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PAPER

Age differences in visual working memory capacity: not based on encoding limitations

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Abstract

Why does visual working memory performance increase with age in childhood? One recent study (Cowan et al., 2010b) ruled out the possibility that the basic cause is a tendency in young children to clutter working memory with less-relevant items (within a concurrent array, colored items presented in one of two shapes). The age differences in memory performance, however, theoretically could result from inadequate encoding of the briefly presented array items by younger children. We replicated the key part of the procedure in children 6–8 and 11–13 years old and college students (total N *= 90), but with a much slower, sequential presentation of the items to ensure adequate encoding. We also required verbal responses during encoding to encourage or discourage labeling of item information. Although verbal labeling affected performance, age differences persisted across labeling conditions, further supporting the existence of a basic growth in capacity.*

Introduction

It is well accepted that younger children perform more poorly than older children and adults on tests of working memory, the current-task information kept in an active state for short-term recall. It is clear that the development of working memory ability is an important component of cognitive development across many tasks (e.g. Andrews & Halford, 2002; Cowan, Elliott, Saults, Morey, Mattox, Hismjatullina & Conway, 2005; Cowan, Fristoe, Elliott, Brunner & Saults, 2006a; Gathercole, Pickering, Ambridge & Wearing, 2004; Hitch, Towse & Hutton, 2001; Johnson, Im-Bolter & Pascual-Leone, 2003). What has been more controversial for many years is the reason behind the age differences in working memory performance. One simple hypothesis, the one advocated here, is that some brain system operates by retaining a limited number of items in an active form, and that this brain system holds fewer items in young children than in older participants (e.g. Burtis, 1982; Case, 1995; Cowan, 2001; Pascual-Leone & Smith, 1969). The notion that there is a working memory faculty limited to no more than a few items is supported by considerable recent research in adults (Awh, Barton & Vogel, 2007; Cowan & Rouder, 2009; Rouder, Morey, Cowan, Zwilling, Morey & Pratte, 2008; Zhang & Luck, 2008; for an opposing view see Bays & Husain, 2008, 2009).

The challenge for advocates of a capacity-growth hypothesis, however, is that it is not logically necessary; other possibilities exist (e.g. Barrouillet, Gavens, Vergauwe, Gaillard & Camos, 2009; Case, Kurland & Goldberg, 1982; Dempster, 1991; Hulme & Tordoff, 1989). The older participants may excel at focusing on more task-relevant information, in which case the holding system in the brain may be more cluttered by information irrelevant to the task at hand in younger children. Also, older participants may be better able to encode the stimuli in a manner that allows the information to be retrieved. In particular, they may form verbal labels for the stimuli that allow these stimuli to be retained using multiple brain systems, adding redundancy to the representation and making recall more reliable. In fact, verbal rehearsal is one of the main ways in which mnemonic processing improves in childhood (e.g. Cowan, Cartwright, Winterowd & Sherk, 1987; Cowan, Saults & Morey, 2006b; Flavell, Beach & Chinsky, 1966; Ornstein, Naus & Liberty, 1975; Tam, Jarrold, Baddeley & Sabatos-DeVito, 2010).

The present research was designed to determine whether an age difference in working memory performance could be obtained across manipulations in factors that could affect the encoding of the stimuli. It was based on the procedure used by Cowan, Morey, AuBuchon, Zwilling and Gilchrist (2010b), illustrated in Figure 1. On each trial in that study, an array was presented for 500 ms and the task was to retain items from the array for a probe item recognition test shortly afterward. The probe was either identical to the array item in the same location or differed

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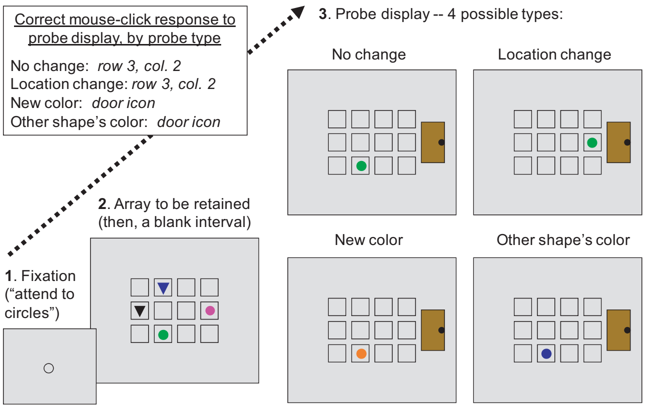

Instructions: "When the probe object appears, mouse-click the location where it belongs."

