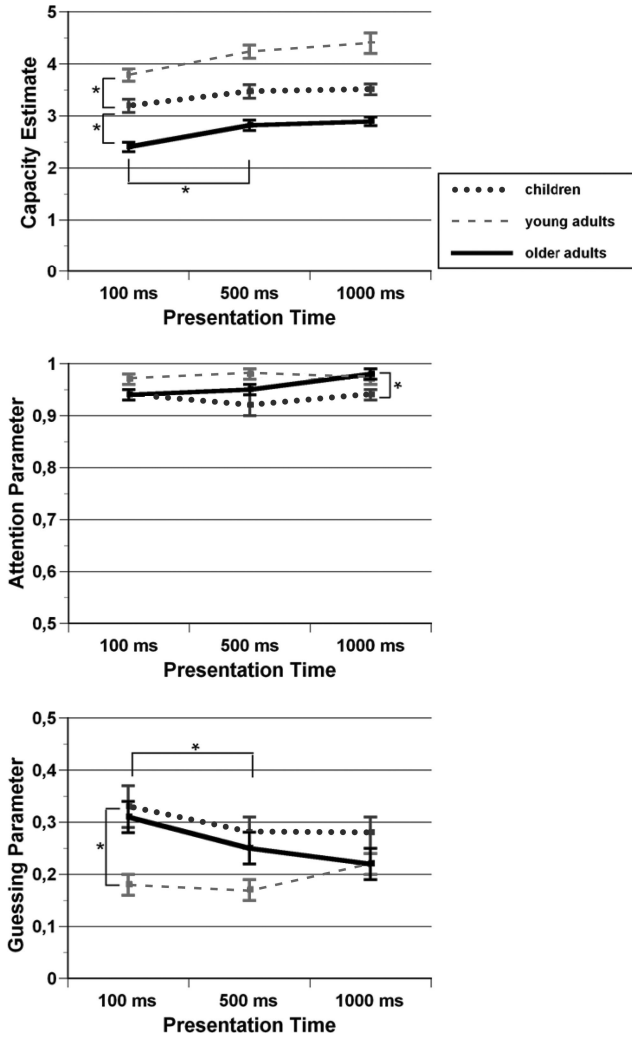


Figure 2. Estimated means and standard errors of the capacity estimate, attention parameter, and guessing parameter in Experiment 1.

not observe ceiling effects at the individual level. Because of experimental constraints, we could only test set sizes up to five targets in Experiment 2. Thus, some participants were artificially constrained in their performance in Experiment 2. For example, a participant who reached a k estimate of 6 in Experiment 1 could maximally reach a k estimate of 5 in Experiment 2. To avoid ceiling effects and ensure reliable measurements in the distracter task, we excluded all participants with capacity estimates higher than 4.5 in any condition of Experiment 1. The final sample of Experiment 2 thus included 30 children, 16 younger adults, and 39 older adults. Note that therefore all age comparisons involving younger adults must be interpreted as lower-bound estimates of the performance advantage observed in younger adults as compared to older adults and children.

Experimental paradigm and stimuli. The experimental paradigm did not differ from the paradigm used in Experiment 1, except with regard to memory and test array (see Figure 1b). In Experiment 2, participants saw displays of colored squares and circles and were instructed to remember only the colors of the

squares. They were explicitly told that circles were irrelevant for the task and that changes would not occur for these distracters. Target set size varied from one to five, including an always equal number of distracters. This led to a total of presented items on the memory and test arrays varying from two to ten. The colors of circles and squares were randomly selected from the same set of colors used in Experiment 1. No color was repeated more than twice. The same restrictions on color changes were applied as in Experiment 1, and the order of presentation time blocks for each participant was the same as in Experiment 1.

