



Development of working memory for verbal–spatial associations [☆]

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Abstract

Verbal-to-spatial associations in working memory may index a core capacity for abstract information limited in the amount concurrently retained. However, what look like associative, abstract representations could instead reflect verbal and spatial codes held separately and then used in parallel. We investigated this issue in two experiments on memory for associations between names and spatial locations, with or without a 1-to-1 correspondence between the two. Participants (children 9–10 and 12–13 years old and college students) saw series of names presented at spatial locations occupied by house icons and indicated the location at which a probe name had appeared. Only adults benefited from 1-to-1 correspondence between names and locations, and this benefit was eliminated by articulatory suppression. We maintain that the 1-to-1 benefit stems from verbal and spatial codes used in parallel. Without rehearsal, performance appears to index working memory for abstract, cross-modal information. Correlations with other tasks suggest that it is an excellent measure of working memory capacity.

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Introduction

Working memory can be defined as the set of mental processes that make a limited amount of information temporarily accessible for the completion of ongoing cognitive tasks. Descriptions of the working-memory system have varied widely (see Miyake & Shah, 1999) and a central question has been about the nature of the information stored in working memory. In a popular

model, Baddeley (1986) proposed that information is saved in phonological and visuospatial forms in separate, code-specific buffers (also see Baddeley & Hitch, 1974). However, this theoretical formulation left out some other types of information that might be needed in working memory. A key type, in particular, is memory for abstract information in the form of associations between verbal and spatial codes, addressed later (e.g., in the episodic buffer of Baddeley, 2000; or in the focus of attention of Cowan, 1999, 2001).

Working memory for verbal–spatial associations is important for both theoretical and practical reasons. Theoretically, it is important for an understanding of working memory capacity. The common conception of both verbal and spatial items in working memory is that, once they are encoded, they are held for a short period

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with little or no effort (Baddeley, 1986). Displacement comes from other items with similar features (e.g. Brooks, 1968). In contrast, however, much of the information that must be retained in working memory is more abstract, including concepts (e.g., while solving a problem: Phillips, Gilhooly, Logie, Della Sala, & Wynn, 2003), propositions (e.g., while comprehending text: Haarman, Davelaar, & Usher, 2003), and, as in the present work, associations between different types of information. Exemplifying the latter for verbal–visual associations, one might have to keep track of which name goes with which person, or which road name goes with which road on a map (given that the names may be too small and numerous to be re-read many times while navigating). Very little is known about working memory capacity for abstract types of information. For practical purposes, as well, it seems important to learn about the limits of these basic types of working memory relevant to comprehension and problem-solving.

There are some leads from research on quite diverse topics in working memory (for a review see Cowan, 2005), including the retention in working memory of data structures (Ericsson & Kintsch, 1995), complex relations between items (Halford, Baker, McCredden, & Bain, 2005), conceptual information (Potter, 1993), conflicting associations (Sohn, Anderson, Reder, & Goode, 2004) and the binding of different types of visual features (Wheeler & Treisman, 2002). However, we know of only one investigation of verbal–spatial associations in working memory (Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000). Also, Postma and de Haan (1996) examined memory for object locations and found a verbal component in the maintenance of the object information.

A problem in trying to ascertain the role of abstract information in working memory is that it is difficult to rule out the use of code-specific information. For example, if one is trying to keep in mind the concepts of liberty, equality, and fraternity, one can do so directly, or one can remember the lexical (or perhaps phonological) codes and regenerate the conceptual information from each of them as it is needed. It seems possible to rule out the use of a specific code, though, in the case of cross-code associations. It would be impractical to retain the association between a name and its location in space solely via verbal coding, or solely via spatial coding. This makes it an attractive case for the study of abstract information in working memory.

There is, nevertheless, a way in which verbal and spatial codes might be used together to preserve verbal–spatial associations, circumventing the need to retain abstract information. Verbal and spatial codes could be retained separately and then used in parallel. Consider, for example, a test situation used in the present research, which we term the *verbal-to-spatial mapping task*. At the beginning of a trial, several locations are

marked with pentagons schematically representing houses at different locations in the visual field. Next, names are temporarily presented one at a time, with each name centered in one of the pentagons as shown in Fig. 1A. Last, a probe name is presented and the computer mouse is to be used to indicate which pentagon contained that name. One way to carry out that task is to remember the associations between names and spatial locations and then retrieve the correct association corresponding to the probe item. However, an alternative strategy would be to encode and retain a verbal list (in the figure, *Beth, Ann, Ruth*) and also a spatial path (in the figure, the top right, the top left, and then the bottom locations). When the probe item (in the figure, *Ann*) is presented, the verbal list would be covertly recited to find its serial position (*Beth, Ann*: Position 2) and the spatial path would be traced to identify the appropriate position (Position 2: after the top right, the *top left*). With this strategy, no cross-code associative information would have to be retained in working memory after all.

The potential benefit of the parallel use of verbal and spatial serial order information is that the relevant codes might be automatically retained for a few seconds, with no strict capacity limit and no need to invest attention during that amount of time (Baddeley, 1986). Some form of rehearsal probably is required to refresh these codes and maintain serial order information long enough for it to be of use (e.g. Henson, Hartley, Burgess, Hitch, & Flude, 2003) but this rehearsal is not supposed to be very attention-demanding, at least in adults (Baddeley, 1986). Supporting this supposition, results of a secondary probe task show that covert verbal maintenance rehearsal is relatively automatic in adults, though it is attention-demanding in children old enough to begin rehearsing (Guttentag, 1984).

It seems unlikely that sophisticated rehearsal strategies would be similarly useful for the actual retention of verbal–spatial associative information. One can perhaps imagine a simple joint rehearsal strategy such as “Beth... here (attending to the location).” However, it would be cumbersome to use a totally verbal rehearsal strategy (e.g., “Beth... top right location”), or a totally visual rehearsal strategy in which a mental image is formed of the visual shape of the word in its location. These would become especially cumbersome as list length increases. The relevant cross-code rehearsal strategy would not appear to be serial in nature, and instead would amount simply to paying attention to the relevant verbal and spatial information at the same time (Cowan, 2001). In contrast to the parallel use of verbal and spatial codes, the storage of abstract information such as verbal–spatial associations therefore presumably taxes attention. It seems limited to a small number of items at once (Baddeley, 2001; Cowan, 2001). If abstract information instead is stored in long-term memory for later retrieval (Baddeley & Logie, 1999; Ericsson & Kintsch,