Figure 1 *After Cowan, Morey, AuBuchon, Zwilling and Gilchrist (2010b, Figure 2). An illustration of the array memory procedure. The present study differed from Cowan* et al. *in that the array items were presented one at a time, and in that a verbal response was added after each item presentation in some conditions.*

from that array item in color, in one of three ways shown in the figure. In the most critical condition, the one to be replicated here, the instructions were to pay attention to items in one shape and not another (e.g. circles and not triangles) throughout the session. The probe tested was in the attended shape 80% of the time, but in the other shape the remaining 20% of the time. After Gold, Fuller, Robinson, McMahon, Braun and Luck (2006), it was possible to obtain two meaningful measures from the results. First, the sum of items recalled from the attended and unattended (or less-attended) shape provided an estimate of the number of items held in working memory. Second, the difference between the number of items recalled in the attended versus unattended shape provided an estimate of the efficiency of the allocation of attention preferentially to the shape that was usually tested, and therefore more relevant than the other shape for maximum performance.

Results of the previous study were clearest for small arrays, which included two circles and two triangles. Cowan *et al.* (2010b) found that children in Grades 1–2 recalled far fewer items in total, but that they favored the relevant shape to the same degree as older children (Grades 6–7) or adults (college students). This strongly suggests that visual working memory capacity increases with age in childhood. The reason for this finding, however, is not yet clear. It could be that the effect occurs because children are not as good at entering the items from a brief, concurrent visual display into working memory. To examine whether that encoding difference can explain the age difference in capacity, the present experiment mirrored that of Cowan *et al.* but with the items presented one at a time, at a slow rate of 1 s per item (Figure 2).

If age differences in the number of items retained in working memory survive this change in procedure, though, there is still an explanation aside from basic capacity growth. It could be that this slower procedure allows time for older participants to engage in verbal encoding and rehearsal of the visual items, enhancing recall. To examine this factor, each participant carried out trials in each of three articulation conditions. In the first condition, the participant remained silent and therefore was free to adopt whatever strategy he or she wished. In a second condition, the color of each item was to be named as it was presented. This should enhance recall generally for individuals who did not spontaneously name the colors. Finally, in a third condition, the participant was to say the word 'wait' after each item presented. This is essentially an articulatory suppression condition (Baddeley, 1986) in which the need to say a word irrelevant to the memory task interrupts more task-relevant verbal processing, such as labeling and covert rehearsal. If the working memory advantage of older participants in this procedure accrues only because they use verbal processing better than younger children, then the age difference might be substantially diminished when naming of the color is required (because item colors are then verbally labeled in all groups, instead of just the older participants) and it should be diminished also when an irrelevant word is required (because it disrupts verbal processing that may otherwise be an advantage for older participants). This last condition, presented after the participants are well practiced in the task, provides the best indication of each age group's basic visual working memory capacity without the assistance of verbal strategies.

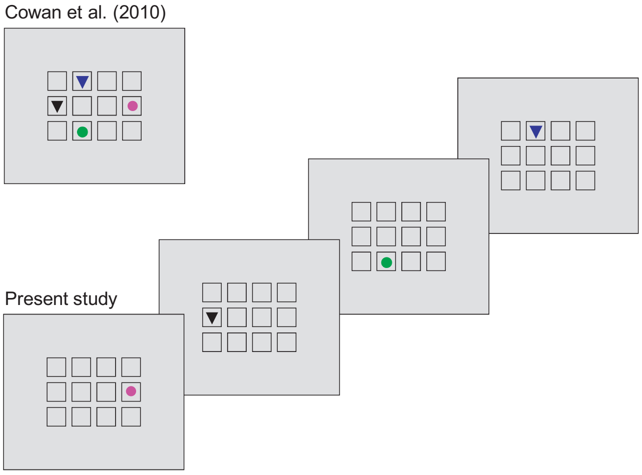

Figure 2 *Comparison of the simultaneous array presentation method of Cowan, Morey, AuBuchon, Zwilling and Gilchrist (2010b) to the sequential array presentation method of the present study.*

Method

Participants

Total $N = 90$ including 30 in each of three age groups: Elementary school Grades 1–2 (Mean age = 7 years, 8 months, SD = 8 months; range 6.3–9.0 years);

Grades 6–7 (Mean age = 12 years, 5 months; *SD* = 6 months; range 11.2–13.5 years); and adults (Mean age = 19 years, 3 months, *SD* = 7 months; range 18.4–21.2 years).

