Title:

Development of visual working memory and distractor resistance in relation to academic performance

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Working memory, Capacity limit, Vision, Distractor resistance, Elementary school children, Academic performance

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Abstract

Visual working memory (VWM) enables active maintenance of goal-relevant visual information in a readily accessible state. The storage capacity of VWM is severely limited, often as few as three simple items. Thus, it is crucial to restrict distractor information from consuming VWM capacity. The present study investigated how VWM storage and distractor resistance develop during childhood in relation to academic performance in the classroom. Elementary school children 7 to 12 years old and adults (total $n = 140$) completed a VWM task with and without visual/verbal distractors during the retention period. The results showed that VWM performance with and without distractors developed at similar rates until reaching adult levels at 10 years of age. In addition, higher VWM performance without distractors was associated with higher academic scores in literacy (reading and writing), mathematics, and science for the younger children (7- to 9-year-olds), while these academic scores for the older children (10- to 12-year-olds) were associated with VWM performance with visual distractors. Taken together, these results suggest that VWM storage and distractor resistance develop at a similar rate, while their contributions to academic performance differ with age.

Introduction

Visual working memory (VWM) enables us to actively maintain visual information for a short period of time in a readily accessible state. VWM serves fundamental roles in many cognitive processes, as demonstrated by robust correlations with broad measures of intellectual ability such as complex reasoning, decision-making, and goal-directed action (Baddeley, 2003; Fukuda, Vogel, Mayr & Awh, 2010; Unsworth, Fukuda, Awh & Vogel, 2014). One of the distinctive characteristics of VWM is its limited capacity: we can only hold up to three simple objects in VWM at a time (Luck & Vogel, 1997). There are two different views regarding whether VWM capacity is best described as a maximal number of items (Awh, Barton & Vogel, 2007; Fukuda, Awh & Vogel, 2010; Zhang & Luck, 2008) or as a fluid amount of mnemonic resources (Bays & Husain, 2008; Ma, Husain & Bays, 2014), but both models share the view that behavioral performance is highly accurate for only a small amount of information (Luck & Vogel, 2013; van den Berg, Awh & Ma, 2014).

VWM capacity increases with age during childhood (Cowan et al., 2005; Heyes, Zokaei, Van der Staaij, Bays & Husain, 2012; Riggs, McTaggart, Simpson & Freeman, 2006; Simmering & Perone, 2013). Riggs et al. (2006) examined how elementary school children's VWM capacity develops using a color change detection task. In this task, a small number of colored squares were briefly presented, followed by a short retention interval, and then a test array. The test array was either identical to the sample array or one of the squares was a different color. The children simply reported whether a change was present or not. The estimated VWM capacity in this task was 1.52 colors for 5-year-olds, 2.89 for 7-year-olds, and 3.83 for 10-year-olds, suggesting that VWM capacity develops during childhood and reaches the adult level (i.e. three objects) around 10 years of age. Adults can hold multi-feature items (e.g. a red square and yellow rectangle) as well as single-feature items (e.g. a red square and yellow square) in VWM, suggesting that the unit of VWM capacity is the integrated object rather than individual features (Luck & Vogel, 1997;

but see also Jiang, Makovski, & Shim, 2009; Magnussen, Greenlee, & Thomas, 1996). Riggs, Simpson, and Potts (2011) found that even young children remember multi-feature items as well as single-feature items in much the same way as adults, supporting the integrated object view of VWM capacity. Thus, the unit of VWM capacity is developmentally invariant as VWM capacity increases to the adult level. Similar findings in the development of VWM capacity were shown across various VWM tasks including: a color array recognition task (Cowan et al., 2005; Simmering, 2012), a Corsi block task (Isaacs & Vargha-Khadem, 1989; Orsini, Schiappa & Grossi, 1981), and a pattern recall task (de Ribaupierre & Bailleux, 1994; Wilson, Scott & Power, 1987). Importantly, the development of VWM capacity stems from the increment of storage space, not from improvement in support processes such as mnemonic strategies, encoding speed, or increment of knowledge (Cowan, 2014; Cowan, AuBuchon, Gilchrist, Ricker & Saults, 2011).

VWM capacity is severely limited, generally to as few as three simple items. This limitation means that efficient mechanisms are required to restrict distractor information from consuming the limited capacity and represent only the task-relevant objects. Previous studies showed that adult participants' VWM capacity is reduced when distractors are presented during encoding or retention periods (McNab & Dolan, 2014; McNab & Klingberg, 2008; Vogel, McCollough & Machizawa, 2005). These findings suggest that VWM capacity is determined by at least two components: VWM storage (Cowan, Fristoe, Elliott, Brunner & Saults, 2006) and distractor resistance (McNab & Dolan, 2014; Vogel et al., 2005). Previous studies revealed that children performed poorly compared to adults when they were presented cognitive tasks with distractors (Cowan et al., 2006; Olesen, Macoveanu, Tegner & Klingberg, 2007; Plude, Enns & Brodeur, 1994). However, it is still unknown how distractor resistance develops during childhood, especially in relation to VWM storage. The present study first seeks to investigate this question using the color array VWM task (Luck & Vogel, 1997).