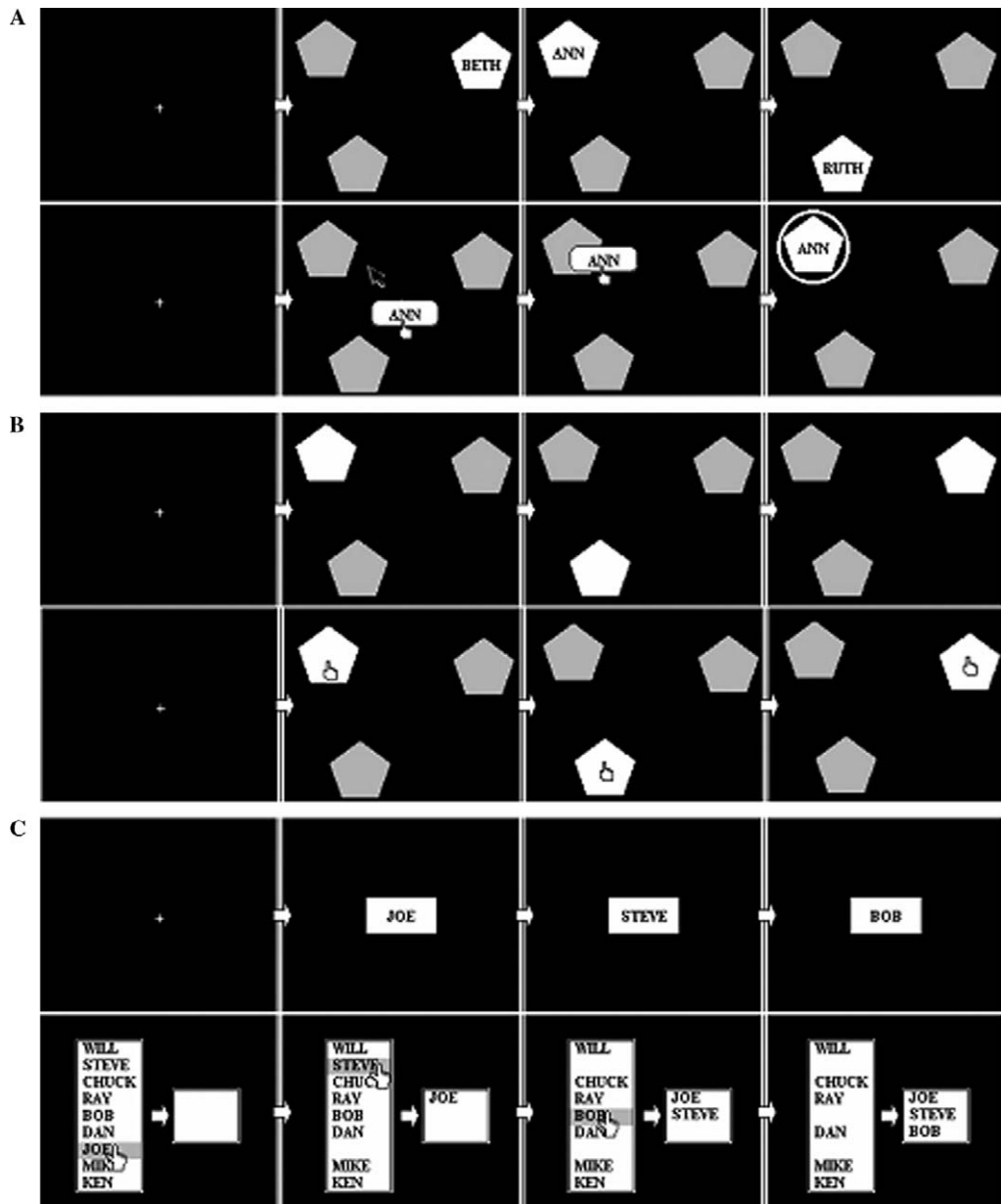


Fig. 1. A depiction of three working memory tasks. (A) Verbal-to-spatial mapping task. (B) Spatial span task. (C) Name span task. For each task, the first row depicts steps in the presentation of stimuli and the second row depicts steps in a correct response. The circle surrounding a pentagon in the last frame of the second row is feedback and would be green because the response was correct, but it would have been red otherwise. The verbal-to-spatial mapping task required one response per trial, whereas the spatial span and name span tasks required that all items be recalled in the presented order.

1995), it still could require considerable attention during retrieval (Naveh-Benjamin & Guez, 2000).

Key variables

A key feature of the present study is that some convergent manipulations are included to help distinguish

the use of associative information from the parallel use of verbal and spatial information. Experiment 1 is a developmental study, on the supposition that young children do not engage in the sophisticated type of rehearsal necessary to carry out the parallel use of verbal and spatial information (described above). Although they begin simple covert rehearsal by about 7 years of

age, there is a progressive improvement in the use of rehearsal and other strategies during the elementary school years (Bjorklund & Douglas, 1997; Flavell, Beach, & Chinsky, 1966; Ornstein & Naus, 1978; Schneider & Sodian, 1997). We selected third- and sixth-grade children and adults based on informal observations indicating that they were old enough to succeed at the task (given well-established basic reading skills) but, at least in the case of third-grade children, young enough to have immature mnemonic strategies.

Experiment 1 also included conditions designed to encourage versus discourage the parallel use of verbal and spatial codes (as opposed to associative information). In some trials, there was a 1-to-1 correspondence between spatial locations and names assigned to them. In other trials (termed *uneven*), there still were equal numbers of names and spatial locations, but not in a 1-to-1 correspondence pattern. Instead, some locations were not assigned any names and others were assigned two names that were non-adjacent in the list. Returning to some spatial locations twice can be viewed as increasing the spatial path complexity, which should increase the difficulty of retaining spatial path information (Kemps, 2001), discouraging the parallel use of a verbal sequence and a spatial path in memory. However, this uneven presentation also decreases the total number of locations that are associated with names, potentially making it easier to use verbal–spatial associative information. We expected that adults would prefer the parallel use of verbal and spatial path rehearsal when possible, and therefore would perform better in the 1-to-1 condition. In contrast, we expected that third-grade children would not be able to carry out the parallel-use strategy and therefore would be limited to the potentially more effortful, albeit more straightforward, strategy in which associative information is remembered. Therefore, they were expected to perform at least as well, and possibly better, in the uneven condition than in the 1-to-1 condition. Sixth-grade children were expected to be intermediate between the other groups and were included to provide insight into the nature of the developmental transition. Finally, in Experiment 2, a rehearsal-blocking task was used in adults to prevent the parallel-use strategy, which should make them respond like young children.

We know of no prior studies of individual differences in forming or remembering verbal–spatial associations. There is evidence that the learning of verbal–visual (name–face) associations is selectively impaired with aging (Naveh-Benjamin, Guez, Kilb, & Reedy, 2004) but we find no comparable work in the domain of working memory. There also is little direct information on childhood developmental changes in the use of associative information in working memory. Recent studies show that the ability to retain associations between objects and their locations, or between object parts, improves with development in infancy (Oakes, Ross-Sheehy, &

Luck, *in press*) and childhood (Cowan, Naveh-Benjamin, Kilb, & Sauls, *in press*; Lorschach & Reimer, 2005; Sluzenski, Newcombe, & Kovacs, 2006). However, we can find no previous study of the childhood development specifically of *verbal–spatial* associations in working memory. There is evidence that children are capable of forming such associations (e.g., in learning the names of body parts; Johnson, Perlmutter, & Trabasso, 1979). Verbal–spatial associations also are implicated in the ability to understand the locations of objects depicted in maps, a skill that improves in the preschool and early elementary school years (e.g. Uttal & Wellman, 1989).