Analysis. We estimated individual performance with the same procedure as described for Experiment 1. Overall analysis was performed by mixed models in SAS as in Experiment 1, additionally including condition (nondistracters versus distracters) as within-subject factor. Estimated means and standard errors are reported in Table 5. To highlight the main results of the experiment, we expressed the difference between performance in the distracter and nondistracter task in relative terms to the nondistracter condition (see Figure 3).

Results

The analysis based on the k estimates yielded significant main effects of age group, $F(2,50.3) = 34.22, p < .05, \rho_I = .76$, presentation time, $F(2, 40) = 41.16, p < .05, \rho_I = .82$, and condition, $F(1,52.9) = 96.58, p < .05, \rho_I = .80$. Furthermore, we observed significant interactions between age group and condition, $F(2,52.2) = 3.27, p < .05, \rho_I = .33$ as well as between condition and presentation time, $F(2,54.7) = 4.18, p < .05, \rho_I = .36$. As in Experiment 1, k estimates were lower for older adults compared to children, $t(59.5) = 5.09, p < .05, d = 1.25$, and children had lower estimates than younger adults, $t(32.2) = 3.31, p < .05, d = 1.01$. The main effect of presentation time was attributable to a general increase in k estimates with longer presentation time, both from 100 ms to 500 ms presentation time, $t(35) = 6.41, p < .05, d = 0.64$, as well as from 500 ms to 1000 ms presentation time, $t(40.2) = 2.06, p < .05, d = 0.22$. The k estimates were significantly lower in the distracter version of the task than in the nondistracter version in all age groups. However, children and older adults were significantly more impaired by the distracters than younger adults, $t(37.8) = 2.29, p < .05, d = 0.33$, and

Table 4
Estimates of Capacity, Attention, and Guessing Parameters (Experiment 1)

Parameter	Time	Children ($n = 34$) M (SE)	Younger adults ($n = 40$) M (mditSE)	Older adults ($n = 39$) M (SE)
Capacity	100 ms	3.19 (0.13)	3.78 (0.12)	2.40 (0.09)
	500 ms	3.47 (0.13)	4.24 (0.13)	2.82 (0.10)
	1000 ms	3.51 (0.10)	4.40 (0.20)	2.89 (0.08)
Attention	100 ms	0.94 (0.01)	0.97 (0.01)	0.94 (0.01)
	500 ms	0.92 (0.02)	0.98 (0.01)	0.95 (0.01)
	1000 ms	0.94 (0.01)	0.97 (0.01)	0.98 (0.01)
Guessing	100 ms	0.33 (0.04)	0.18 (0.02)	0.30 (0.03)
	500 ms	0.28 (0.03)	0.17 (0.02)	0.25 (0.03)
	1000 ms	0.28 (0.03)	0.22 (0.02)	0.22 (0.03)

Table 5
Estimates of Capacity, Attention, and Guessing Parameters (Experiment 2)

Parameter	Time	Children ($n = 30$)		Younger adults ($n = 16$)		Older adults ($n = 39$)	
		No distracters $M (SE)$	With distracters $M (SE)$	No distracters $M (SE)$	With distracters $M (SE)$	No distracters $M (SE)$	With distracters $M (SE)$
Capacity	100 ms	3.06 (0.12)	2.30 (0.14)	3.36 (0.12)	2.91 (0.19)	2.40 (.09)	1.66 (0.09)
	500 ms	3.32 (0.11)	2.71 (0.13)	3.66 (0.12)	3.16 (0.18)	2.82 (.10)	2.19 (0.08)
	1000 ms	3.40 (0.09)	2.76 (0.13)	3.60 (0.08)	3.55 (0.18)	2.89 (.08)	2.39 (0.11)
Attention	100 ms	0.93 (0.01)	0.92 (0.01)	0.97 (0.01)	0.95 (0.02)	0.94 (0.01)	0.97 (0.01)
	500 ms	0.92 (0.02)	0.90 (0.02)	0.98 (0.01)	0.95 (0.01)	0.95 (0.01)	0.95 (0.01)
	1000 ms	0.94 (0.01)	0.93 (0.01)	0.98 (0.01)	0.95 (0.02)	0.98 (0.01)	0.97 (0.01)
Guessing	100 ms	0.29 (0.03)	0.27 (0.03)	0.14 (0.03)	0.14 (0.03)	0.30 (0.03)	0.29 (0.04)
	500 ms	0.26 (0.04)	0.29 (0.04)	0.18 (0.03)	0.22 (0.03)	0.25 (0.03)	0.20 (0.03)
	1000 ms	0.25 (0.03)	0.26 (0.04)	0.20 (0.03)	0.18 (0.03)	0.22 (0.03)	0.20 (0.03)