There are two possibilities regarding the development of VWM storage and distractor resistance supported by research. The first is that the two VWM functions develop at the same time at the same rate. This is plausible because there is a strong relationship between WM storage and the ability to restrict distractor information from consuming WM capacity. Several studies have shown that adults with high WM capacity are better at inhibiting irrelevant information than those with low WM capacity (Engle, Tuholski, Laughlin & Conway, 1999; Kane, Bleckley, Conway & Engle, 2001; McNab & Klingberg, 2008; Vogel et al., 2005). Recent developmental studies also support this possibility by showing that attentional control within VWM develops during childhood (Shimi & Scerif, 2015; Shimi, Nobre, Astle & Scerif, 2014). Presenting a cue during VWM maintenance that indicated a to-be-tested location, researchers found that older children (11-year-olds) showed an equivalent cueing benefit to adults, whereas younger children (7-year-olds) benefited less from the cue than the older children. Considering that VWM storage also developed to the adult level around 10 years of age (Riggs et al., 2006), it is plausible that VWM storage and distractor resistance develop to adult levels at a similar rate over time. Neuroimaging studies also support this possibility by showing that WM storage and distractor resistance share the same frontoparietal cortical network (Edin et al., 2009; Wager & Smith, 2003). On the other hand, the second possibility is that VWM storage and distractor resistance develop at different rates during childhood. It is well known that WM storage is mainly reflected in the parietal cortex (Todd & Marois, 2004; Xu & Chun, 2006), while distractor-resistant maintenance is heavily represented in the frontal cortex (Kessler & Kiefer, 2005; Postle, 2005; Sakai, Rowe & Passingham, 2002). Neural development studies have also reported that cortical gray matter in the parietal areas develops earlier than in frontal areas during childhood through early adulthood (Fuster, 2002; Gogtay et al., 2004; Toga, Thompson & Sowell, 2006; Yeatman, Dougherty, Myall, Wandell & Feldman, 2012). Considering these neural studies, it is possible that VWM storage develops earlier than distractor resistance. We explored both possibilities.

The second purpose of this study was to investigate how VWM storage and distractor resistance are related to children's academic performance in elementary school. Children's WM storage and executive control have been robustly correlated with intelligence and academic performance in kindergarten and elementary school (Alloway & Alloway, 2010; Cowan et al., 2005; 2006; Gathercole, Lamont & Alloway, 2006), but we focused on VWM storage and distractor resistance in relation to specific academic subjects and general learning ability. Previous studies reported that VWM plays a key role in learning mathematics (Bull, Espy & Wiebe, 2008; Geary, 2011; Holmes & Adams, 2006; Jarvis & Gathercole, 2003; Rasmussen & Bisanz, 2005). However, there is the possibility that VWM capacity is related to performance in other academic subjects. St Clair-Thompson and Gathercole (2006) found that visuo-spatial WM performance was correlated to academic achievement in English, mathematics, and science, suggesting that visuo-spatial WM supports general academic learning rather than the acquisition of skill and knowledge in one particular subject. Another line of studies also supports the notion that WM plays a critical role in general learning by showing that children with poor WM skills often fail to remember their teacher's instructions, causing them to lose track of their progress when performing difficult tasks (Gathercole et al., 2006; Gathercole, Durling, Evans, Jeffcock & Stone, 2008; Engle, Carullo & Collins, 1991). Given these studies, it is still unclear whether VWM storage and the ability to restrict distractors are related to performance across many academic subjects or just a few. We investigated this issue by measuring VWM storage and distractor resistance performance in relation to elementary school children's academic achievement in six subjects: literacy (reading and writing), mathematics, science, music, art, and sports. Literacy, mathematics, and science require heavy use of cognitive executive abilities, whereas art, music, and physical education require heavier use of skill acquisition abilities. We included all six so that we could detail contributions from VWM abilities to academic scores and rule out other factors. We expected VWM performance would only correlate with the academic subjects

that require heavier use of cognitive executive abilities (literacy, mathematics, and science). If the academic scores in music, art, and physical education also correlated with VWM ability scores, the observed correlation would likely to be driven by the children's motivation or attitude toward testing or other factors. These distinctions should help us investigate the nature of the correlation between VWM abilities and academic achievement.