The importance of individual differences

A secondary purpose of this research is to further the discussion of what might constitute an ideal measure of working memory for the purpose of understanding individual differences in cognition. For reasons to be explained, we suspect that tasks requiring verbal–spatial associations might be good candidates because they measure working memory for abstract information, for which capacity is limited.

Typically, measures of working memory have been considered close correlates of various types of intellectual aptitude if they include separate storage and processing components (e.g. Conway, Cowan, Bunting, Theriault, & Minkoff, 2002; Conway et al., 2005; Daneman & Merikle, 1996; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Kyllonen & Christal, 1990). In such tasks, each processing episode is followed by a word to be retained. The processing episodes have included sentences to be comprehended, in listening or reading span (Daneman & Carpenter, 1980); arrays to be counted, in counting span (Case, Kurland, & Goldberg, 1982); and mathematical equations to be solved, in operation span (Turner & Engle, 1989). After the last processing episode, the words are to be recalled and the length of the word list that can be recalled along with successful processing is the working memory span. The original rationale for such tasks was that resources are shared between storage and processing, and that recall depends on efficient processing, which is what these tasks presumably measure.

Cowan et al. (2005) have suggested, however, that it is not necessary to include separate storage and processing task components to obtain a good measure of working memory. The combination of storage and processing may work by restricting the use of mnemonic strategies that can supplement a basic working-memory capacity (cf. Conlin, Gathercole, & Adams, 2005; Friedman & Miyake, 2004; Lépine, Barrouillet, & Camos, 2005). Such strategies may include grouping items into larger chunks and engaging in covert verbal rehearsal. Another way to prevent such strategic processing is to present lists or arrays of

items in such a way that they cannot be rehearsed during presentation (e.g., Cowan, 2001; Cowan et al., 2005). For example, Cowan et al. used a running memory span procedure (based on Cohen & Heath, 1990) with a rapid, 4 items/s presentation rate. From 12 to 20 spoken digits were presented and, when the list ended, the task was to recall as many items as possible from the end of the list in the presented order. Given the fast rate and unpredictable stopping point, it was impossible to rehearse items or rehearse an updated list of the most recent items. (On that point see also Hockey, 1973.) High correlations with aptitude were obtained even though the measures such as running span did not include separate storage and processing components. It is not known whether the high correlations result from individual differences in the core capacity limit or in the ability to use a sophisticated mnemonic strategy despite the restrictions of the task.

The verbal-to-spatial mapping task also should index basic working memory capacity without including separate storage and processing components, if in fact it depends substantially on either verbal–spatial associative information for which capacity is limited, or a sophisticated method of overcoming that limit. To examine the viability of this measure for individual-difference studies, we compare the verbal-to-spatial mapping task to performance on counting span and running span tasks. We also examine performance on tasks limited to single modalities involved in verbal-to-spatial mapping: a spatial span task (Fig. 1B) that is like the Corsi task (Berch, Krikorian, & Huha, 1998) and a name span task (Fig. 1C) similar to other word span tasks (e.g. Case et al., 1982). We use these tasks to show that the verbal-to-spatial mapping task picks up individual variation beyond the component tasks considered jointly, another way of implicating memory for the verbal–spatial associations.

Experiment 1

Method

Participants

The 96 participants included 32 third-grade children (mean age = 103.56 months, $SD = 4.26$), 32 sixth-grade children (mean age = 143.16 months, $SD = 4.36$), and 32 college students (mean age = 227.99 months, $SD = 10.93$). In each age group, there were 16 male and 16 female participants. Children were recruited from the community and paid, whereas college students participated as part of an introductory psychology course requirement. All participants reported normal or corrected-to-normal vision and hearing and spoke English as their first language.

Apparatus, stimuli, and procedure

Testing was conducted in 85–95 min sessions individually with each participant, in a quiet room. The computer was equipped with headphones and desktop loudspeakers. The experiment consisted of five different tasks, in the same order for all participants to minimize method-based variation between them, given our interest in individual differences: (1) the verbal-to-spatial mapping task, (2) the spatial span task, (3) the name span task, (4) the counting span task, and (5) the running span task. Each task is described below.

Verbal-to-spatial mapping task. In this task, participants were shown the locations of some verbal labels and then, after a short delay, had to place one of those verbal labels in the correct location. This is illustrated for a 3-location trial in Fig. 1A. The verbal labels were two sets of common, phonologically distinct, one-syllable names. One set consisted of girls' names, *Ann, Beth, Grace, Dawn, Ruth, Eve, Liz, Marge,* and *Joy*, and the other set consisted of boys' names, *Bob, Dan, Joe, Mike, Ken, Chuck, Will, Steve,* and *Ray*. The sets were never mixed within a trial. The locations were marked by gray pentagons (resembling houses, all identical) on a black background. Each pentagon was 29 mm in diameter, subtending a visual angle of about 3.5° at a viewing distance of 50 cm. The rest of the computer screen was black, so this display area had no visible border. On each trial, from three to seven pentagons were randomly arranged with the restriction that the distance between the centers of any two pentagons, and between any pentagon and the center of the viewing area, were at least 7° of visual angle.

The same number of names as pentagons was presented on each trial. However, there were two kinds of trials, which differed in the way names were matched to locations. In the *1-to-1 correspondence* trials, each name appeared in a different location. In the *uneven assignment* trials, in contrast, at least one location had two names appear in that pentagon, and thus at least one pentagon did not have any name appear in it. Still, there were restrictions placed on the randomization: Two names presented consecutively never appeared in the same location, and no location ever had more than two names on the same trial. In the uneven assignment trials with 3–7 pentagons, the mean numbers of pentagons with names assigned to them were 2.00, 2.75, 3.75, 4.00, and 4.75, respectively. The mean numbers of names per non-empty pentagon thus were 1.50, 1.45, 1.33, 1.50, and 1.47, respectively.

A trial began with the presentation of a white fixation cross for 1 s. Next, the arrangement of 3–7 gray pentagons was shown for 1 s. Then names were shown in their locations, one at a time. This occurred when one of the pentagons changed to white with a name in its center. The name was in black letters 4.5 mm high. After 1 s, the name disappeared and the pentagon changed back

to gray. One second later, another name appeared in a pentagon as it turned white for 1 s. This sequence of a name every 2 s, displayed for 1 s, continued until all names for that trial were shown. After a delay of 2 s (fixation cross only), the gray pentagons reappeared. One of the names appeared in a small white box in the center of the screen, attached to a hand cursor, and could be moved with the computer mouse. The participant was to try to remember which pentagon contained that name, move the name to that location, and click the mouse button. If the selected location was the correct answer, a green circle appeared around that pentagon. Otherwise, a red circle appeared around the correct pentagon. The participant started the next trial when ready.