Design

The basic design was comparable to the 80%–20% trial block of Cowan *et al.* (2010b) with two circles and two triangles per array, with two major exceptions. First, items in each array were presented one at a time (1 item/s), rather than all at once (see Figure 2). Second, there were three separate trial blocks differing in the instructions about articulation during the stimulus presentation: say nothing, name the color of each item just after it is presented, and say 'wait' just after each item is presented.

This trial block order was constant across participants because we felt that having only one order of the articulation conditions prevented undesirable carryover effects. Specifically, the silent condition had to come first so that neither naming nor suppression would be encouraged, allowing an assessment of the participant's spontaneous strategy; next, the full benefit of instructed color-naming could be examined without contamination from instructed suppression; and last, the most critical condition, that of rehearsal suppression (often known as articulatory suppression), could be presented following the extensive task practice provided by the first two conditions.

On 60% of the trials in each block, the color of a probe item differed from the item in the same location within the just-presented array, in ways shown in Figure 1. On the other 40% of the trials, the probe was identical to the corresponding array item. This distribution of change and no-change trials was selected for practical reasons, to allow the correct proportion of circle (80%) and triangle (20%) probe trials in each change condition. The task was to indicate where the probe item belonged, which was analyzed primarily to determine whether the probe was judged to have changed from the corresponding array item.

Apparatus, stimuli and procedure

The apparatus and stimuli were identical to that of Cowan *et al.* (2010b) except for the sequential presentation of array items as shown in Figure 2. As in that study, the participant was instructed to attend to the colors of one shape (in this study, circles) and ignore the other (triangles). Also as in Cowan *et al.*, to keep the participants' interest, the problem was cast as a classroom in which the items represented children. The task was to click the seat (box) in which the probe item (child) belonged and, if that child belonged nowhere in the classroom (array), the door icon was to be clicked, sending the probe child to the principal. Participants were told in advance that most of the time they would be asked about the circles, but that some of the time they would be asked about the triangles. Additionally, the instructions included an example in which they were asked about the triangles. However, it was made clear that they should focus their energy on the circles, as follows: 'The circles are your students. Another teacher is watching the triangles. If you catch a triangle switching seats, that's okay too, but you REALLY want to catch the circles.'

Each trial was participant-initiated and began with a 1-s presentation of an empty fixation circle in the center of the screen, followed by a 500-ms display of the grid of nine empty squares on a grey background (Figure 1). The grid remained on the screen throughout the presentation of four stimuli (two circles and two triangles). Each item in an array was colored differently, with colors drawn from the set *black*, *white*, *red*, *blue*, *yellow*, *green*, *purple*, *brown and pink*. Each item was presented in a different location for 500 ms with a 500-ms blank interval separating items. The last item was immediately followed by a 1.5-s retention interval with no grid displayed. Then the grid returned with a single probe item, and a response was to be made indicating where the probe item belonged.

As shown in Figure 1, when the probe did not match the corresponding array item it could take on the color of an item of the same shape that had appeared at a different array location; it could take on a new color that had not appeared in the array; or it could take on the color of an item in the array of the shape that differed from the one at the tested location.

The items to be retained were presented in a pseudorandom order, with constraints to ensure that circles and triangles were presented in each serial position about equally often. Each of the three articulation conditions began with a block of 13 practice trials, followed by 50 experimental trials. The practice trials (and triangle probes among them) included 5 (1) no-change trials, 3 (1) location-change trials, 2 (1) new-color trials, and 3 (1) other-shape's-color trials, presented in a different random order for each participant. Each block of experimental trials included 20 (4) no-change trials, 10 (2) location-change trials, 10 (2) new-color trials, and 10 (2) other-shape's-color trials, presented in a different random order for each participant.