We also examined whether the relationship between the two VWM abilities and academic performance changes at different ages. Studies have shown that the contribution of VWM storage to children's performance in mathematics decreases with age (De Smedt et al., 2009; Holmes, Adams & Hamilton, 2008; McKenzie, Bull & Gray, 2003; Passolunghi, Vercelloni & Schadee, 2007; Rasmussen & Bisanz, 2005,). Interestingly, this was coupled with an increase in the contribution of central executive and verbal WM in older children's performance in mathematics. This might be due to that children in the later elementary grades generally learn more complex problems than those in the earlier elementary grades. These studies lead to our hypothesis that VWM distractor resistance plays a more critical role in classroom learning for older children than for younger children in order to focus on only task-relevant information in VWM.

The present study investigates two issues. First, we examined the development of VWM storage and distractor resistance of elementary school children 7 to 12 years old. Second, we examined the relationship between those VWM abilities and academic performance, as well as changes in these metrics at different ages. To achieve this, we used a modified version of the color array VWM task (Luck & Vogel, 1997) in which we asked elementary school children to remember the positions of 4 colored squares for a 2 sec retention period filled with either blank, visual, or verbal distractors. We examined how the children's VWM performance with and without distractors was correlated to their academic performance in literacy, mathematics, science, music, art, and sports.

Methods

Participants

A total of 121 Japanese elementary school children from a single school participated in the VWM experiment (see Table 1 for participant information). We grouped the children into six age groups (by year from 7- to 12-years-old) based on their school grade. The Japanese elementary school year starts in April and ends in March, children's grade placement is tied to their age, there is no grade repetition or skipping, and attendance is compulsory, therefore all of the children within any given age group had received the same length of formal schooling. We conducted the VWM experiment and academic evaluation at the end of the school year in March, and as a result, all of the children in the youngest group (7-year-olds) had received elementary school education for one year, while those in the oldest group (12-year-olds) had received school education for six years. One child's data was discarded from the analysis due to chance performance in all of the VWM conditions. An adult group comprised of students from universities in Japan ($N = 19$; mean age = 18.7) completed the same experiment. The experiment was conducted in accordance with the ethical guidelines of the American Psychological Association and was approved by the local Committee of Ethics, The University of Tokyo.

Procedure

Visual working memory task

The VWM tasks and instructions were presented in a quiet school computer room during school hours. The children were grouped by age (which was the same as school grade) and tested simultaneously by six experimenters. The adult participants were individually tested in a university laboratory. Stimuli were presented by a desktop computer to a 17-inch color monitor with a 60 Hz refresh rate viewed at a distance of about 57 cm with normal interior lighting.

We used a modified version of the Luck & Vogel (1997) VWM task. As in

Figure 1, the sample color array was presented for 1 sec followed by a 2 sec retention period that contained either a blank display, visual distractors, or verbal distractors. The participants were asked to remember the positions and colors of the squares and ignore the distractors. In the test phase, the participants indicated the sample stimulus color at the cued location by pressing the appropriate key. The test display was presented until the participant's response.

In the sample display, four colored squares ($1^\circ \times 1^\circ$) were simultaneously presented at four of eight possible locations equally spaced on an imaginary circle with a 3° radius. The sample array was fixed to 4 squares, and their positions were randomized on each trial. Each sample stimulus color was selected randomly without replacement from a set of nine highly discriminable colors (pink, red, orange, yellow, yellow-green, green, aqua, blue, black, and white). During the retention period, one of three distractor conditions was randomly selected for display. In the blank condition, a blank display was presented. In the visual distractor condition, four black figures were sequentially presented for 300 ms each with 200 ms ISI. The black figures were randomly selected from clovers, spades, hearts, stars, triangles, and circles, and their positions were randomly selected from eight possible, equally spaced locations on two imaginary circles with a 1° or 5° radius that did not overlap with the locations of the sample color squares. In the verbal distractor condition, the verbal name of each visual distractor (clover, spade, heart, star, triangle, or circle) was delivered through headphones in the same time course as the visual distractors were presented in the visual distractor condition. In the test phase, a test cue was presented at one of the sample color square positions. Each test cue consisted of two colored rectangles half the height of the sample squares, one above the other. One of the rectangles was the same color as the sample square at that location, and the other was a new color that was not presented in the sample display. Participants were asked to indicate which rectangle matched the color of the sample stimulus at that location by pressing one of two keys (up or down) on a keyboard. The responses were

unspeeded with strong emphasis on accuracy.

For instructions, the participants were shown a slide of the task procedure as in Figure 1, and were asked to indicate a correct response for the example trial. All of the participants answered the example trial correctly. After the instructions, the participants practiced 6 trials, 2 from each distractor condition (blank, visual distractor, and verbal distractor), and then performed 30 test trials (10 trials per distractor condition). Before the VWM task, a color vision check was conducted for each participant by presenting two test displays in random order. One test display contained nine different color squares used in the VWM task. The participants were asked whether the colors were all different or not. All of the participants answered “different” for this display. The other test display also contained nine squares, but we presented one randomly selected color twice. The participants were again asked whether the colors were all different or not. All participants reported that “there was two of the same color” in this display. This confirmed that sample stimulus colors were highly discriminable for all of the participants. The experiment was completed within 30 minutes, including the instruction, color vision check, practice, and test trials. The data was collected at the end of the school year, independent of any academic evaluation.