One block of 6 practice trials included a 1-to-1 and an uneven trial at each of three list lengths: 3, 5, and 7. Half of these practice trials used boys' names and the other half used girls' names. Participants were told "We're going to play a game where you try to remember where some boys or girls were, after you see their names in different places." They were then asked to read lists of the boys' and girls' names aloud. Reading mistakes were immediately corrected. The experimenter then proceeded to the practice trials. If the participant failed the first 3-name practice trial, the experimenter queried the participant's understanding of the task and provided guidance as needed. After the practice trials, the experimenter explained that the next trials would be the same, except that they only use boys' names (or girls' names, depending on which block was first). Again, the participant was to read aloud the list of names to be used in the next block of trials. There were two blocks of experimental trials, one using only boys' names and the other, only girls' names. The order of blocks was counterbalanced across participants for each gender and age group. (For each participant, the same order was used in the name span task described below.) Each block had 20 trials, including two 1-to-1 trials and two uneven trials at each of five list lengths: 3, 4, 5, 6, and 7 names and locations. These trials were intermixed in a pseudo-random order that was used for all participants.

Spatial span task. In this task, illustrated in Fig. 1B, participants were shown a sequence of locations and then, after a short delay, had to reproduce the sequence when shown the locations all at once. This task used the same arrangement of spatial stimuli (pentagons) as the mapping task, but without the verbal stimuli. However, it was administered like a typical span task. Three trials of a list length were presented. If the participant got at least one trial correct, the list length increased by one. Each block of trials began with three trials, each with three pentagons or locations. If at least one trial was answered correctly, the participant then tried three trials with four locations each. The participant continued until missing all three trials at a list length or until completing three trials with nine locations, the maximum list length.

Then each participant received slightly different instructions and did the other block of trials in the same manner.

Each trial began with the presentation of a white fixation cross in the center of the screen for 1 s. Next, an arrangement of 3–9 gray pentagons was shown. After 1 s, one of the pentagons turned white for 1 s (i.e., lit up), then back to gray. One second later, another location lit up for 1 s. As in the mapping task, this continued until the total number of times any pentagons lit up was the same as the number of pentagons. After the last pentagon lit up for 1 s, there was a 2-s delay when the screen was blank, except for a white fixation cross. Then, all of the gray pentagons reappeared. The participant was to click the same pentagons that had turned white, in the same order that they had changed. Each pentagon turned white when selected, then back to gray as the participant went on to the next response location. Once the correct number of responses was made, the screen went blank and the participant was free to start the next trial.

Similar to the verbal-to-spatial mapping task described above, there were two kinds of spatial span trials, which differed in the way the lighting events were matched to locations. In the 1-to-1 trials, each location (that is, each pentagon) lit once and only once. In the uneven trials, at least one pentagon lit up twice and thus at least one pentagon did not ever light. Rather than mixing the trial types, separate span determinations were run for the 1-to-1 and uneven conditions. Their order was counterbalanced between participants, as described above.

Name span task. In this task, illustrated in Fig. 1C, participants were shown a sequence of words and then had to reproduce the sequence when shown a list of the complete set of words used in the task. The verbal stimuli were the same boys' and girls' names used in the mapping task, in separate trial blocks. The trials were administered like a typical span task, in two separate blocks with each run using one set of names, boys' or girls'. The counterbalanced order for these blocks was identical to that used in the verbal-to-spatial mapping task. As in the spatial span task, three trials of a list length were presented. If the participant got at least one trial correct, the list length increased by one.

Each trial began with the presentation of a white fixation cross in the center of the screen for 1 s. Next, a white box (31 mm wide by 17 mm high) appeared in the center of the screen. It contained one of the names, which disappeared one second later. One second after that, another name appeared for 1 s. This continued until the box disappeared and only the white fixation cross was visible. Then, 2 s later, the response screen appeared, with two white rectangles and an arrow between. The rectangle on the left (69 mm high by 25 mm wide) contained a vertical list of all the names from the appropriate set, boys or girls. The one on the

right showed the same number of blank lines as words in the list. The participant was to use the mouse to click on the names in the response box, on the left, to match the names in the presented list. Each selected name moved to the box on the right. The participant continued clicking and moving words from the left box to the right, until the box on the right was filled with the number of words in the current list. Then the screen went blank and the participant could begin the next trial.

Counting span task. The version of the counting span task was the same as the one used by Cowan et al. (2005, Experiment 2). Participants counted visual targets aloud and announced the total, in each of several arrays, and then tried to remember and type each of the previous total counts in the same order. The arrays consisted of random arrangements of dark blue circles, light blue circles, and dark blue squares displayed on a black background within an area 223 mm high by 316 mm wide. Participants were instructed to count, aloud, only the dark blue circles, repeat the total aloud, and then press the spacebar to see the next array. After several arrays, the participant heard an auditory cue, which was a 100-ms sawtooth wave presented by generic desktop speakers at about 65 dB(A), and saw a white box cue for their recall answer. The participant was to use the number pad to type the totals in order and then press the “Enter” key. A screen display then announced the number of displays to be seen in the next trial and the participant pressed the spacebar to continue.

The counting span began with three trials with two-array displays. Each participant continued to do trials with one additional array added each time that the participant was correct on at least one trial out of three at a particular list length, up to a maximum list length of seven arrays.

Running span task. In the running span task (see Cowan et al., 2005), participants pressed a key to initiate the trial. Following the word “READY” that appeared on the screen 1 s later and lasted for 1 s, they heard quickly presented lists of uncertain lengths of 12–21 spoken digits. When each list ended, the participant was to try to remember as many digits as possible from the end of the list and type them in the order presented. Each time the participant typed a number, it appeared in the center of the screen.

The lists consisted of randomly arranged time-compressed digits (1–9) played with an intensity of 66–69 dB(A) over audiometric headphones at a rapid presentation rate of 4/s. The digits were spoken in a male voice and digitally recorded. To allow such a rapid rate of presentation, each digit had to fit within a 250-ms window. This was accomplished by compressing the duration of the sound files without changing their pitch, using sound editing software. Since the longest recorded spoken digit had to be compressed by about 68% to fit within a 250 ms window, all of the original files were

compressed this same proportional amount. Still, the digits were quite easily intelligible.

Pseudorandom lists of 12–21 digits were generated with the following two restrictions. First, no digit could be repeated in a 7-item moving window. This avoided the duplication of any digits when recalling the last 7 items, and yet provided no clues to anticipate the end of the list. Second, no 2-digit sequence could occur more than once in a list. This restriction prevented repeating patterns of digit sequences within a list. Two practice trials at lists length 12 and 21 were followed by 30 experimental trials, including 3 consecutive 10-trial blocks, each containing one trial at each list length, from 12 to 21, arranged in a random order.