$t(27.4) = 2.31, p < .05, d = 0.32$, respectively, but did not differ from each other, $t(52.7) = 0.36, p > .05$.

To follow up on this finding, we computed the relative difference between the k estimates in both conditions with regard to the k estimate in the distracter-free version of the task. The relative difference showed a main effect of age, $F(2,52.2) = 5.49, p < .05, \rho_I = .42$, confirming that the result above was not attributable to generally lower performance levels in children and older adults, but to larger impairments in children and older adults as compared with younger adults, $t(38.1) = 2.30, p < .05, d = 0.66$, and $t(32.1) = 3.28, p < .05, d = 0.92$, respectively. Again, both groups did not differ from each other, $t(58.6) = 0.75, p > .05$. Furthermore, the relative difference might be interpreted in terms of allocation of WM processes to distracters: whereas younger adults allocated only 10% of their processing capacity to distracters, children and older adults allocated about 20%. Relative distracter effects decreased with longer presentation time in all age groups, $F(2,58.7) = 6.75, p < .05, \rho_I = .43$. This effect was attributable to a general linear trend, as revealed by a significant difference between 100 ms and 1000 ms presentation times, $t(64.1) = 3.67, p < .05, d = 0.46$, and trends for the difference between 100 ms and 500 ms and between 500 ms and 1000 ms presentation times, $t(63.6) = 1.67, p < .1, d = 0.22$ and $t(49.7) = 1.81, p < .1, d = 0.25$. Expressed in relative differences, distracters captured about

22% of WM capacity with the shortest presentation time, but only 12% with the longest presentation time. Although this decrease in the distracter effect was found in all age groups and did not show any interaction with age, $F < 0.84, p > .5$, younger adults showed no distracter effects at all with long presentation times (relative difference 0%, see Figure 3).

The guessing parameter did not show any effects involving the condition factor, all $F < 1.34$, all $p > .27$.

The attention parameter showed a main effect of age group, $F(2, 53) = 8.52, p < .05, \rho_I = .49$, indicating that children again revealed lower estimates than younger adults, $t(43.6) = 4.0, p < .05, d = 1.01$, and older adults, $t(50.9) = 3.56, p < .05, d = 0.90$, whereas the younger and older adults did not differ, $t(42.3) = 0.60, p > .05$. Furthermore, we observed a main effect of condition, $F(1, 59) = 5.61, p < .05, \rho_I = .29$, revealing that attention estimates were generally lower in the distracter condition. There was also a main effect of presentation time, $F(2, 65.7) = 4.5, p < .05, \rho_I = .35$, that was driven by an increase in the attention estimate from 500 ms to 1000 ms presentation time, $t(62.2) = 2.34, p < .05, d = 0.32$. Estimates of the 100 ms and 500 ms presentation time conditions did not differ, $t(63.9) = 0.26, p > .05$. Additionally, the interaction of condition and age group, $F(2,50.8) = 3.43, p < .05, \rho_I = .34$, reached significance. This effect was driven by significant lower attention estimates in the group of younger adults for the distracter condition compared to the nondistracter condition, $t(15) = 2.96, p > .05, d = 0.98$. For children and older adults, the attention estimates did not differ between the two conditions, $t(29) = 1.04, p > .05$, and $t(38) = -0.31, p > .05$, respectively.

