Object-based encoding in visual working memory: A life span study

Qiong Zhang
Department of Psychology and Behavioral Sciences, Zhejiang University, Hang Zhou, China

Mowei Shen
Department of Psychology and Behavioral Sciences, Zhejiang University, Hang Zhou, China

Ning Tang
Department of Psychology and Behavioral Sciences, Zhejiang University, Hang Zhou, China

Guohua Zhao
Department of Neurology, Second Affiliated Hospital, College of Medicine, Zhejiang University, Hang Zhou, China

Zaifeng Gao
Department of Psychology and Behavioral Sciences, Zhejiang University, Hang Zhou, China

Recent studies on development of visual working memory (VWM) predominantly focus on VWM capacity and spatial-based information filtering in VWM. Here we explored another new aspect of VWM development: object-based encoding (OBE), which refers to the fact that even if one feature dimension is required to be selected into VWM, the other irrelevant dimensions are also extracted. We explored the OBE in children, young adults, and old adults, by probing an “irrelevant-change distracting effect” in which a change of stored irrelevant feature dramatically affects the performance of task-relevant features in a change-detection task. Participants were required to remember two or four simple colored shapes, while color was used as the relevant dimension. We found that changes to irrelevant shapes led to a significant distracting effect across the three age groups in both load conditions; however, children showed a greater degree of OBE than did young and old adults. These results suggest that OBE exists in VWM over the life span (6–67 years), yet continues to develop along with VWM.

Introduction

Studies on visual working memory (VWM), a key component of working memory, have observed that only 3–4 simple objects can be stored in VWM in samples of young adults (Baddeley, 2003; Fukuda, Awh, & Vogel, 2010; but also see Bays & Husain, 2008). However, this limited capacity has a very close relationship with several critical capabilities in humans. For instance, this small capacity of VWM positively correlates with reading ability, filtering efficiency, and intelligence (e.g., Cowan, Elliott, Scott Saults, Morey, Mattox, Hismajtullina, et al. 2005; Vogel, McCollough, & Machizawa, 2005). In the last decade, researchers have extensively investigated VWM mechanisms (e.g., Anderson, Bell, & Awh, 2012; Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Z. Gao & Bentin, 2011; Luck & Hollingworth, 2008; van den Berg, Shin, Chou, George, & Ma, 2012; Xu & Chun, 2006), including the developing traces of VWM in humans (see Astle & Scerif, 2011 for a state-of-the-art review). Since the capacity of VWM plays a very important role in a number of high-level cognitive activities, several cross-sectional studies have examined the development of VWM capacity and the underlying factors contributing to VWM’s development (e.g., Cowan et al., 2011; Perone, Simmering, & Spencer, 2011; Riggins, McTaggart, Simpson, & Freeman, 2006; Ross-Sheehy, Oakes, & Luck, 2003; Simmering, 2012; Thomason et al., 2009). These studies have shown that the development of VWM capacity exhibits an inverted-U pattern: VWM grows gradually and reaches peak capacity (3–4 simple objects) at around 7–10 years.
of age but declines as we get older. Given the importance of VWM in our daily lives, and VWM’s excellent predictive power of general cognitive abilities, we are interested in searching for the critical factors that drive VWM capacity development. Since previous VWM studies in young adults have revealed that individual differences in VWM capacity can be predicted by attentional filtering ability, i.e., filtering out task-irrelevant distractors while processing task-relevant ones (Cowan & Morey, 2006; McNab & Klingberg, 2008; Vogel et al., 2005), several researchers initiated investigations into the development of attentional filtering ability in VWM (Astle, Nobre, & Scerif, 2012; Cowan et al., 2011; Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010; Jost, Bryck, Vogel, & Mayr, 2011; Sander, Werkle-Bergner, & Lindenberger, 2011a). Following the seminal work of Vogel et al. (2005), the basic experimental settings in these studies involve presenting visual targets and a few distractors simultaneously at distinct spatial locations in order to examine the developmental trajectory of filtering ability. Results generally demonstrate that adolescents (6–12 years old) and older adults (64–92 years old) have deficits in filtering task-irrelevant information when compared to young adults.