Results

We present first the age differences in the unimodal tasks; next, age differences in the verbal-to-spatial mapping task; and then correlations between measures and regressions predicting the more conventional counting and running spans from the remaining variables.

Age differences

Unimodal tasks. Two different measures of span were used for the spatial, name, and counting span tasks. The *maximum* measure is the longest list recalled correctly by an individual, whereas the *sum* measure is the number of correctly recalled lists, summed across list lengths. The maximum measure is useful as a guideline to how many items can be recalled correctly, whereas the sum measure proved to be more reliable. For running span, these measures are impossible. Running span is measured as the mean number of items recalled on a trial in the correct serial positions, scored from the end of the list.

All of the unimodal memory tasks produced large effects of age group, as shown in Table 1. Also, in the spatial span task, performance was uniformly higher in the 1-to-1 condition than in the uneven condition, but this effect did not interact with age group (see table note). Although this result may seem intuitively obvious, it is noteworthy that a different pattern was obtained across groups in the verbal-to-spatial mapping task.

Verbal-to-spatial mapping task. Fig. 2 shows the full pattern of results and Table 2 shows the results averaged across list lengths. The analysis of the proportion correct in this task included age group as a between-subject factor and two within-subject factors: the type of trial (1-to-1 or uneven) and the list length (3–7). This analysis produced large main effects of age group, $F(2, 93) = 45.58$, $MSE = 0.10$, and list length, $F(4, 372) = 183.27$, $MSE = 0.04$; p 's < .001. Performance levels were higher for older participants and shorter lists. The main effect of trial type did not approach significance. All possible two-way interactions were significant: Trial Type \times Age Group, $F(2, 93) = 4.62$, $MSE = 0.02$, $p < .05$; List

Table 1
Experiment 1. Proportion correct performance (with SD) on the unimodal span tasks, and age group effects

Task	Age group			Group effect	
	Grade 3	Grade 6	College	<i>F</i> (2, 93)	MSE
<i>Spatial span</i>					
1-to-1(maximum)	5.59 (1.43)	6.72 (1.05)	7.44 (0.88)	21.06*	1.31
Uneven (max.)	4.84 (0.81)	5.69 (1.03)	6.66 (1.04)	28.36*	0.93
1-to-1 (sum)	7.47 (3.06)	11.34 (2.72)	13.50 (2.81)	36.42*	8.21
Uneven (sum)	6.22 (2.34)	8.94 (2.41)	11.38 (2.64)	33.76*	6.08
<i>Name span</i>					
(Maximum)	4.78 (1.07)	5.56 (1.13)	6.91 (1.06)	31.24*	1.18
(Sum)	9.62 (4.56)	14.94 (4.87)	21.72 (5.96)	44.09*	26.66
<i>Counting span</i>					
(Maximum)	3.56 (1.29)	4.09 (1.38)	4.88 (0.87)	9.67*	1.44
(Sum)	4.84 (2.58)	6.03 (3.20)	8.26 (2.45)	11.82*	7.63
<i>Running span</i>	2.09 (0.67)	2.80 (0.74)	3.17 (0.75)	18.56*	0.52

Note. The maximum and sum measures are, respectively, the longest list recalled correctly and the number of correctly recalled lists. Running span is measured as the mean number of items correct. Spatial span analyzed for 1-to-1 and uneven measures together produced significant effects of the measure [for maximum and sum measures, respectively, $F(1,93) = 47.05$ and 53.57 , $MSE = 0.74$ and 3.44], but no interaction with age group [$F(2, 93) = 0.51$ and 1.79 , $p > .60$ and $.17$, respectively].

* $p < .05$.

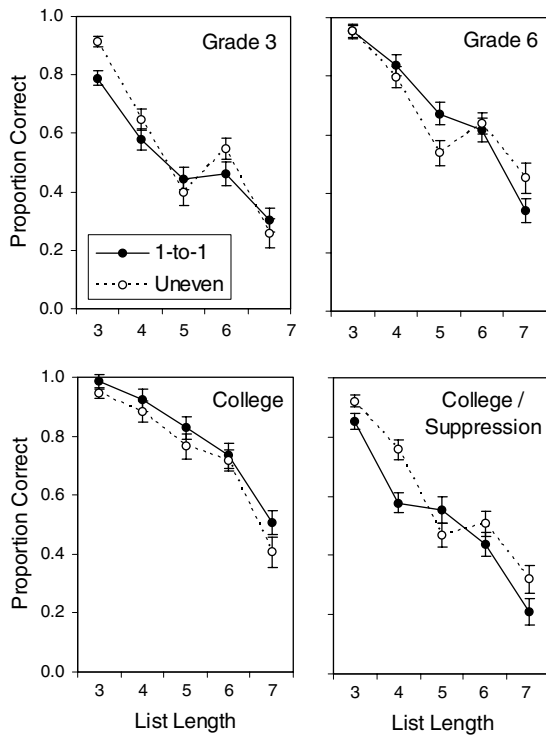


Fig. 2. Proportion correct in the verbal-to-spatial mapping task as a function of the list length, for children in third grade (top left) and sixth grade (top right) and college students (bottom left) in Experiment 1, as well as for college students in Experiment 2, who carried out articulatory suppression during the task (bottom right). Error bars are standard errors.

Length \times Age Group, $F(8, 372) = 4.06$, $MSE = 0.04$, $p < .001$; and Trial Type \times List Length, $F(4, 372) = 2.61$, $p < .05$. Finally, the three-way interaction approached significance, $F(8, 372) = 1.92$, $MSE = 0.04$, $p < .06$.

The most noteworthy effect is the interaction of age group and trial type. As one can see from both Fig. 2 and Table 2, Grade 3 children had higher performance levels for the uneven trials, Grade 6 children showed little difference between the trial types, and adults (college students) had higher performance levels for the 1-to-1 trials. Planned comparisons showed that the differences were significant (at $p < .05$) for the third-grade children and adults, in opposite directions; but not for the sixth-grade children. One explanation for this difference has to do with the strategies used in each age group. For a given list length, the uneven trials always involved fewer relevant stimulus locations than 1-to-1 trials and some of those locations were reinforced by two names. Therefore, remembering stimuli by locations could prove to be easier in that condition. However, as explained in the introduction, the 1-to-1 condition facilitated the parallel use of phonological rehearsal of the sequence of names and visual rehearsal of the spatial path of locations. That could prove easier for individuals who are able to coordinate these two types of unimodal, sequential maintenance processes.

The remaining, List Length \times Age Group and Trial Type \times List Length interactions (and the marginal three-way interaction) are of less theoretical significance. They did not appear to occur because of any clear differences

Table 2
Proportion correct performance (with *SD*) on the visual-to-spatial mapping memory task

Mapping	Group			
	Grade 3	Grade 6	College	College/suppression
1-to-1	0.52 (0.11)	0.68 (0.13)	0.80 (0.12)	0.53 (0.15)
Uneven	0.55 (0.10)	0.68 (0.13)	0.74 (0.12)	0.60 (0.14)
Difference	−0.03*	0.00	+0.06*	−0.07*

Note. Proportions are averaged across list lengths. College/suppression result is from Experiment 2 and all other results are from Experiment 1.