Academic scores

Children’s academic scores were recorded as one of 3 levels (3-good, 2-average, 1-poor) in each of 6 subjects: literacy (reading and writing in Japanese), mathematics, science, music, art, and sports (physical education). They were evaluated at the end of the school year by their teacher in each subject and graded on an absolute scale based on test scores and classroom activities. Individual’s scores were normalized into Z-scores within the same age group (which was the same as school grade) and academic subject.

Results

Development of visual working memory

We used % correct in each of the three distractor conditions for VWM performance. VWM performance increased with age in all three distractor conditions (Figure 2). This observation was supported by a two-way ANOVA with age and distractor condition as factors, yielding main effects for age ($F(6, 132) = 14.01, p < .001$) and distractor condition ($F(2, 12) = 8.65, p < .001$). The interaction was not significant ($F(12, 264) = 0.78, p > .66$). Accounting for the effect of age, 7- to 9-year-olds showed lower VWM performance than 10- to 12-year-olds and adults when the data was collapsed across distractor conditions (Tukey's HSD tests, $ps < .05$). These results show that VWM storage (VWM performance in the blank condition) develops to the adult level (i.e. three items) at 10 years of age at a similar rate over time as the process of excluding visual/verbal distractors from VWM (VWM performance in the visual/verbal distractor condition). Looking at the effect of distractors, VWM performance in the visual ($M = 75\%$) and verbal distractor conditions ($M = 76\%$) was lower than in the blank condition ($M = 81\%$) when the data was collapsed across age groups (Tukey's HSD tests, $ps < .005$). The result indicates that the visual and verbal distractors interfered with the VWM representations. The children's VWM performance was moderately correlated among the three distractor conditions as shown in Table 2.

We grouped the children into six age groups (7 to 12 years old) based on their school grade. Consequently, we could control the length of formal school education (educational age) compared to VWM performance. However, there might be a relative age (chronological age) effect on VWM and academic performance. To investigate this, we first calculated a relative age within the age group (school grade), and then correlated the relative age with VWM or academic performance, collapsing the school grade. The results in Table 3 showed that none of the correlations reached significance ($rs < .15, ps > .10$). We then divided the children into a younger group (7- to 9-year-olds) and an

older group (10- to 12-year-olds), and performed the correlation analysis after collapsing school grade. We did not observe any significant correlations between the relative age and VWM or academic performance as shown in Table 3 ($r_s < .18$, $p_s > .18$). These results do not show a chronological age effect on the development of VWM storage and distractor resistance, however, we do not mean to suggest that the VWM development is solely driven by education, or deny the possibility of the relative age effect.

Visual working memory and academic performance

To investigate the relationship between VWM performance in the three distractor conditions (blank, visual, and verbal) and academic scores, a fixed-order hierarchical linear regression analysis was performed for each academic subject. The regression model was as in Figure 3a, in which each child's VWM performance in the three distractor conditions was used to predict their academic score in literacy, mathematics, science, music, art, or sports. The regression had two steps: first, we included only VWM performance in the blank condition (VWM storage) as a performance baseline to predict academic scores in the regression model; second, we added two types of distractor performance measures (resistance to visual and verbal distractor interference) to the model and checked whether the R^2 change from step 1 to 2 was significant by F -test. Here, a significant R^2 change suggested that distractor resistance explains additional variance beyond VWM storage (see also Alloway & Alloway (2010) for the logic behind this two-step analysis). Before the regression, we calculated the Z-scores of each child's VWM performance and academic score within each age group (which was the same as their school grade). Zero-order correlations are shown in the Supplementary Table S1 and S2.

In order to investigate the general trend, we collapsed age groups. As shown in Figure 3b, good fits were obtained for literacy, mathematics, and science in the first step (adjusted $R^2 = 0.05$, $F(1, 118) = 6.06$, $p < .02$, for literacy; adjusted $R^2 = 0.07$, $F(1, 118) = 8.41$, $p < .01$, for mathematics; adjusted $R^2 = 0.05$, $F(3,$