Beyond the development of VWM capacity or related issues, VWM development should manifest in other areas as well. Indeed, recent studies have explored the development of representation precision stored in VWM; these studies have shown that precision gradually improves from 6 to 10 years of age and continues to improve into early adulthood (Burnett Heyes et al., 2012). In the current study, we explored another new aspect of VWM development: object-based encoding (OBE) in VWM. It is an important processing phenomenon which has been consistently observed in recent studies assessing young adult samples (e.g., Gao, Gao, Li, Sun, & Shen, 2011; Z. Gao, Li, Yin, & Shen, 2010; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009; Xu, 2010; Yin, Z. Gao et al., 2012; Yin, Zhou et al., 2012; Zhou et al., 2012). A typical characteristic of OBE is that even only one feature dimension is required for selection into VWM, the other task-irrelevant feature dimensions, which together with the target dimension belong to the same object, are also selected into VWM. This OBE is also a basic and important selection process at the perceptual stage of our visual system (Scholl, 2001). Therefore, OBE reflects an important aspect of visual information processing. However, to our knowledge, no study has explored the life span developmental trajectory of OBE in VWM.

In addition, assessment of OBE is complementary to the aforementioned life span studies on attentional filtering ability in VWM. It is well accepted that there are two fundamental ways to filter visual information in the outer environment: (a) targets and distracters are presented at distinct spatial locations, and distracter filtering operates in a spatial-based manner and (b) targets and distracters share one spatial location, presented as one object (e.g., red square), and distracter filtering operates in a feature-based manner. All the aforementioned developmental studies on VWM filtering deal with spatial-based filtering, whereas OBE actually taps into feature-based filtering, the development of which has yet to be explored. While findings related to the development of filtering ability in VWM have been promising, researchers have recently come to realize that spatial-based filtering alone cannot explain the full developmental trajectory of VWM capacity (e.g., Astle & Scerif, 2011; Cowan et al., 2011). Therefore, feature-based filtering may also contribute to VWM capacity development.

The current study addressed the life span developmental trajectory of OBE in VWM by taking advantage of an “irrelevant-change distracting effect” in VWM, which is commonly used to probe OBE in VWM. This distracting effect is usually demonstrated in a change-detection task, wherein the type of change of irrelevant features (no irrelevant-change vs. irrelevant-change) is manipulated. For example, participants are presented with a few multiple-featured objects (e.g., two colored shapes), and they are required to remember one feature dimension (e.g., color) while ignoring the other one (informing participants explicitly that the other feature—in this case, shape—must be ignored in order to avoid diminished performance). After an interval period (blank screen), a test array is presented, and participants judge whether a change in the target dimension occurred (50% of trials) by comparing the test array to the memory array. Critically, the task-irrelevant dimension also changes in 50% of the trials. A significant “irrelevant-change distracting effect” is consistently observed by showing that the change of task-irrelevant feature(s) dramatically influences detecting changes to the target dimension and elicits a more negative ERP component anterior N2 (Yin et al., 2011; Yin et al., 2012). However, when elements, which form the multiple-featured objects (e.g., colored shapes), are presented at distinct locations (e.g., two colors and two shapes are displayed at four locations), changes in task-irrelevant feature(s) do not influence the change detection of target dimensions or elicit an anterior N2 (Z. Gao, unpublished data). These results suggest that irrelevant simple features are automatically encoded into VWM in an object-based manner. Moreover, automatic OBE is fairly robust. Irrelevant feature encoding has been revealed in both low (e.g., two objects) and high (e.g., six objects) memory load conditions (Xu, 2010; Yin, Zhou et al., 2012) and occurs even when irrelevant changes happen with a probability of 16% while remembering eight objects...
(Shen, Tang, Wu, Shui, & Z. Gao, 2013). Moreover, this phenomenon has been consistently demonstrated using simple shapes, colors, orientations, and sizes (T. Gao et al., 2011; Z. Gao et al., 2010; Woodman, Vogel, & Luck, 2012).