Theoretically based analyses

The initial analysis of results was based on *hits*, defined as the overall proportion of changes in which some change was detected, and *false alarms*, defined as the proportion of no-change trials in which the participant incorrectly indicated that there was a change. Based on these proportions it was possible to estimate the number of items of the tested shape loaded into working memory, k_x, where x is the tested shape (which was the to-be-attended circles, a, or the to-be-ignored triangles, i). The formula (after Cowan, 2001) is based on the notion that, for these 2-item sets, the likelihood that the probed item is in working memory is $k_x/2$. If so, the participant knows whether there has been a change. If the probed item is not in working memory (which occurs on

1 – $k_x/2$ of the trials with this tested shape), then the participant must guess 'change' with some probability g reflecting the participant's bias. These assumptions lead to the formula,

$$k_x = 2(\mathit{hits} - \mathit{false\ alarms}) \qquad (1)$$

The k_a and k_i values, for the shapes to be attended and ignored, respectively, can be used in two basic ways. First, their sum ($k_a + k_i$) provides an estimate of the total number of items that the individual entered into working memory on each trial.

Second, they can be used to assess the efficiency of the allocation of attention preferentially to the items of the shape to be attended. One estimate is the difference between values for attended and ignored shapes ($k_a - k_i$). Although Cowan *et al.* (2010b) used that metric, it may be impure inasmuch as the difference measure could depend on capacity. We consider here another metric that, in hindsight, seems more compelling, the proportion of remembered items coming from the set to be attended [$k_a/(k_a + k_i)$]. It more directly reflects the concept that a limited capacity can be divided up into different proportions, according to the allocation of attention. We know of no way to use proportion correct to obtain a comparably principled measure of the allocation of working memory to more- versus less-relevant items.

The k measure should be thought of as the number of items loaded into working memory, not the capacity *per se*. The difference is that k validly reflects the number of items loaded into working memory even if ceiling effects in some of the adults prevent a fair estimate of their capacity. Note that an age difference in k still would indicate an age difference in capacity.

The k measure here also can be considered a nonparametric signal detection measure based on a double high threshold model. It is more appropriate than a d′ measure of signal detection, inasmuch as the proportion of hits in this type of procedure is, across response-bias changes, a linear function of the proportion of false alarms (Rouder *et al.*, 2008). That is unlike the curvilinear functions usually obtained in perception and long-term memory procedures, which conform to a parametric model of signal detection. The linear function implies that there is no partial knowledge of an item; it is in working memory or out of working memory (cf. Zhang & Luck, 2008).

We also briefly report proportion correct and use it to examine performance separately for each probe type shown in Figure 1.

Results

Items in working memory

Measurement using *k* scores

Figure 3 shows the number of items in working memory, summed across both to-be-attended and to-be-ignored shapes ($k_a + k_i$), for the three articulation conditions in this study and, for comparison, in the comparable 80%–20% trial blocks of Cowan *et al.* (2010b), in which the presentation of array items was brief and simultaneous. An ANOVA of the present results with age group between participants and articulation condition within participants produced large main effects of age group, $F(2, 87) = 29.98$, MSE = 0.76, $\eta_p = .41$, $p < .001$, and articulation condition, $F(2, 174) = 53.00$, MSE = 0.29, $\eta_p = .38$, $p < .001$, but no interaction between them, $F(4, 174) = 1.68$, $p = .16$. Newman-Keuls post-hoc analyses indicated that all age groups differed from one another at $p < .05$, as did all articulation conditions. The number of items in working memory increased steadily with age. The basis of the effect of articulation condition was that the number also increased in the transition from required silence to required naming of the colors of all items as they appeared, and then markedly decreased again in the transition from required naming to required pronunciation of an irrelevant word.