116) = 6.95, $p < .01$, for science). In the second step, we added two distractor performance measures (visual and verbal) to the regression model and found that R^2 change was significant for mathematics and science ($ps < .01$). In the second step, good fits were obtained for mathematics and science (adjusted $R^2 = 0.14$, $F(3, 116) = 6.69$, $p < .01$, for mathematics; adjusted $R^2 = 0.13$, $F(3, 116) = 6.02$, $p < .01$, for science). VWM performance in the visual distractor condition uniquely predicted the academic score in mathematics and science (standardized beta = .31, $p < .001$ and .32, $p < .001$, respectively), suggesting that distractor resistance to visual stimuli contributes to performance in mathematics and science. We also obtained a good fit for literacy (adjusted $R^2 = 0.08$, $F(3, 116) = 3.43$, $p < .02$), but VWM performance in any of the three distractor conditions did not significantly predict scores in literacy at the second step (standardized betas $< .15$, $ps > .13$). Similarly, academic performance in music, art, and sports were not predicted by VWM performance in any of the three distractor conditions in the first or second step. These results suggest that distractor resistance selectively predicts academic performance in mathematics and science.

In the previous section, we found that VWM storage and distractor resistance developed at a similar rate over time until they reached adult levels at 10 years of age, but it was still possible that the VWM component contributing to academic performance changed with age. We investigated this possibility by grouping the children into a younger group (7- to 9-year-olds) and an older group (10- to 12-year-olds) and performed the hierarchical linear regression as shown in Figure 3a again. As for the younger children (Figure 3c), good fits were obtained for literacy, mathematics, and science in the first step (adjusted $R^2 = 0.10$, $F(1, 118) = 7.17$, $p < .01$, for literacy; adjusted $R^2 = 0.13$, $F(1, 118) = 9.57$, $p < .01$, for mathematics; adjusted $R^2 = 0.17$, $F(3, 116) = 12.8$, $p < .01$, for science). In the second step, we added two distractor performance measures (visual and verbal) to the regression model, but R^2 changes did not reach significance in any of the academic subjects. Verifying this result, VWM performance in the blank condition alone predicted the academic scores in

literacy, mathematics, and science in the second step (standardized beta = .27, .27, and .37, $ps < .05$, respectively). These results suggest that VWM storage, rather than distractor-resistance, uniquely predicted the younger children's academic scores.

As for the older children's scores (Figure 3d), we did not find significant fits for any academic subjects in the first step. In the second step, adding two the distractor performance measures (visual and verbal) to the regression model significantly improved the model fits for mathematics and science ($ps < .01$ for R^2 changes), and significant fits were obtained (adjusted $R^2 = 0.15$, $F(3, 52) = 3.15$, $p < .05$, for mathematics; adjusted $R^2 = 0.17$, $F(3, 52) = 3.64$, $p < .01$, for science). VWM performance in the visual distractor condition uniquely predicted the academic scores in mathematics and science (standardized beta = .39, $p < .01$ and .43, $p < .05$, respectively). These results suggest that distractor resistance, rather than VWM storage, was the predicting factor for academic scores in mathematics and science for the older children. None of VWM performance scores in the three distractor conditions predicted academic performance in music, art, or sports for the younger or older children in the first or second step.

Discussion

The present study investigated how VWM storage and distractor resistance develop in elementary school children 7 to 12 years old. The results showed that children's VWM performance with and without distractors correlated with each other, and that both develop at a similar rate until they reach adult levels at 10 years of age. On the other hand, VWM performance with and without distractors contributed differently to academic performance depending on the child's age. VWM storage (VWM performance in the blank condition) predicted academic scores in literacy (reading and writing), mathematics, and science for the younger children (7- to 9-year-olds), while distractor resistance to visual stimuli (VWM performance in the visual distractor condition) predicted academic scores in mathematics and science for the older children (10- to 12-year-olds).

Development of visual working memory

Previous studies have shown that VWM storage capacity develops to the adult level around 10 years of age (Riggs et al., 2006). Children perform poorly compared to adults when they are presented cognitive tasks with distractors (Cowan et al., 2006; Olesen et al., 2007; Plude et al., 1994). Other recent studies have also shown that attentional control within VWM develops during childhood (Shimi & Scerif, 2015; Shimi, et al., 2014). The present study investigated how VWM storage and distractor resistance develops during childhood by comparing VWM measures from groups of different ages. We first found that VWM storage increased with age. Without visual distractors, the seven-year-old children's VWM storage was about half of the adults' storage capacity (i.e., 1.6 objects), and it increased to the adults' level (i.e., 2.8 objects) by age 10, which supported Riggs et al's study (2006) (see Supplementary analysis 1 in the footnote and Supplementary Table S3 about calculating VWM capacity). In addition, VWM distractor resistance (which was equal to VWM performance in the visual/verbal distractor condition) also reached the adult level at 10 years of age, suggesting that the process of

excluding visual/verbal distractors from VWM develops in a similar time course as VWM storage. Studies with adult participants have also shown that individuals with high WM capacity are better at inhibiting irrelevant information than those with low WM capacity (Engle et al., 1999; Kane et al., 2001; McNab & Klingberg, 2008; Vogel et al., 2005). In agreement with these studies, we found significant correlations in VWM performance with and without distractors, suggesting that VWM storage development during childhood is closely correlated to VWM distractor resistance.