However, all previous studies assessing OBE in VWM recruited young adult participants. To our knowledge, no study has investigated OBE in children and old adults, which impedes our understanding of the developmental trajectory of OBE in VWM. Therefore, the current study explored the life span developmental trajectory of OBE by assessing the “irrelevant-change distracting effect” in groups of children, young adults, and old adults. Considering that developmental differences become apparent predominately within resource-demanding situations (e.g., Cowan et al., 2011; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Gazzaley, Cooney, Rissman, & D’Esposito, 2005), such as high VWM load, we investigated the distracting effect in both low and high memory load conditions.

Assessment of the “irrelevant-change distracting effect” allowed us to examine the following three distinct hypotheses. First, the development of OBE is a critical aspect of VWM development and exhibits an inverted-U developmental pattern. OBE is maximized in young adulthood but not present in childhood or old age. This prediction, to some extent, is reasonable given that for the same number of to-be-memorized objects, it is actually a higher mental load to children and older adults compared to young adults. Consequently, children and old adults may select only task-relevant features into a limited storage buffer (for a discussion see Cowan et al., 2011; Xu, 2010). In contrast to our first prediction, but consistent with previous findings on spatial-based information selection in VWM (e.g., Astle et al., 2012; Cowan et al., 2011; Jost et al., 2011), the second hypothesis suggests that children and old adults would exhibit a larger distracting effect than young adults, an effect which would be indicated by an upright-U pattern. Finally, the OBE may exist within all three age groups, and keep constant, being a basic function of our vision system.

**Method**

**Participants**

Two separate groups of participants were tested in low and high memory load conditions, respectively. This procedure was done to minimize the number of trials each group performed, especially for staving off fatigue in the children and old adults. Each load condition was tested on all three age groups (children, young adults, and old adults), with 20 participants in each group (50% male). Children were Grade 1 students from a primary school in Hangzhou, Zhejiang province, China; young adults were undergraduates at Zhejiang University, China; and older adults were local residents of Hangzhou, Zhejiang province, China. Average ages for all three groups were as follows: children $= 6.65 \pm 0.29$ (Mean $\pm$ SD), young adults $= 21.55 \pm 1.23$, and old adults $= 66.75 \pm 6.47$ years for the low memory load condition; children $= 6.68 \pm 0.35$, young adults $= 22.04 \pm 1.76$, and old adults $= 64.67 \pm 5.53$ years for the high memory load condition. Before the experiment, all participants were informed about the aim of the experiment and signed informed consent forms. All participants had normal color vision and normal or corrected-to-normal visual acuity.

We chose children who were in Grade 1 for the following reasons. According to our pilot study, as well as the existing literature (e.g., Cowan, Naveh-Benjamin et al., 2006; Riggs et al., 2006), 6–7 years old children are able to perform a cognitive experimental task that requires pressing a computer button; for younger children, the task, particularly change-detection tasks (e.g., Simmering, 2012), needs to be modified. The current setting allowed us to conduct the same testing program and provided us direct comparisons among the three age groups.

**Stimuli and apparatus**

Colored shapes were used as stimuli ($2.29^\circ \times 2.29^\circ$ of visual angle from a viewing distance of 60 cm), with color being the target dimension. A set of seven distinct shapes and seven colors (see Figure 1) were used in this experiment. Previous studies using a change-detection task found that old adults and 6–7-year-old children could only, at most, maintain 2–3 objects in VWM (Cowan et al., 2011; Cowan et al., 2010; Sander, Werkle-Bergner, & Lindenberger, 2011b). Therefore, two objects were displayed in the low memory load condition, while four objects were displayed in the high memory load condition. In each trial, the memorized and tested objects were randomly displayed at two or four distinct positions. These locations were randomly selected from six predefined locations, which were evenly distributed (separated by an angle of 60°) in an invisible circle with a radius of 3.07° visual degrees to the center of a gray (128, 128, 128, RGB) LCD-screen on a 14-inch laptop computer (60 Hz refresh rate).