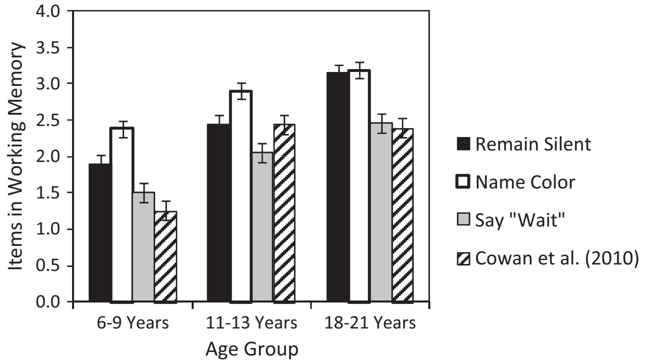

Figure 3 *The mean number of items in working memory in each age group. The first three bars within each age group reflect different conditions of the required verbal response after each presented item. The fourth bar within each age group reflects the comparable 80%–20% condition from Cowan, Morey, AuBuchon, Zwilling and Gilchrist (2010b), which involved brief simultaneous presentation of the array items. Error bars are standard errors.*

In the fairest estimate of the growth of capacity, $k_a + k_i$ in the suppression condition, notice that the increase is greatest between the younger and older children, though still increasing between the older children and the adults (Figure 3).

To examine the interaction of age group and articulation conditions with more power, we returned to the k scores and calculated the benefit of naming (name – silent) and the cost of suppression (silent – suppression) for each individual. Analysis of the benefit of naming revealed a main effect of age group, $F(2, 87) = 3.15$, MSE = 0.59, $\eta_p = .07$, $p < .05$. Newman-Keuls tests indicated that the adults benefitted from required naming less than the older children, $p < .05$. In contrast, the cost of suppression did not reliably distinguish between the groups, $F(2, 87) = 1.03$, $p = .36$. These analyses suggest that the silent condition in this experiment is not a good indication of the growth of capacity, given the likely role of articulation processes in the older participants.

The suppression condition is theoretically closest in its effect to the brief simultaneous presentation of items used by Cowan *et al.* (2010b) because verbal articulation and rehearsal are typically not used to retain such arrays, with adults' performance on them unaffected by articulatory suppression (e.g. Morey & Cowan, 2004). Figure 3 does show that the k measures in these two cases are fairly similar (cf. the rightmost two bars for each age group). In an ANOVA comparing the results of Cowan *et al.* (2010b) to the present suppression condition, there was no effect of experiment, $F(1, 174) = 0.05$, $p = .83$. In contrast, there were main effects of experiment when the 2010 results were compared to the present silent condition, $F(1, 174) = 54.07$, MSE = 0.53, $\eta_p = .24$, $p < .001$, or to the present naming condition, $F(1, 174) = 17.74$, MSE = 0.56, $\eta_p = .09$, $p < .001$, indicating the working memory advantages of sequential presentation with no conflicting articulation task (Figure 3).

Proportion correct

In Table 1, a response was counted correct only if the right kind of response was chosen. In particular, if the color was new or belonged to an item of the other shape, credit was given only for the door icon response and, if the color was from an item of the same shape at a different location, credit was given only if the participant selected a box other than the one with the probe in it. An analysis of the proportion correct produced the same effects as the k scores.

Efficiency of attention allocation

Measurement using k scores

The principled measure of attention allocation was the proportion of remembered items from the set to be attended $[k_a/(k_a + k_i)]$. It is shown in Figure 4 for all articulation conditions of this experiment and, for comparison, in the 80%–20% trial blocks of Cowan *et al.* (2010b), which used rapid, simultaneous presentation of array items. (A few participants yielded negative numbers for this ratio, which were adjusted upward to zero.) An ANOVA of this measure in the present study with the same factors as used in the analysis of items in working memory still did not produce an effect of age group, $F(2, 174) = 1.59$, $p = .21$, or a significant interaction of age group with articulation condition, $F(4, 174) = .95$, $p = .44$. Neither did it produce a significant main effect of articulation condition, $F(2, 174) = 2.59$, $p = .08$. The proportions were significantly above .5, indicating consistent preferential treatment of items to be attended as opposed to ignored, in both the younger children (.58) and older children (.57), though not in adults (.53), pooled SEM = 0.02. It may be that adults