Experiment 2: Summary of results. The results of this experiment indicate that the presentation of distracters impaired performance in comparison with the distracter-free task version in all three age groups. The effect of distracters was reduced with increasing presentation time in all age groups but remained reliable in children and older adults.

General Discussion

Summary of Main Findings

Results of Experiment 1 revealed that visual WM performance as measured with the k score was reliably lower in children and older adults than in younger adults, with older adults showing the

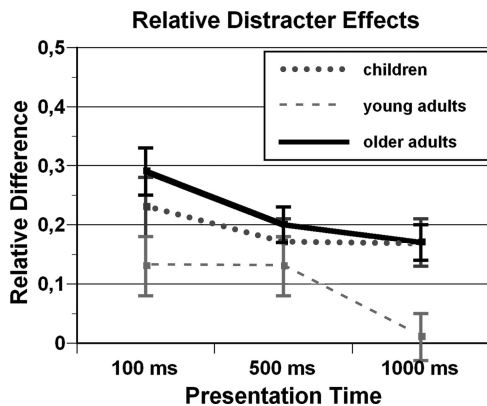


Figure 3. Effect of distracters on performance relative to performance without distracters (Experiment 2).

lowest performance of all three age groups. This observation is in line with the inverted U-shaped function of memory performance across the lifespan (Cowan et al., 2006; Gathercole, 1999; Park & Payer, 2006). As a novel finding, we could show that in all age groups, longer presentation time yielded better performance. Contrary to our hypothesis, younger adults did not show larger improvements with longer presentation time than children and older adults. The performance improvement with longer presentation times is at odds with the previously reported independence of encoding duration and WM capacity (e.g., Vogel, Woodman, & Luck, 2001). In our view, the two-component framework introduced by Shing et al. (2008, 2010) provides a plausible explanation for these findings. In line with this framework, we suggest that under conditions of very short presentation times, WM performance is mainly driven by the efficiency of fast low-level binding mechanisms. In contrast, with longer presentation times, WM performance may improve because time-consuming cognitive control mechanisms can be implemented for goal-directed behavior (Shing et al., 2008, 2010; Werkle-Bergner et al., 2006).

In agreement with this interpretation, Experiment 2 revealed that the presentation of distracters significantly impaired performance in the change detection task as compared with the distracter-free version, especially in the condition with short presentation times. We interpret this difference in performance as a reflection of the need to gain control over visual input to perform successfully (Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Sauseng et al., 2009; Vogel, McCollough, & Machizawa, 2005). At the same time, the influence of distracters on performance was less detrimental with increasing presentation time, regardless of age. In line with Experiment 1, we suggest that this reduction in impairment reflects increasing efficiency of control over the visual input with prolonged encoding duration. This finding is also in line with the time-based resource sharing hypothesis of WM (Barrouillet & Camos, 2007), suggesting that time plays a major role in determining the impact of control processes on performance.

Furthermore, younger adults did not show distracter effects with very long presentation times, whereas children and older adults were still impaired by the presence of distracters. This finding suggests that the selection of relevant items for maintenance and/or the exclusion of irrelevant items is achieved almost perfectly in younger adults, given enough time. Thus, in line with the two-component framework (Shing et al., 2008, 2010), we suggest that the remaining age differences in distracter effects with longer presentation times reflect lower levels of strategic functioning in children and older adults.

A Process-Oriented View on Capacity Limits

It is an open question whether WM capacity is fixed or variable within individuals (Awh, Barton, & Vogel, 2007; Bays & Husain, 2008; Rouder et al., 2008; Zhang & Luck, 2008). The model we applied to our data assumes that WM does not vary as a function of different set sizes (Cowan et al., 2005; Rouder et al., 2008). However, the present data indicate that the maximum performance for a given person was subject to intraindividual variation depending on experimental condition (i.e., whether the presentation rate was fast or slow).