In the low memory load condition, the two objects were displayed for 200 ms. However, in the high memory load condition, to ensure the children and old adults have enough processing time, the four objects were displayed for 500 ms (see also Cowan et al., 2010; Sander et al., 2011). After the practice sessions, most of
the children and adults over 64 in both load conditions reported that they saw each memorized objects clearly.

**Procedure**

Each trial began with a 1000-ms reminder sentence, “please prepare for the next comparison” (in Chinese) to prepare participants for the preceding trial (Figure 2). This reminder cue length was used to provide enough time for children and old adults to prepare for the upcoming task. After a 100–200-ms blank interval, a memory array was presented on the screen for 200 ms (two objects) or 500 ms (four objects), followed by a 1000-ms blank interval. Finally, a test array was presented on the screen until a response was initiated. If no response was made within 2000 ms, a new trial started automatically. Both the memory and test arrays contained the same number of objects (either two objects or four objects). Participants were instructed to detect whether one color changed in the test array compared to the memory array while ignoring the shapes. The inter-trial blank interval was 1600–1800 ms. Seating in a twilight (to make children and old adults comfortable) and sound-shielded room, participants were instructed to press “Change” (in Chinese, left Ctrl on the keyboard) if a color changed and “No change” (in Chinese, right Ctrl on the keyboard) if no change occurred. Response accuracy was emphasized and reported.2

The color and the shape within the test array changed independently, each with a change probability of 50%. When a change occurred, a new feature not used in the memory array was adopted in the test array. In the color-change condition, only one color changed. However, in the shape-change condition, all shapes in the test array changed. This was designed to raise the probability of detecting OBE. In summary, there were two types of relationships between the memory and test arrays in terms of the irrelevant feature: either the shapes were identical (No irrelevant-change; short for No-IC) or the shapes changed (Irrelevant-change; short for IC). For each memory load, there were 32 trials in each change type (16 trials of color-change), resulting in 64 trials, which were presented randomly. For each load condition, the experiment was divided into 2 blocks with a 5-minute break in between, which resulted in a 15-minute experimental phase. Before the experiment, at least 16 practice trials were completed to ensure that participants fully understood the task.

**Analysis**

We took accuracy as our main dependent variable. We used signal detection theory (SDT) to assess accuracy, which allowed us to disentangle change sensitivity ($d'$) from response biases (criterion, $c$; MacMillan & Creelman, 1991). We calculated $d'$ by using the following formula: $Z_{hit\ rate} - Z_{false\ alarm\ rate}$; $c$ was estimated by the following formula: $-0.5(Z_{hit\ rate} + Z_{false\ alarm\ rate})$. Here, a hit refers to the successful detection of a change in color while a false alarm (FA) refers to an incorrect color-change response. Since our previous studies revealed that the OBE could be revealed on $d'$ scores, $c$ values, or both (e.g., Yin et al. 2012; Shen et al., 2013), we hence took both as indexes of interest.

We first examined whether the OBE existed in the two load conditions. Mixed-model, three-way Analysis of Variances (ANOVAs) were conducted on $d'$ scores and $c$ values by using Change type (No-IC, IC) as a within-subjects factor and Age group (children, young adults, and old adults) and Load (two objects, four objects) as between-subjects factors. Any significant main effects of Age group were followed up with a post hoc Newman-Keuls test.