Table 1 *Proportion correct in every condition within every age group*

		Articulation condition					
		Remain silent		Name color		Say 'wait'	
Change type	Attention condition	Mean	*SE*	Mean	*SE*	Mean	*SE*
Grades 1–2							
No change	Attend	0.70	0.03	0.78	0.03	0.58	0.03
	Ignore	0.63	0.05	0.72	0.04	0.60	0.05
Location change	Attend	0.48	0.04	0.66	0.04	0.45	0.04
	Ignore	0.40	0.07	0.57	0.06	0.37	0.06
New color	Attend	0.85	0.03	0.94	0.02	0.78	0.03
	Ignore	0.72	0.06	0.85	0.04	0.73	0.06
Other shape's color	Attend	0.60	0.04	0.37	0.03	0.54	0.04
	Ignore	0.43	0.06	0.35	0.06	0.50	0.08
Grades 6–7							
No change	Attend	0.85	0.02	0.81	0.02	0.71	0.03
	Ignore	0.71	0.05	0.80	0.04	0.65	0.05
Location change	Attend	0.69	0.06	0.80	0.04	0.57	0.05
	Ignore	0.55	0.08	0.62	0.07	0.45	0.07
New color	Attend	0.92	0.02	0.98	0.01	0.84	0.03
	Ignore	0.83	0.05	0.98	0.02	0.85	0.05
Other shape's color	Attend	0.51	0.05	0.37	0.05	0.60	0.04
	Ignore	0.35	0.06	0.47	0.07	0.60	0.07
Adult							
No change	Attend	0.88	0.02	0.89	0.02	0.80	0.02
	Ignore	0.87	0.03	0.84	0.03	0.72	0.04
Location change	Attend	0.79	0.04	0.77	0.03	0.57	0.04
	Ignore	0.70	0.07	0.72	0.07	0.47	0.07
New color	Attend	0.94	0.02	0.99	0.01	0.87	0.03
	Ignore	0.93	0.04	0.93	0.03	0.90	0.04
Other shape's color	Attend	0.59	0.06	0.45	0.04	0.65	0.04
	Ignore	0.52	0.07	0.45	0.08	0.60	0.07

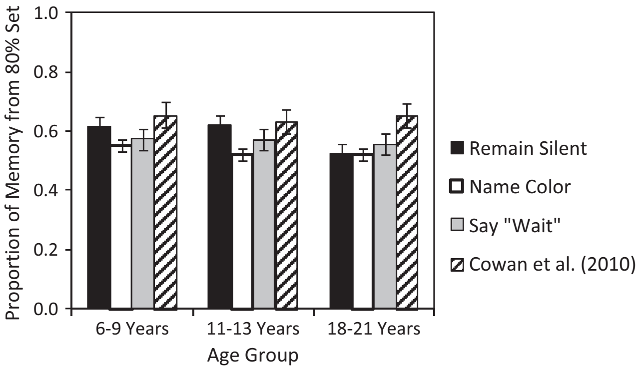

Figure 4 *The mean proportion of remembered items that came from the set that was to be attended and was tested on 80% of the trials. The first three bars within each age group reflect different conditions of the required verbal response after each presented item. The fourth bar within each age group reflects the comparable 80%–20% condition from Cowan, Morey, AuBuchon, Zwilling and Gilchrist (2010b), which involved brief simultaneous presentation of the array items. Error bars are standard errors.*

have less need to allocate attention preferentially to more-relevant items because they have enough capacity to encode most items. Analyses of the benefit of naming and of the cost of suppression showed no effects of age group.

As in the analysis of items in working memory, the results for the efficiency of attention were compared across experiments. As illustrated in Figure 4, the efficiency was higher in Cowan *et al.* (2010b) than in the present experiment, resulting in an effect of experiment in a comparison of the 2010 data with the naming condition, $F(1, 172) = 15.00$, $MSE = 0.04$, $\eta_p = .08$, $p < .001$, and with the suppression condition, $F(1, 172) = 5.36$, $MSE = 0.05$, $\eta_p = .03$, $p < .05$. In none of the conditions did the interaction of experiment with age group approach significance; in each case $F(2, 172) < 1.11$, $p > .33$. Children in both age groups allocated attention at least as well as adults did. That may be because adults could better afford to remember the less-relevant items in addition to the more-relevant items, given their larger capacity.

Proportion correct

In an ANOVA of proportion correct (Table 1), more- and less-relevant probed shape conditions were entered separately into the analysis. There was a significant advantage for more-relevant ($M = .83$, $SEM = .01$) compared to less-relevant ($M = .78$, $SEM = .01$) items, $F(2, 87) = 17.54$, $MSE = .01$, $\eta_p = .17$, $p < .001$. There were no interactions with age group (relevance × age group: $F(2, 87) = 0.76$, $p = .47$; relevance × age group × articulation condition, $F(4, 174) = 1.61$, $p = .17$), again suggesting that the relevance manipulation was effective across age groups.