Several previous studies have established the view that WM capacity is independent of encoding duration (Gold, Wilk, McMa-

hon, Buchanan, & Luck, 2003; Sperling, 1960; Vogel, Woodman, & Luck, 2001), but others have reported correlations between stimulus complexity as measured by visual search rate and WM capacity (Alvarez & Cavanagh, 2004; Eng, Chen, & Jiang, 2005). Interestingly, although the independence of WM capacity and presentation time is commonly cited, several studies relied on longer presentation times when investigating (a) more complex stimuli (Alvarez & Cavanagh, 2008; Curby & Gauthier, 2007) or (b) samples other than healthy younger adults (Cowan et al., 2006; Gold et al., 2006; Riggs et al., 2006) to rule out differences in WM capacity resulting from insufficient encoding. Sufficient encoding time certainly contributes to successful WM maintenance (e.g., Eng, Chen, & Jiang, 2005), and, in this sense, may not be extraneous to the construct under study. For example, the relation between encoding time and WM is treated explicitly within the theory of visual attention (Bundesen, 1990; Bundesen, Habekost, & Kyllingsbaek, 2005; see also Shibuya & Bundesen, 1988). In this theory, visual processing speed and visual span are considered as two separate, capacity-limiting parameters. When encoding time is not sufficient, the limiting factor is visual processing speed. Only when speed is not a constraining factor can visual span be determined properly. Although mathematically independent, both factors tend to co-vary empirically in healthy subjects. Also, lesions in parietal cortex often lead to reductions in both visual processing speed and visual span (Habekost & Starrfelt, 2009).

In addition, there is accumulating evidence from neuroimaging studies that the filtering of information may be achieved by prefrontal top-down control (McNab & Klingberg, 2008). For example, Gazzaley et al. (2007) showed through functional connectivity analysis that coupling between PFC and visual association cortex correlates with selection and suppression effects in a WM task. Furthermore, differential abilities to focus on relevant information only and to inhibit irrelevant information has recently been suggested to explain inter-individual (Sauseng et al., 2009; Vogel, McCollough, & Machizawa, 2005) as well as age differences (Gazzaley et al., 2008) in WM capacity.

From a process-oriented view of WM, capacity measures are a complex function of various processes that have to be accomplished successfully. Each component process may be sensitive to the experimental conditions at hand and may therefore increase or decrease the likelihood for reporting a change, or the absence thereof. Therefore, the reported intra-individual variation in estimated k scores may not only reflect differences in a storage space for discrete items (Bays & Husain, 2008; Zimmer, 2008). Instead, we attribute these differences to more efficient encoding and selection processes that occur before maintenance proper (e.g., Shing et al., 2010).

Lifespan Age-Differences in Visual WM: The Interplay of Strategic and Associative Components

In the present study, individuals of all age groups profited from longer encoding time to increase their performance, suggesting that individual perceptual encoding speed does indeed generally contribute to WM performance (Alvarez & Cavanagh, 2004; Eng, Chen, & Jiang, 2005; Vogel, Woodman, & Luck, 2006). At the same time, the speed of information uptake does not fully explain the observed age differences in WM performance, because differences between age groups persisted at long presentation times. We

interpret this finding in terms of age differences in the interplay between low-level binding and strategic control processes during encoding, selection, and consolidation.

Prominent theories of child cognitive development (Diamond, 2002) and aging (Hasher & Zacks, 1988) postulate an age-related impairment in the inhibition of irrelevant information (Dempster, 1992; Fuster, 2002). Brain-imaging evidence is generally consistent with these claims. For example, a recent study by Olesen, Macoveanu, Tegner, and Klingberg (2007) investigated neural correlates of distraction in children and younger adults. The stronger activity in frontal and parietal cortices in younger adults compared to children was interpreted as more stable representations. Larger behavioral distraction effects in children were paralleled by stronger superior frontal sulcus activity.