As detailed in the Results section, below, we observed that OBE emerged in all three age groups. Since VWM capacity might influence the degree of OBE observed in the three age groups, we conducted separate Analysis of Covariances (ANCOVAs) on the irrelevant-change distracting effect by controlling for
VWM capacity and using Age group as the between-subjects factor. In this case, we could objectively compare the degree of OBE among the three age groups. The irrelevant-change distracting effect was calculated by subtracting IC performance from No-IC performance for both $d'$ and $c$ values (results are referred to as $d'$-difference and $c$-difference, respectively). For the VWM capacity estimation, because we used a whole-probe method in the current study, we employed Pashler’s formula (Pashler, 1988; Rouder, Morey, Morey, & Cowan, 2011): $K = S \times (H - F)/(1 - F)$, where $K$ is VWM capacity, $S$ is the number of displayed objects, $H$ is the hit rate, and $F$ is the false alarm rate. To avoid underestimating VWM capacity, the estimation was conducted on the No-IC condition within the two load conditions. Considering that VWM capacity was possibly underestimated in the two-object condition, particularly for the young adults, we conducted ANCOVAs for the two-object and four-object conditions, separately.

Results

Whether OBE emerges across the three age groups

ANOVA on $d'$ scores

Replicating previous findings on VWM capacity (e.g., Cowan et al., 2011; Jost et al., 2011; Sander et al., 2011a), Figure 3a shows an inverted-U pattern for $d'$ across the three age groups in both load conditions. The three-way mixed-model ANOVA revealed a main effect of Load, $F(1, 114) = 120.03$, $p < 0.001$, $\eta_p^2 = 0.51$, where $d'$ scores were considerably higher in the 2-object ($d' = 2.39$) relative to the four-object ($d' = 1.11$) condition. Furthermore, a significant main effect of Change type, $F(1, 114) = 31.27$, $p < 0.001$, $\eta_p^2 = 0.22$, suggested that irrelevant change impaired performance on target detection. A significant interaction between Load and Change type was observed, $F(1, 114) = 5.29$, $p = 0.02$, $\eta_p^2 = 0.04$, suggesting that the distracting effect was larger in the four-object condition than in the two-object condition. To further elaborate this interaction, one-way ANOVAs with Change type as the within-subjects factor were conducted, separately, for two-object and four-object load conditions. Change type was significant in both the two-object, $F(1, 59) = 4.61$, $p < 0.05$, $\eta_p^2 = 0.07$, and four-object conditions, $F(1, 59) = 37.64$, $p < 0.001$, $\eta_p^2 = 0.39$.

A significant main effect of Age group was also observed, $F(2, 114) = 30.02$, $p < 0.001$, $\eta_p^2 = 0.36$. Post hoc comparisons showed that $d'$ scores were significantly higher for young adults ($d' = 2.39$) than for both old adults ($d' = 1.45$; $p < 0.05$) and children ($d' = 1.41$; $p < 0.05$), yet no differences were found between children and old adults ($p = 0.77$). The Change type $\times$ Age group interaction was not significant, $F(2, 114) = 1.72$, $p = 0.18$, $\eta_p^2 = 0.03$; neither was the Load $\times$ Age group interaction ($F = 1$) nor Change type $\times$ Load $\times$ Age group interaction ($F < 1$) interaction. These results suggest that the irrelevant-change distracting effect was fairly stable and not modulated by age.