In the meantime, a supplementary analysis revealed that the younger children (7- to 9-year-olds) showed equivalent distractor-interference from the visual and verbal stimuli, while the older children (10- to 12-year olds) only showed distractor-interference from the visual stimuli (see Supplementary analysis 2 in footnote and Figure 2). In their seminal model of WM, Baddeley and Hitch (1974) suggested that there are two independent WM stores: one that maintains visuo-spatial information for brief periods of time (visual WM) and the other that temporarily maintains phonological information (verbal WM). Luck and Vogel (1997) showed that VWM maintenance did not interfere with maintaining (rehearsing) phonological information with adult participants. Similar functional independence was found in children by Hale, Bronik and Fry (1997). They used a dual task paradigm to test 10-year-old children's memory of either spatial or verbal information while concurrently remembering other spatial or verbal information as a secondary task. The children's primary memory performance had interference from the second task only within the same domain (i.e., from the spatial-spatial or verbal-verbal memory task). On the other hand, other studies have shown that the two WM stores are not completely dissociated. Hale et al. (1997) showed that children younger than 8 years old suffered from a domain non-specific interference (i.e., spatial-verbal or verbal-spatial memory task). A heavy verbal load greatly decreased VWM performance even with adult participants (Morey & Cowan, 2004). In the present study, we found that the younger children suffered from general interference more than the older children and adults, suggesting that

domain specificity of VWM storage develops with age.

It should be noted that distractor filtering at the encoding stage and distractor resistance during maintenance might rely on different mechanisms (i.e., directing attention in space during encoding versus attending to internal representations over external inputs during maintenance). This is particularly plausible in light of recent research by Macnab and Dolan (2014) and Macnab et al. (2015), which clearly showed that distractor-filtering performance during the encoding and delay periods were separable in terms of their contribution to the WM capacity of adult participants. Developmental studies also support this by showing that the visuospatial attentional control at the encoding and maintenance stages differed developmentally (Shimi, Kuo, Astle, Nobre & Scerif, 2014; Shimi, Nobre, Astle & Scerif, 2014).

Visual working memory and academic performance

We examined how VWM storage and distractor resistance were related to academic performance in the classroom as well as general learning ability. The result showed that only academic performance in specific subjects was related to our VWM measures. VWM storage (VWM performance without distractors) selectively predicted academic performance in mathematics, science, and literacy for the younger children (7- to 9-year-olds). In mathematics, it is necessary to extract numerical information from tables, graphs, and story problems by representing them in VWM (Holmes et al., 2008). VWM is also required to perform multi-digit calculations (Trbovich & LeFevre, 2003). In addition, VWM might be used to construct visual representations of numerical processes such as estimation and number magnitude in a spatial form like mental number lines (Dehaene, Spelke, Pinel, Stanescu & Tsivkin, 1999; Jordan, Hanich & Kaplan, 2003). These same visual cognitive processes should also be required to learn in science class. As for the link to literacy, Luck (2008) suggested that VWM plays a key role in learning object categories through the comparison of perceptual input and visual memory representations (see also, Andrews & Halford, 2002; Gentner & Namy, 1999;

Halford, Wilson & Phillips, 1998). Young children learn many concepts, categories, and letters during their first years in school. Likewise, children have to visually perceive the shape of each letter to differentiate them from other letters in order to write. These processes help to explain why VWM storage predicts literacy performance for the younger children.

We also found that the contributions of VWM storage and distractor resistance to academic performance changed between ages. VWM storage (VWM performance without distractors) predicted academic performance in mathematics and science for the younger children (7- to 9-year-olds), while these scores for the older children (10- to 12-year-olds) were predicted by VWM distractor resistance (VWM performance in the visual distractor condition). This was not due to systematic age-related changes of the variance of VWM performances: both younger and older children showed comparable individual variation in VWM performance in all three distractor conditions (see Supplementary Table S3). Younger children learn simpler concepts, calculations, and story problems in mathematics and science than older children, and as a result, their VWM storage may play a more significant role than distractor resistance. As math and science problems increase in complexity along with age, children need more efficient VWM distractor resistance to represent only goal-relevant information in VWM. Studies have shown that visuospatial WM contributes to young children's scores in mathematics more than older children's scores (De Smedt et al., 2009; Rasmussen & Bisanz, 2005). This is coupled with an increase in the role of central executive functioning in older children (Holmes et al., 2008; McKenzie et al., 2003; Passolunghi et al., 2007). The present study extends these findings by showing that one of the important central executive functions is the individual's distractor resistance: their ability to exclude task-irrelevant visual information from VWM. We also found that VWM resistance for verbal distractors did not predict academic performance. This might be because there is usually less verbal noise than visual noise in the classroom, and children more often suffer from visual interference when learning in class.