* $p < .05$, *t* test, 2-tailed.

in the rate of decline in performance as a function of the list length. Fig. 2 shows a similar rate for all age groups and for both trial types. These interactions might be explained in that performance on uneven, 5-item lists was worse than one would expect given a smooth, decreasing function across list lengths, especially in children.

Errors in the uneven version of the verbal-to-spatial mapping task only rarely involved selection of an “empty” pentagon (i.e., a location that did not get assigned a name on the trial in question). The proportions of all erroneous responses in 3- through 7-item lists in which an empty pentagon was selected were, for third-grade children, .09, .11, .04, .10, and .11, respectively; for sixth-grade children, .17, .04, .03, .02, .03, respectively; and for adults, .00, .00, .03, .00, and .01, respectively. No participant selected an empty pentagon more than twice for trials of a particular list length, or more than 5 times in all. If participants had guessed randomly, the proportion of erroneous responses at empty pentagons would have been much larger: .50, .42, .31, .40, and .38 for 3- through 7-item lists, respectively.

Further analysis distinguished between different types of errors in the uneven condition. To determine whether age differences could reflect differences in the tendency to select locations that had been assigned one versus two names, we carried out an analysis of proportion correct with age group between subjects and three conditions within subjects: the 1-to-1 condition, the uneven condition trials in which the one name had been assigned to the target location, and uneven condition trials in which two names had been assigned to the target location. List length was another within-subject variable in the analysis but need not be reported here; and seven-item lists had to be excluded due to insufficient data for this analysis. As illustrated in Fig. 3, there was a significant interaction of Age Group \times Condition, $F(4, 186) = 6.80$, $MSE = 0.08$, $p < .001$. Newman-Keuls analyses indicated that, in third-grade children, uneven-2-name trials were significantly above both other types, which did not differ; in sixth-grade children, uneven-2-name trials were significantly below both other types, which did not differ; and in college students, uneven-1-name

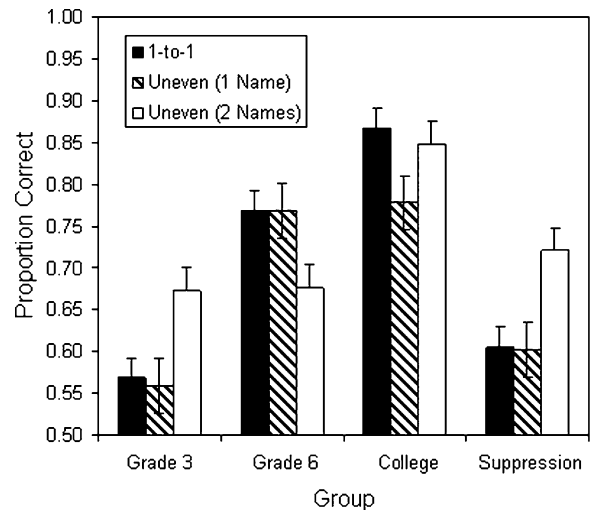


Fig. 3. Proportion correct in the verbal-to-spatial mapping task (averaged across List Lengths 3–6) for children in third grade, children in sixth grade, and college students in Experiment 1, as well as for college students in Experiment 2, who carried out articulatory suppression during the task. Black bars: 1-to-1 condition. Striped bars: uneven condition trials in which the target location had one name. White bars: uneven condition trials in which the target location had two names. Error bars are standard errors.

trials were significantly below both other types, which did not differ. Notice that, interestingly, sixth-grade children’s pattern was transitional in that uneven-1-name trials were at the same level as adults, whereas the uneven-2-name trials were at the same level as third-grade children and 1-to-1 trials were intermediate.

Last, we also examined the proportion of errors in which an erroneous 1- versus 2-name location was selected, but no significant age group differences could be observed. By random selection among non-empty locations, one would expect .69 of the responses to go to locations with 1 name, whereas participants yielded proportions slightly lower than that (third-graders, .62; sixth-graders, .57; adults, .55).

Table 3
Correlations between measures

Measure	1	2	3	4	5	6	7
1. Mapping task (1-to-1)	0.70	0.69	0.69	0.61	0.70	0.53	0.47
2. Mapping task (uneven)	0.67	0.54	0.68	0.57	0.72	0.58	0.57
3. Spatial span (1-to-1)	0.67	0.66	0.86	0.73	0.60	0.51	0.41
4. Spatial span (uneven)	0.57	0.55	0.71	0.89	0.63	0.49	0.34
5. Name span	0.67	0.71	0.57	0.59	0.94	0.53	0.57
6. Counting span	0.49	0.56	0.48	0.44	0.47	0.79	0.38
7. Running span	0.45	0.56	0.38	0.31	0.55	0.35	0.92

Note. The correlations above the diagonal are raw, and those below the diagonal are partial correlations with age group variance removed. The measures used were the proportion correct across list length for the mapping task; the sum measure for spatial, name, and counting span tasks; and the mean number correct for running span. All correlations are significant at $p < .05$. In bold on diagonal: Cronbach's alpha measure of reliability based on data including all list lengths for each of 3–4 repeated measures.

Correlations

Table 3 shows the correlations between measures, including both raw correlations (above the diagonal) and partial correlations with age group variance removed (below the diagonal). All of the measures were significantly correlated with one another. Of particular interest, our measure that theoretically should be the best indication of the use of verbal–spatial associations in working memory, the uneven version of the mapping task, showed large correlations with both counting and running spans (e.g., partial correlations of .56).

An anomalous aspect of the uneven condition of the verbal-to-spatial mapping task is that many of its correlations with other variables exceeded its estimated reliability (Table 3). One way that this could happen is if there were a change in mapping task performance with practice, so that not all portions of the test contributed equally to its overall stability, a situation that would violate assumptions of the measure of reliability.¹ This appears to be what happened. The first half of the uneven condition performance correlated with running span and counting span only moderately ($r = .29$ and $.40$, respectively), whereas the second half of the uneven condition correlated with these measures somewhat more strongly ($r = .43$ and $.58$, respectively). Similarly, the first half of the uneven condition trials correlated with the 1-to-1 condition mean moderately ($r = .49$), whereas the second half of the uneven condition trials

correlated with the 1-to-1 condition mean strongly ($r = .68$), a significant difference between dependent correlations, $t(93) = 2.23$, $p < .05$, 2-tailed. Thus, it was performance in the second half of the uneven condition that tended to drive the overall correlations of that measure with other measures.

Regressions

As shown in Table 4, hierarchical regression analyses were carried out using as dependent measures our two benchmark indices of working memory, counting span and running span. The results were similar for both measures. In the first set of regressions, we first removed the variance due to unimodal, spatial and name spans and found significant variance remaining that was accounted for by the verbal-to-spatial mapping task. The second set of regressions shows that the situation was similar when age group variance was removed first, followed by the unimodal spans and then the mapping task. Given that the unique contribution of the mapping task was undiminished from the first set of analyses to the second, this unique portion appears to reflect within-age, individual difference variation rather than age group variation.