ANOVA on $c$ values

The three-way mixed-model ANOVA revealed that $c$ values (see Figure 3b) were significantly lower in the two-object ($c = 0.042$) relative to the four-object condition ($c = 0.33$; $F(1, 114) = 28.28$, $p < 0.001$, $\eta_p^2 = 0.20$). A significant main effect of Change type was observed, $F(1, 114) = 17.11$, $p < 0.001$, $\eta_p^2 = 0.13$, indicating that participants had a stronger tendency to make “change” responses in the IC condition as compared to the No-IC condition. Importantly, Change type was further modulated by Age group, $F(2, 114) = 3.91$, $p < 0.025$, $\eta_p^2 = 0.06$, suggesting that the distracting effect was different across the three age groups. To deconstruct this interaction, we first estimated the distracting effect by calculating the difference between the IC and No-IC (No-IC – IC) conditions. We then ran one-sample $t$ tests against 0 to check whether the distracting effect was significant in the age groups. This step was followed by Newman-Keuls tests among the three age groups to compare the distracting effect across age. The distracting effect was not significantly greater than 0 for young adults ($c$-difference = 0.01; $p > 0.8$), yet the distracting effect was significantly larger than 0 for both children ($c$-difference = 0.24; $p < 0.01$) and old adults ($c$-difference = 0.18; $p < 0.01$). The Newman-Keuls tests showed that the distracting effect for young adults was significantly smaller than the effect for children ($p < 0.05$) and old adults ($p = 0.05$); no differences were observed between children and old adults ($p > 0.05$).
A significant main effect of Age group was also observed, $F(2, 114) = 5.02$, $p < 0.001$, $\eta_p^2 = 0.08$. Post hoc comparisons revealed that $c$ values were significantly higher for old adults ($c = 0.31$) than for young adults ($c = 0.14$; $p < 0.05$) and children ($c = 0.11$; $p < 0.05$); there were no differences between young adults and children ($p > 0.05$). These results suggest that old adults had a stronger tendency to press “no change” than did the other two groups (see also Cowan, Naveh-Benjamin et al., 2006). The other ones were non-significant ($Fs < 1$).

Comparing OBE among the age groups: ANCOVAs on $d'$ and $c$ values

The ANCOVA did not reveal a significant main effect of age group ($F < 1$) in the two-object condition for $d'$ scores. However, in the four-object condition the main effect of Age group reached significance, $F(2, 56) = 3.68$, $p < 0.05$, $\eta_p^2 = 0.12$. Post hoc comparisons revealed that children ($d'$-difference $= 0.86$) demonstrated a significantly higher distracting effect than did young adults ($d'$-difference $= 0.29$; $p < 0.05$) and old adults ($d'$-difference $= 0.46$; $p < 0.05$). Although the distracting effect for old adults seemed to be larger than that of young adults, no significant difference between these two groups emerged ($p > 0.4$).

As for the $c$ values, ANCOVAs did not reveal a significant main effect of Age group in either the two-object, $F(2, 56) = 1.12$, $p > 0.3$, $\eta_p^2 = 0.04$, or four-object condition, $F < 1$.

Discussion

The current study explored the life span developmental trajectory of OBE in VWM by assessing an irrelevant-change distracting effect. Three main findings were revealed: (a) OBE existed in children, young, and old adults (particularly as shown by the ANOVA results on $d'$ scores). (b) After balancing the VWM capacity among the three age groups (i.e., ANCOVAs), the degree of OBE revealed by $d'$ score was significantly larger for children than for young and old adults in the high memory load condition (i.e., four objects); no difference was found in the low load condition (i.e., two objects). (c) The response criterions of children and old adults considerably dropped in the IC condition comparing to the No-IC condition, whereas young adults did not change their criterion dramatically. However, there was no difference on the degree of criterion change among the three age groups after controlling for the VWM capacity factor.

OBE manifesting in all three age groups indicates that this manner of information selection is rather stable from 6–7 years old to 60–73 years old. This finding provides developmental evidence supporting the view that OBE in VWM is robust. Recently, to examine whether OBE could be erased in young adults, we manipulated several factors in a change detection task (Shen et al., 2013): (a) the change rate of an irrelevant percept (16%, 20%, and 50%), (b) the encoding time of memory array (100 ms vs. 1000 ms), (c) the memory load of target dimension (two, six, and eight objects), (d) the task instruction (informing vs. not informing participants about the irrelevant change), and (e) the available resources left for the target feature (double task vs. single task). In line with current results, we found that OBE existed regardless of these manipulations. Moreover, the current study actually tested the influence of memory load of target dimension from a developmental perspective, and replicated the finding that high memory load could not erase OBE (Shen et al., 2013; Yin et al., 2012).