Performance in different trial types

An ANOVA of proportion correct (as shown in Table 1) to examine performance in different trial types included age group as well as several within-participant factors: the articulatory condition, the to-be-attended versus to-be-ignored status of the probed item's shape, and the probe type (no change, location change, new color, and other shape's color). Only effects that include the probe type will be discussed, as the other effects are logically redundant with the previous analyses and are consistent with them. First, there was a huge main effect of the probe type, $F(3, 261) = 121.88$, $MSE = .13$, $\eta_p = .58$, $p < .001$. As in Cowan *et al.* (2010b), performance was best for new colors ($M = .88$, $SEM = 0.01$), slightly worse for no-change trials ($M = .75$, $SEM = .01$), rather worse still for location-change trials ($M = .59$, $SEM = 0.02$), and worst of all when the probe color was drawn from an item of the other shape ($M = .50$, $SEM = 0.02$). Newman-Keuls tests showed that all of these means differed from one another.

The probe type interacted with the articulation condition, $F(6, 522) = 19.67$, $MSE = 0.07$, $\eta_p = .18$, $p < .001$. This was a crossover interaction. For three probe types, performance increased from silence to color-naming and then decreased markedly for articulatory suppression. This was the case for no-change probes ($M = .77$, .80, and .68 for the three articulation conditions, respectively), location-change probes ($M = .60$, .69, and .49), and new-color probes ($M = .87$, .95, and .83). When the probe was the color of an item of the other shape, though, the pattern was changed ($M = .50$, .41, and .58). Here suppression actually improved performance compared to silence or color-naming. One explanation is that, in the absence of verbal encoding of the color in the suppression condition, the shape and color are both encoded integrally as an image (i.e. bound together), making it less likely that one shape's color could be mistaken for the color of an item in the other shape. The effects of the trial type did not interact with age group, $F(6, 261) = 1.08$, $p = .38$.

Discussion

Cowan *et al.* (2010b) found that an increase in working memory ability during the elementary school years could not be accounted for by the ability to allocate attention to the more relevant stimuli, thus avoiding clutter in working memory. In particular, in arrays with two more-relevant and two less-relevant stimuli, children in Grades 1–2 favored the more-relevant stimuli to the same degree as older children (Grades 6–7) and adults (college students). Yet, the younger children appeared to have held considerably fewer items in working memory. The present work establishes the generality of that finding and clarifies the reason for it. In particular, it shows that this age difference in working memory ability cannot be attributed to young children's inability to encode items from a quickly presented array. Here we presented items one at a time at a slow, 1 item/s rate, and found a similar age difference. We also found that the age difference remained no matter whether verbal encoding and rehearsal processes were left uncontrolled, were encouraged through required color-naming during item presentations, or were discouraged through required pronunciation of an irrelevant word during item presentations. Taken together, these findings strengthen the conclusion that there is an increase in visual working memory holding capacity during the elementary school years and, to a lesser degree, between those years and adulthood. Neither the ability to allocate attention nor the ability to encode stimuli verbally can explain that developmental change.

The findings in the older age groups differ slightly from the findings of Cowan *et al.* (2010b). They found capacity in the adults that was not substantially higher than in the older children, whereas the present procedure yielded significantly increased capacity from one age group to the next. The difference between experiments appears to be that older children used some verbal mediation of visual working memory for sequential visual arrays, and therefore performed worse for sequences under articulatory suppression than for simultaneous visual arrays in the 2010 study, unlike the other age groups (Figure 3). This could reflect a developmental phase as children shift their working memory reliance from visual to verbal information (Hitch, Halliday, Schaafstal & Schraagen, 1988), even though adults do not seem to rely on verbal information to retain visual arrays (Morey & Cowan, 2004).

The experiment replicated Cowan *et al.* (2010b) in showing no significant age differences in the preferential allocation to items in the more-often-tested shape. In fact, the trend was toward the most efficient allocation of attention in the youngest group. We suspect that the lower capacity in the youngest group could have encouraged them to try to be selective, whereas older participants had enough capacity to attempt to encode all items. The preferential treatment of the more-often-tested shape was strongest in the silent condition, whereas requiring a certain type of encoding process for all items understandably tended to negate participants' ability to be preferential in their encoding of items into working memory.