VWM storage and distractor resistance selectively predicted academic performance in literacy, mathematics, and science, all of which require heavy cognitive processing. They did not predict performance in music, art, and sports (physical education), which are more closely related to skill acquisition abilities rather than cognitive executive abilities. The results for music, art, and physical education suggest that the results for literacy, mathematics, and science are unlikely to be driven by the children's motivation or attitude during testing, while also allowing us to show the specific VWM contribution to each academic score.

Implications for classroom practices

WM is known to play critical roles in higher cognitive functioning (Baddeley, 2003; Unsworth et al., 2014). However, the link between WM and classroom activities hasn't been clear (Gathercole et al., 2006; 2008). The present study shows that VWM storage predicts academic performance in literacy, mathematics, and science for the young children (7- to 9-year-olds), while distractor resistance predicts performance in mathematics and science for the older children (10- to 12-year-olds). These results suggest that excluding as many visual distractions from the classroom as possible would be effective in improving children's academic performance for all ages. In addition, the younger children showed much lower VWM storage even without distractors, than the older children and adults. From this, we can assert that trying to present as few items as possible at once would aid learning in the classroom, especially for young children. Recently, Fisher, Godwin, and Seltman (2014) reported that 5-year-old kindergarten children showed smaller gains when they had a science lesson in a highly decorated classroom than children who took the same lesson in an undecorated room. The visual decorations interfered with children's learning by adding unnecessary cognitive load, which led them to spend less time attending the main task. In our study, even older children's VWM representations were shown to be highly susceptible to visual distraction. Our results suggest that reducing unnecessary VWM load by decreasing the

number of to-be-remembered items as well as reducing the number of visual distractions would promote successful learning in the classroom by elementary school children.

Footnote

Supplementary analysis 1: Each participant's VWM capacity was estimated in Figure 2 and Table S3 with a standard formula that assumes if a participant can access and hold K items from an array of S items, then that participant can indicate which color was presented at the cued location in K/S trials (Cowan, 2001; Luck & Vogel, 1997). To correct for guessing, this procedure also takes into account chance level performance. The formula is $K=S(P-50)/50$, in which K is the VWM capacity, S is the set size of the memory array, and P is percentage correct.

Supplementary analysis 2: We divided the children into a younger group (7- to 9-year-olds) and an older group (10- to 12-year-olds), and separately performed one-way ANOVAs on VWM performance with the distractor condition as a factor. The younger children showed a main effect for distractor condition ($F(2, 63) = 5.94$ $p < .005$). A subsequent Tukey's HSD revealed that VWM performance in the visual distractor condition ($M = 65\%$) and verbal distractor condition ($M = 67\%$) were both lower than in the blank condition ($M = 74\%$) ($ps < .005$). The older children also showed a marginally significant main effect for the distractor condition ($F(2, 55) = 2.16$ $p < .11$). This time, however, VWM performance in the visual distractor condition ($M = 81\%$) was marginally lower than in the blank condition ($M = 86\%$), but VWM performance in the verbal distractor condition ($M = 84\%$) was not significantly lower than in the blank condition (Tukey's HSD tests, $p = .10$ and $p > .77$, respectively). These results suggest that VWM becomes distractor resistant to verbal distractors at an earlier age than distractor resistance to visual distractors. We are aware that these results should be treated as supplemental observations because the interaction of age and distractor condition did not reach significance using a two-way ANOVA with age and distractor condition as factors (see the Result section).

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Table

Table 1
Participant information

Age group (Elementary school grade)		<i>N</i> (boys)	Mean age (<i>SD</i>)
Elementary school children	7 (1)	19 (7)	7.4 (0.4)
	8 (2)	23 (13)	8.4 (0.4)
	9 (3)	22 (14)	9.4 (0.4)
	10 (4)	18 (9)	10.3 (0.3)
	11 (5)	18 (11)	11.4 (0.4)
	12 (6)	20 (13)	12.3 (0.3)
Adult (University students)		19 (9)	18.7 (0.7)

Note: Children in the same age group were all in the same grade.