Importantly, after controlling for the VWM capacity factor, the current study revealed a new aspect of VWM development: The degree of OBE in VWM was significantly larger for children than that for young and old adults. Moreover, congruent with the previous implication that developmental differences on VWM are usually revealed within resource-demanding situations (e.g., Cowan et al., 2006; Cowan et al., 2010; Gazzaley, Cooney, McEvoy, Knight, & D’Esposito, 2005), the above difference only emerged in the high memory load condition (i.e., remembering four objects). These findings, to some extent, provide new evidence that children tend to encode multi-feature/modal information in a more integrative way than do young adults (Cowan, Saults, & Morey, 2006). Cowan and colleagues explored age differences in the nature of multi-modal binding in children and young adults, focusing on spatial-verbal associative information (e.g., giving a name to a location, which is marked by a pentagon, and the corresponding relationship needs to be retained). They found that young adults could maintain spatial-verbal binding by separately maintaining each feature within each format in parallel (i.e., feature-based encoding); however, children maintained spatial-verbal binding in an abstract, cross-modal (neither in the spatial nor verbal) format. It is worth noting that like the current finding, Cowan et al.’s findings (2006) were also revealed in a high memory load condition for children (Grade 3 students), given that 3 to 7 spatial-verbal associations needed to be remembered. Consequently, this integrative manner of information processing may be a way by which children bypass overloaded information from the outer environment.
The current ANCOVA findings on $d'$ score also shed light on the developmental trajectory of feature-based filtering. Consistent with findings observed by Cowan and colleagues regarding spatial-based filtering in VWM (Cowan et al., 2011; Cowan et al., 2010), the current results suggest that children are less efficient in filtering irrelevant information than are young adults in the high memory load condition. However, children are just as efficient as young adults in the low memory load condition. Therefore, although feature-based filtering and spatial-based filtering are distinct filtering mechanisms, the development of these mechanisms are quite similar as we move from childhood to young adulthood.

Besides, although there was no statistically significant difference on the degree of OBE between young and old adults, a trend was revealed on $d'$ scores that larger OBE for old adults (0.46) than for young (0.29) adults. There are at least two explanations to this finding. First, albeit the age of the old adults in the current study was similar to most of the previous studies involving old adults, the age may be still somewhat lower such that the raised OBE for old adults could not be revealed clearly. Corroborating this alternative, the VWM capacity for old adults ($K = 1.80$) is a little bit higher than that for children ($K = 1.56$) in current study. Therefore, further study may consider testing older adults than the current samples to check whether a higher OBE indeed existed for old adults. Second, it is also possible that there is indeed no difference between young and old adults on the degree of OBE. Previous studies have revealed that, compared to young adults, old adults have deficits in the early stages of information processing. The old adults do not suppress distracters very well or the initiation of suppression is delayed. However, these age differences are not prominent during later processing stages of memory tasks (e.g., retention; Gazzaley, Clapp et al., 2008; Gazzaley et al., 2005; Gazzaley, Cooney, Risman et al., 2005; Jost et al., 2011). Therefore, it is possible that the lack of age differences between young and older adult samples was due to the paradigm used here, which could not differentiate early and later processing stages. Future ERP or MEG studies (given their temporal sensitivity) may be helpful in elucidating whether there is any difference between young and old adults at different processing stages in the feature-based filtering domain.