It will take a multi-pronged attack to establish beyond a doubt that basic working memory capacity increases in childhood. Early studies making that contention relied upon various assumptions about how items were encoded (Burtis, 1982; Case, 1972; Pascual-Leone & Smith, 1969). What we have tried to do more recently is to manipulate and measure encoding processes, rather than rely on assumptions about them. For example, Cowan, Hismjatullina, AuBuchon, Saults, Horton, Leadbitter and Towse (2010a) showed children and adults pictures arranged in consistent pairs or triplets, and then tested memory for lists composed of pictures from one condition. In the memory test, younger children performed poorer than older ones in their access to the pre-exposed chunks, where access was defined as the proportion of chunks for which at least one item was recalled. They also had lower scores for the completion of accessed sets. Although either or both of these measures could be taken simply to indicate overall poorer recall in younger children, the evidence specifically for a growth in capacity was that the increase across age groups in multi-item chunk access remained significant even with statistical control for the increase in completion of those chunks. Gilchrist, Cowan and Naveh-Benjamin (2009), using lists of simple, unrelated sentences as the stimuli to be recalled verbatim, found developmental growth in access to clauses (i.e. the proportion of clauses for which at least one word of substance was recalled), despite the absence of a developmental change in the completion of clauses that were accessed. The present study adds to this progress in demonstrating that the manner of encoding stimuli cannot account for developmental increases in working memory capacity during the elementary school years.

Recent work has led to some clear hypotheses regarding what aspects of brain function could account for an increase in visual (and perhaps general) working memory capacity. The inferior part of the intraparietal sulcus produces neural activity that increases with memory load, but only up the participant's span measured behaviorally (Todd & Marois, 2004; Xu & Chun, 2006). This area also appears to develop richer myelination with working memory practice in adults (Takeuchi, Sekiguchi, Taki, Yokoyama, Yomogida, Komuro, Yamanouchi, Suzuki & Kawashima, 2010). Therefore, one might expect that this area continues to mature during the elementary school years, an expectation that is in keeping with findings about brain development (e.g. Gogtay, Giedd, Lusk, Hayashi, Greenstein, Vaituzis, Nugent, Herman, Clasen, Toga, Rapoport & Thompson, 2004).

There are both theoretical and practical issues that remain unresolved. Theoretically, it is not clear why the limit in working memory capacity occurs. Two leading theories involve speed mechanisms. In one theory, it is the speed at which an attentional refreshing process can be used to reactivate items before their neural activation decays from working memory (Barrouillet *et al.*, 2009). In another theory, it is the speed at which neural representations of different items can fire in sequence within one cycle of a limiting, slower neural rhythm (Lisman & Idiart, 1995; Luck & Vogel, 1998; Siegel, Warden & Miller, 2009). It is not really clear whether these theories are mutually compatible, or even if they can refer to the same time scale. It is also not clear whether, instead, multiple items' representations could be in the same active state within working memory virtually at the same moment, as in a literal interpretation of Cowan (1988).

One point of practical interest is the strong correlations between working memory ability and broad aspects of cognitive development (e.g. Gathercole *et al.*, 2004; Lépine, Barrouillet & Camos, 2005; Hitch *et al.*, 2001), which has been observed even for visual array item recognition tasks such as the present one (Cowan *et al.*, 2005; Cowan *et al.*, 2006a). However, there is as yet no clear estimate of the extent to which cognitive development depends on working memory capacity expressed in items *per se* as opposed to, say, memory for the relation between items (Andrews & Halford, 2002) or for the speed of mnemonic processing (Case *et al.*, 1982; Lépine *et al.*, 2005). Moreover, in some circumstances, apparently unlike the present one, the ability to engage in sophisticated rehearsal strategies is critical (Cowan *et al.*, 2006b; Flavell *et al.*, 1966; Ornstein *et al.*, 1975) so a better understanding is needed of the conditions under which capacity limits versus strategic abilities dominate age differences in performance. In any case, now that it seems clear that capacity measured in items does increase with development, the practical consequences of this finding warrant intensive investigation.

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