In a study of cognitive aging, Gazzaley et al. (2005, 2008) recently observed that older adults were more impaired by distracters than younger adults, especially when WM load was high. Related electrophysiological evidence (Gazzaley et al., 2008) elucidated characteristics of the timing of the suppression deficit in older adults. In this study, older participants were characterized by reduced suppression in early time windows. However, later suppression processes were not impaired. Gazzaley et al. (2008) argue that cognitive aging can be characterized by a combination of deficits in perceptual speed and suppression, such that inhibition processes are not totally abolished, but delayed. Our behavioral results are in line with this finding, suggesting that distracters are less efficiently suppressed when the demand on controlled processing is already high, that is, under conditions of high WM load or short presentation time. Older adults and children may therefore profit from increased processing time to stabilize relevant representations and to filter out irrelevant representations. From this perspective, the persisting distracter effects with longer presentation times would reflect the lower functionality of strategic processes in children and older adults, possibly related to the maturation and senescence of related brain structures (Raz & Rodrigue, 2006; Sowell et al., 2003; Toga, Thompson, & Sowell, 2006).

Age Differences in Attention and Guessing Bias

Besides general age differences in capacity-related estimates of WM, we also observed age-differential effects in attention and guessing parameters. Children attained lower scores in the attention parameter than both younger and older adults, suggesting problems in maintaining attention throughout a whole block of testing. According to Rouder and colleagues (2008), the attention parameter reflects trial-by-trial variation in attention, as it captures imperfect performance in conditions when the WM load is lower than the individual capacity limit. Along similar lines, Kyllingsbaek and Bundesen (2009) recently suggested a new unforced version of the change detection paradigm in which participants were encouraged to respond with a "Don't know" button whenever they were not sure of their response. The authors showed that accounting for imperfect performance attributable to attentional lapses reduces the variance of the capacity estimate.

Reduced sustained attention in children compared with younger adults is a common finding in developmental psychology (Betts, McKay, Maruff, & Anderson, 2006; Klenberg, Korkman, & Lahti-Nuutila, 2001). With regard to brain maturation, the ability to

maintain attention over longer periods is closely related to prefrontal cortex functionality (Shallice, Stuss, Alexander, Picton, & Derkzen, 2008; Stuss, Shallice, Alexander, & Picton, 1995). Thus, the observed age specificity of the attention deficit is consistent with the literature and possibly relates to less mature control processes in children. Furthermore, this finding also underlines the necessity to account for imperfect performance in models of WM, even at load levels below the individual capacity limit (Kyllingsbaek & Bundesen, 2009; Rouder et al., 2008).

With regard to the guessing parameter, all age groups showed the tendency to guess that no change had occurred rather than assuming a change, that is, a conservative response bias. However, this bias was more pronounced in younger adults compared with the other age groups. With longer presentation times, children and older adults also increasingly adopted a strategy to guess rather conservatively. Within the model applied here, the guessing bias indicates whether participants will guess "change" or "no change" whenever they are unsure, no matter how often this happens.

We did not a priori expect any differences in guessing between groups and conditions. However, post hoc we considered one possible explanation for the observed differences that is not related to performance per se but rather to the subjective judgment of one's own performance: It is conceivable that people are generally more certain about change responses. Previous studies also report that participants are more likely to guess no-change responses than change responses, thus errors in the change detection tasks are mainly driven by misses of changes than by false alarms (Simmering-Best, 2008). Possibly, whenever a specific item is a consolidated member of the memory set, a change can be detected with certainty. When participants have gained the impression that they master the task, they will be more likely to guess "no change," based on their experience of being able to detect true changes, even in cases when no change has actually occurred but they could not fully retain the memory set.

If this assumption holds, then participants should be more confident when rating "subjective change trials" (i.e., all trials in which a "change" response had been given, independent of its correctness, thus hits and false alarms) than when rating "subjective no-change trials" (thus misses and correct rejections). Moreover, confidence ratings should be higher with longer presentation times. The present data revealed the expected pattern² (see also Table 6).