In addition, the current study revealed a significant interaction between Age-group and Change-type on $c$ values, showing that the Irrelevant-change significantly affected the criterion of children and old adults but not of young adults. This finding fits well with the development of executive function (or the top-down control ability) of our cognitive system. Ample studies have provided consistent evidence revealing that frontal lobe, which is considered as the neural substrate of executive function, develops from children to young adults, but then degrades at old ages (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001; Oakes, Ross-Sheehey, & Luck, 2006; Zelazo, Craik, & Booth, 2004). Besides, recent studies have shown evidence that the top-down control ability rises with the increase of the VWM capacity, and drops with the reduction of VWM capacity (Cowan & Morey, 2006; McNab & Klingberg, 2008; Vogel et al., 2005). Related, the current study replicated previous findings that VWM capacity is higher for young adults than that for children and old adults. Therefore, although the irrelevant features were encoded into VWM in three age groups and their changes dramatically impaired the target's detection performance, only young adults could keep their response criterion from significantly rising in the IC condition.

Finally, it is worth noting that the current study explored the distracting effect by manipulating whether all of the irrelevant features changed within the test array. This manipulation is different from most previous studies in which only one irrelevant feature changed in an IC condition (T. Gao et al., 2011; Z. Gao et al., 2010; Yin, Gao et al., 2012; Yin et al., 2011; Yin, Zhou et al., 2012). We argue that the way of irrelevant feature change depends on the aim of the task. If the aim is examining the robustness of OBE, or exploring a way to erase the distracting effect, one irrelevant feature change is preferable since it is more parsimonious. However, akin to the current study, if the aim is to explore whether OBE emerges in a variety of groups/conditions, changing all of the irrelevant features is favorable.

**Keywords:** visual working memory, object-based encoding, attentional filtering, life span

**Acknowledgments**

This research is supported by the National Natural Science Foundation of China (No. 31271089, 31170974, 31100753, 81000484), Project of Humanities and Social Sciences, Ministry of Education (No. 09YJC740065; 07JZD0029;10YJCXLX060), the Research Fund for the Doctoral Program of Higher Education of China (No. 20120101120085), Science Foundation for Excellent Youth Scholar of Ministry of Education of China (No. 20100101120008), National Key Technologies R&D Program (No. 2012BAI36B02), the Social Sciences Foundation of Zhejiang Province (No. 08CGWW006YBQ, 11ZJQN033YB), the Research Fund of Department of Education of Zhejiang Province (No. Y201224811).
Commercial relationships: none
Corresponding author: Zaifeng Gao.
Email: zaifengg@zju.edu.cn.
Address: Department of Psychology and Behavioral Sciences, Xixi Campus, Zhejiang University, Hang Zhou, China.

Footnotes

1 The stimuli were larger than the stimuli usually used in VWM tasks, which aims at accommodating old adults based on our pilot experiment.

2 Different from our previous study that both accuracy and RT were emphasized (e.g., Yin et al., 2012; Shen et al., 2013), we only emphasized accuracy here. There are four reasons for this change: (a) Remembering the same number of objects is more difficult for children and old adults than for young adults (as is shown by the current study). (b) Accuracy usually is the most important dependent variable in VWM tasks. (c) In one pilot experiment we tried to emphasize both, the old adult participants told us that they were not comfortable with this setting since they felt strong time pressure. (d) Due to the degeneration of motor systems, pressing the keyboard was not very stable in old adults. The old adults were quite often observed pressing more than once to make a response during the practice. To this end, albeit the RT could offer valuable information, we considered that RT is not a proper index at the current study (particularly to children and old adults); hence, we decided not to analyze it anymore.

3 For analyses of hits and FAs, please see the supplementary material.

4 Using Pashler’s formula (Pashler, 1988), the estimated capacity of VWM for children, young adults and old adults based on the No-IC condition of load four was 1.56, 3.01, and 1.80, respectively. These results are generally consistent with previous findings using a change-detection task for VWM and suggest that our low/high memory load setting was valid.

References


Gao, T., Gao, Z., Li, J., Sun, Z., & Shen, M. (2011). The perceptual root of object-based storage: An...