Table 2
Pearson's correlations of visual working performance among three distractor conditions

Age group, Distractor condition	1	2	3
All children (7 to 12 years old, N=120)			
1. Blank	—		
2. Visual distractor	0.38 **	—	
3. Verbal distractor	0.29 **	0.31 **	—
Younger children (7 to 9 years old, N=64)			
1. Blank	—		
2. Visual distractor	0.42 **	—	
3. Verbal distractor	0.39 **	0.36 **	—
Older children (10 to 12 years old, N=56)			
1. Blank	—		
2. Visual distractor	0.32 *	—	
3. Verbal distractor	0.18	0.24 +	—

+ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$

Table 3
Pearson's correlations between relative age within age group (=school grade) and visual working memory performance or academic scores

Age group	Visual working memory performance			Academic scores					
	Blank	Visual distractor	Verbal distractor	Literacy	Mathematics	Science	Music	Art	Sports
All children (7 to 12 years old, N=120)	-0.01	0.13	-0.03	0.06	0.02	0.15	0.13	-0.05	0.02
Younger children (7 to 9 years old, N=64)	0.02	0.14	-0.03	0.13	-0.02	0.17	0.01	-0.05	0.14
Older children (10 to 12 years old, N=56)	-0.06	0.12	-0.05	0.04	0.09	0.11	0.18	0.07	-0.04

+ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$

Figures

Figure1

Figure1. Visual working memory task: Participants were asked to remember the positions of 4 colored squares displayed for 1-sec followed by one of three types of 2-sec retention periods: a blank display in the blank condition, task irrelevant visual figures in the visual distractor condition, or a blank display was presented and the names of the visual figures were delivered to the participant through headphones in the verbal distractor condition. Participants were instructed to ignore the distractors if presented. After the retention period, a two alternative forced-choice test was presented at one of the sample color locations. The participants reported the sample color by pressing the up or down key on a keyboard (pressing the down key was correct in the example).

Figure2

Figure2. Visual working memory (VWM) performance as a function of age (which was the same as elementary school grade, see methods) for the three distractor conditions (blank, visual distractor, and verbal distractor). VWM performance reached the adult level at 10 years of age in all three distractor conditions. VWM performance in the visual/verbal distractor conditions was lower than in the blank condition. The right vertical axis indicates estimated visual working memory capacity based on percent correct (see Supplementary analysis 1 in the footnote and Supplementary Table S3). Error bars are standard error.

a Regression model

b All children (7 to 12 years old, N = 120)

Step 1		Literacy	Mathematics	Science	Music	Art	Sports
Model fit	R ²	.05	.07	.05	.01	.00	.00
	F (1, 118)	6.06	8.41	6.95	1.29	0.03	0.26
	p	.02*	.01**	.01**	.26	.86	.61
Standardized beta		.22**	.26**	.23**	.10	.02	-.05

F-test for R² change from step 1 to 2

p	.13	.01**	.01**	.22	.91	.24
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Step 2

p < 0.10⁺ p < 0.05* p < 0.01**

Figure3

c Younger children (7 to 9 years old, N = 64)

Step 1		Literacy	Mathematics	Science	Music	Art	Sports
Model fit	R ²	.10	.13	.17	.00	.00	.00
	F (1, 118)	7.17	9.57	12.8	0.95	0.11	0.20
	p	.01**	.01**	.01**	.33	.74	.65
Standardized beta		.32**	.37**	.41**	.12	-.04	-.05

F-test for R² change from step 1 to 2

p	.63	.25	.23	.08 ⁺	1.0	.72
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d Older children (10 to 12 years old, N = 56)

Step 1		Literacy	Mathematics	Science	Music	Art	Sports
Model fit	R ²	.01	.02	.00	.01	.01	.00
	F (1, 118)	0.59	1.02	0.42	0.43	0.77	0.09
	p	.45	.32	.53	.52	.38	.76
Standardized beta		.10	.14	.01	.08	.12	-.04

F-test for R² change from step 1 to 2

p	.13	.02**	.01**	.93	.73	.25
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Figure3

Figure3. Regression model and results in a fixed-order hierarchical linear regression analysis. **a**, In the regression model, individual children's VWM performance in the three distractor conditions (blank, visual distractor, and verbal distractor) was used to predict their academic score in literacy (reading and writing), mathematics, science, music, art, or sports. The regression had two steps: first, we included only VWM performance in the blank condition (VWM storage) as a performance baseline to predict academic scores in the regression model; second, we added two types of distractor performance measures (resistance to visual and verbal distractor interference) to the model and checked whether the R^2 change from step 1 to 2 was significant by F-test. Here, a significant R^2 change suggested that distractor resistance explains additional variance beyond VWM storage (see also the Results section). **b-d**, The results of the regression analysis are shown in the bar graph and table. The tables show the model fit of each regression (for each academic subject) at the first and second steps. Standardized beta in the first step (from VWM performance in the blank condition to each of the academic score) is shown in the table. Standardized betas in the second step are shown in the bar graph. **b**, Children's (7- to 12-year-olds) academic performance in mathematics and science were selectively predicted by VWM performance in the visual distractor condition. **c**, The younger children's (7- to 9-year-olds) academic performance in literacy, mathematics, and science were predicted by VWM performance in the blank condition. **d**, The older children's (10- to 12- year-olds) academic performance in mathematics and science were predicted by VWM performance in the visual distractor condition.