The third set of regressions in Table 4 shows that the verbal-to-spatial mapping task accounted for a large portion of the variation (as the correlations already showed) and that no significant residual variation is accounted for by the age group and unimodal span measures. This is a strong endorsement of the mapping task as a powerful measure of working memory.

The fourth and fifth sets of regressions in Table 4 compare the value of the 1-to-1 and uneven versions of the verbal-to-spatial mapping task. There are significant unique contributions of each task (for the uneven version, 9 and 12% of the variance for the two dependent measures; for the 1-to-1 version, 3 and 1% of the variance). In all, the mapping task accounted for 37% of the variance in counting span and 34% of the variance in running span. Not shown in the table, it accounted for

¹ One can easily construct a hypothetical data set illustrating this possibility. Include $N = 10$ with 4 repeated measures of Task 1. For Measurement 1 of that task, define the 10 scores as 1, 2, 1, 2, 1, ... etc. For Measurement 2, define the 10 scores as 10, 9, 10, 9, ... etc. For both Measurements 3 and 4, define the 10 scores as 1, 2, 3, ... 10. Define the means for Task 2 also as 1, 2, 3, ... 10. The 10 means across Measurements 1–4 of Task 1 are 3.25, 3.75, 4.25, 4.75, and so on, monotonically increasing across subjects. The correlation between these Task 1 means and Task 2 is 1.0, yet Cronbach's alpha measure of reliability for Task 1 is only .65.

Table 4
Regression analyses

Step	Variables	Dependent variable	
		Counting span ΔR^2	Running span ΔR^2
1	Spatial and name spans	.34*	.33*
2	Mapping task (1-to-1 and uneven)	.05*	.05*
1	Age group	.08*	.03 n.s.
2	Spatial and name spans	.27*	.30*
3	Mapping task (1-to-1 and uneven)	.05*	.05*
1	Mapping task (1-to-1 and uneven)	.37*	.34*
2	Age group, spatial and name spans	.03 n.s.	.04 n.s.
1	Mapping task (1-to-1)	.28*	.22*
2	Mapping task (uneven)	.09*	.12*
1	Mapping task (uneven)	.34*	.33*
2	Mapping task (1-to-1)	.03*	.01*

* $p < .05$.

31% of the within-age-group variance for both tasks, using both versions as predictors or just the uneven version alone, rivaling the task reliabilities.

Discussion

There are several key findings of this experiment. First, although the levels of performance were fairly similar for the 1-to-1 and uneven versions of the task, they produced exactly the kind of Age Group \times Trial Type interaction that would be expected according to increasing contribution of a serial rehearsal process. Specifically, for third-grade children there was a significant advantage for the uneven condition over the 1-to-1 condition, for sixth-grade children there was no difference between conditions, and for college students there was an advantage for the 1-to-1 condition over the uneven condition. (See Table 2 and Fig. 2.)

The advantage of the uneven condition in the young children could be explained by the fact that fewer locations need to be remembered, some of them reinforced by two names. Adding two names to the same condition may be like adding features to the same object, which, according to at least two very different lines of inquiry, seems to impose less of a memory load than adding new objects to be remembered (Luck & Vogel, 1997; Radvansky & Zacks, 1991).

However, in the more mature participants, this tendency appears to have been counteracted by the ability to use a dual-code strategy by rehearsing the verbal sequence and the spatial path and applying them in parallel. This can explain why the direction of the trial type effect reversed across age groups, as predicted. Theoretically, another factor could be the weakening with age in a tendency for performance on target locations with two

names to be strengthened relative to one-name locations. However, the data in the uneven condition suggest that an advantage for locations with two names actually was present in adults as well as in third-grade children.

Participants rarely selected empty pentagons that occurred in the uneven condition, and that aspect of the results helps in the interpretation of several other findings. The fact that there were fewer non-empty pentagons (name-bearing locations) in the uneven condition than in trials with the same number of names in the 1-to-1 condition could confer at least two advantages on the uneven condition if empty pentagons are excluded. Fewer name-bearing locations must be retained in memory in the uneven condition and, for any given list length, the correct location could be guessed more easily in the uneven condition.

The finding that participants rarely selected empty pentagons also helps to explain a non-monotonic pattern of performance across list lengths in the uneven condition, with poorer-than-expected performance for 5-item lists. For lists of 3–7 items, if an individual always guessed but restricted these guesses to non-empty pentagons, the chance for any one of them to be selected would be monotonic across list lengths: .50, .36, .27, .25, and .21, respectively (based on information from the methods section; e.g., for 4-item lists, $1/2.75 = .36$). However, not all non-empty pentagons were equally likely to be correct. For example, in a 3-item list, the pentagon with one name was correct on 1/3 of the trials and the pentagon with two names was correct on 2/3 of the trials, and selecting either pentagon equally often would result in a guessing rate of $(.5)(.33) + (.5)(.66) = .5$. In general, let N = the number of names (i.e., the set size), F = the mean number of filled pentagons, S = the mean number of pentagons

with a single name, and T = the mean number of pentagons with two names. Then it can be calculated that $S = 2F - N$ and $T = F - S$. The proportion of correct guesses would be $(1/F)(S/F) + (2/F)(T/F)$, which comes out to .75, .53, .36, .38, and .31 for lists of 3–7 items, respectively, creating a non-monotonic trend in guessing that puts 5-item lists at a disadvantage relative to its neighbors.

Correlations and regressions

The correlations and regressions suggest that both versions of the verbal-to-spatial mapping task are excellent working memory tasks in the sense that they pick up a great deal of individual variance. They are both rather highly correlated with other working memory tasks, both in raw correlations and in partial correlations with age group variance removed (Table 3). Moreover, they explain individual variance in two tasks that have been shown to be excellent predictors of mental aptitudes, counting span and running span (Cowan et al., 2005). The predictive ability includes that from the component tasks, spatial span and name span, as well as additional variance not found in the component tasks (Table 4).

Experiment 2

Although age differences in the trial type effect were as predicted, that constitutes rather weak evidence that the basis of the age difference is, at least in part, the development of rehearsal capabilities. Further evidence can be obtained by suppressing rehearsal in adults, which has a profound effect on performance. For example, Cowan, Cartwright, Winterowd, and Sher (1987) examined adults' serial recall of lists of phonologically similar or dissimilar words and found that a concurrent articulatory suppression task (reciting meaningless letters) reduced both the level of performance and the magnitude of the phonological similarity effect to resemble what is typically found in 5-year-old children. The question in this second experiment was whether articulatory suppression would reverse the trial type effect in adults, making their performance resemble that of young children.