Limitations of the Study

The interpretation of the present analyses is constrained by model fit. We fitted our data at the individual level. Overall, model fit was reliably better in younger adults than in children and older adults and improved with longer presentation times. Furthermore, model fits in Experiment 2 were generally better than in Experiment 1. Differences in model fit between age groups are an inherent problem of lifespan research (cf. Kliegl & Lindenberger, 1993) and point to the larger issue of finding an appropriate metric for capturing developmental change (Kagan, 1980).

² Repeated measures ANOVA [perceived CHANGE (2), TIME (3), AGE (3)] revealed reliable effects of CHANGE, $F(1, 100) = 32.70$, $p < .05$, and TIME, $F(2, 99) = 23.138$, $p < .05$. No interactions were observed (all $F < 1.36$, all $p > .258$).

Table 6
Means and Standard Errors of Confidence Ratings for Subjective No-Change and Change Trials

Time	Children (<i>n</i> = 31)		Younger adults (<i>n</i> = 39)		Older adults (<i>n</i> = 33)	
	No-change <i>M</i> (<i>SE</i>)	Change <i>M</i> (<i>SE</i>)	No-change <i>M</i> (<i>SE</i>)	Change <i>M</i> (<i>SE</i>)	No-change <i>M</i> (<i>SE</i>)	Change <i>M</i> (<i>SE</i>)
100 ms	2.35 (.06)	2.43 (.05)	2.42 (.05)	2.46 (.04)	2.36 (.06)	2.48 (.05)
500 ms	2.43 (.06)	2.50 (.05)	2.50 (.04)	2.56 (.03)	2.45 (.05)	2.58 (.04)
1000 ms	2.49 (.07)	2.56 (.06)	2.52 (.05)	2.58 (.04)	2.56 (.05)	2.61 (.04)

Note. We excluded 10 participants from the analysis of the confidence ratings because they did not fully use the rating scale (less than three low and medium confidence ratings).

We suggest that the present model-based approach to estimates of WM performance has several advantages: First, it is based on the widely used Cowan formula to estimate WM capacity (Cowan, 2001). Second, the data were modeled at the level of individuals instead of group averages (Nesselrode, Gerstorf, Hardy, & Ram, 2007). Third, the model does not assume an ideal observer and allows for imperfect performance for set sizes within the capacity limit. This imperfection is modeled by the inclusion of an attention and a guessing parameter that are usually set to chance levels in traditional analysis. Including these parameters in the model allows more realistic estimation of WM performance (Kyllingsbaek & Bundesen, 2009; Rouder et al., 2008). Nevertheless, we cannot rule out the possibility that some of the observed age group differences in fit relate to mechanisms that were not captured by the model but are relevant for the phenomenon under study.

Summary

This study explored lifespan age-differences in WM performance in a change detection task by testing groups of children, younger adults, and older adults. We found that longer presentation times were associated with better performance in all age groups. Children outperformed older adults, and distracter effects were larger in children and older adults than in younger adults.

We interpret these results within a two-component framework (cf. Shing et al., 2008, 2010). According to this framework, children's WM performance is primarily characterized by immaturity of the strategic control component, reflected as a lower ability to gain control over visual input than younger adults. However, the binding component is assumed to be relatively mature in children. In contrast, older adults' WM performance reflects both lower levels of functioning in the low-level binding and the strategic control component. The finding that children showed generally higher performance than older adults points to age differences in the binding component. Improved performance with increasing presentation time was interpreted as a signature of the increasing implementation of control mechanisms. Age differences in the control component are reflected in remaining age differences with longer presentation time and larger distracter effects in children and older adults as compared to younger adults. Future investigations need to further scrutinize the contributions of encoding, maintenance, and comparison processes to age differences in WM.

Furthermore, age changes in the neural implementation of the binding and control components of WM need to be delineated.

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