Method

The 32 participants (mean age = 249.47 months, $SD = 72.39$) included 16 men and 16 women, college students who had not participated in Experiment 1. The apparatus, stimuli and procedure were the same as in that experiment except for the addition of articulatory suppression in the verbal-to-spatial mapping task. Just before that task, participants practiced reciting the word *the* at a rate of 3 times per second, aided by a computer display that kept time. At the beginning of every trial in

the verbal-to-spatial mapping task, the word **THE** appeared for 1 s just before the appearance of the pentagons (schematic houses) as a prompt for the participant to begin reciting that word over and over at the practiced rate. Just after the pentagons all disappeared at the end of the list presentation, the word **THE** appeared for 1 s, struck through as shown, as a prompt indicating that recitation could cease and that the memory probe would be presented next. The experimenter listened to ensure that recitation of *the* continued faithfully throughout the task.

Results and discussion

As shown in Table 2, participants in this experiment displayed an advantage of the uneven condition over the 1-to-1 condition, like the younger children in Experiment 1 and unlike its adults. They also were at a level of performance more comparable to the younger children than to the adults of Experiment 1.

An ANOVA was carried out using adults of Experiment 1 and Experiment 2 to assess the effects of articulatory suppression, present only in Experiment 2. The within-subject factors of this analysis were the trial type (1-to-1 versus uneven) and the list length (3–7 items). Only effects that include experiment as a factor will be presented. All such effects were significant. There was a main effect of experiment, $F(1, 62) = 52.19$, $MSE = 0.13$, $p < .001$; there were two-way interactions of Trial Type \times Experiment, $F(1, 62) = 14.71$, $MSE = 0.04$, $p < .001$, and List Length \times Experiment, $F(4, 248) = 5.04$, $MSE = 0.04$; and there was a three-way, Trial Type \times List Length \times Experiment interaction, $F(4, 248) = 2.41$, $MSE = 0.03$, $p < .05$.

The Trial Type \times Experiment interaction is the most important effect, as it indicates that the effect of trial type depended on the presence versus absence of articulatory suppression. Table 2 shows that this was a cross-over interaction. Planned comparisons showed that the effect of trial type was significant in both experiments, in opposite directions.

Fig. 2 shows performance for the 1-to-1 and uneven trial types for each group in both experiments as a function of the list length. It can be seen in that figure that the similarity between young children in Experiment 1 and adults in Experiment 2 (with articulatory suppression) was striking. Performance in the uneven condition with 5 items was somewhat worse than one would expect given a monotonic forgetting function, an anomaly that can be observed to some extent in all groups and was discussed in Experiment 1. However, the rehearsal processes used by adults in Experiment 1 appear to have almost entirely eliminated this irregularity. This aspect of the data can account for the List Length \times Experiment interaction and three-way interaction obtained in the cross-experiment ANOVA of adult results. This

pattern of results can be taken as a further suggestion that rehearsal could account for changes in the pattern of performance as a function of age in Experiment 1.

A further analysis was conducted to determine whether there was an advantage for trials in which two names were assigned to the target location (see Fig. 3). The analysis was similar to that in Experiment 1, but without the group factor. There was an effect of condition, $F(2, 62) = 5.48$, $MSE = 0.11$, $p < .01$. Newman–Keuls tests showed that performance in uneven trials with two names assigned to the target location was significantly above both the 1-to-1 trials and the uneven trials in which only one name was assigned, which did not differ from one another. In fact, the pattern of performance closely matches that of third-grade children in Experiment 1.

General discussion

We have shown that childhood development of working memory for verbal-to-spatial associations involves more than just an improvement over time. It involves a pattern reversal from third grade to adulthood. In third-grade children, a 1-to-1 correspondence between locations and names was harmful, compared to an uneven assignment condition (which had the same number of names, but in which zero, one, or two names could appear at any particular location). In contrast, in college students, a 1-to-1 correspondence was helpful rather than harmful. A second experiment showed that the suppression of articulation in adults reversed this pattern, making their performance closely resemble that of third-grade children. The uneven version of the verbal-to-spatial mapping task may provide a preferable measure of working memory capacity inasmuch as it was aided less by sophisticated rehearsal strategies.

Further insight into performance can be obtained by examining separately the trials from the uneven condition in which one versus two names were assigned to the target location (see Fig. 3). Third-grade children from Experiment 1 and college students carrying out articulatory suppression (Experiment 2) showed nearly identical performance patterns in which performance on 1-to-1 trials and uneven-1-name trials were similar, and were lower than performance on uneven-2-name trials. This pattern appears to indicate a strengthening of memory for locations in which two names appeared. The nearly identical performance patterns of these two groups further suggests that the difference between college students and children in this task is primarily in the contribution of rehearsal strategies in college students, except when rehearsal has been eliminated by suppression.

College students free to rehearse showed much better performance overall and a somewhat different pattern. The advantage for uneven-2-name over uneven-1-name

trials persisted, and still can be attributed to a strengthening of memory for target locations with two names. However, in these participants, 1-to-1 trials resulted in performance comparable to uneven-2-name trials, not lower as in children and college students under suppression. We can reasonably attribute these changes to the contribution of rehearsal. The strategy of serially rehearsing the names and the spatial path, and then using this information by identifying the correct serial position as a cue to the correct location (described in the introduction), may be especially useful for the 1-to-1 condition. Serial positions in the spatial path should be more memorable there than in the uneven condition, as memory for a spatial path is hurt by complexity of the path (Kemps, 2001). Given the advantage of rehearsing adults (Experiment 1) over the other groups in *all* conditions, though, it appears that they benefit from rehearsal to some extent in all conditions.

The pattern of performance in sixth-grade children was unique. It appears that they have progressed way beyond third-grade children in memory for target locations with only one name (in both the 1-to-one and uneven conditions), but with no noticeable advance over third-grade children in memory for target locations with two names assigned. One way to understand this pattern, albeit speculatively, is that sixth-grade children may attempt rehearsal, but in a faulty manner that breaks down for locations assigned to two names. Perhaps an inaccurate spatial path is used in those cases, which fails to represent the return to some locations.

What is the mechanism that explains the part of performance remaining when rehearsal does not operate? Apparently, this residual working memory resource is similar in third-grade children and adults. It can include about half of the items on a 6-item list (Fig. 3, third-grade children and adults under suppression) and, based on such data, can be estimated to include about 3 abstract items (in this case, verbal-spatial associations). This description and capacity is consistent with expectations for a core working memory capacity (Broadbent, 1975), the focus of attention (Cowan, 2001), or what has been termed the episodic buffer (Baddeley, 2000, 2001).

The present pattern of performance is new and not easily related to previous tests of the development of working memory, which have generally not required cross-code associations. Future work could relate this task to a known difference between memory in children and adults: that children are more susceptible to interference because they cannot inhibit irrelevant associations (e.g. Bjorklund & Harnishfeger, 1990). One might suppose that there is more interference in the uneven condition because two names often are associated with one location, so that the associations might become confused with one another (as in the fan effect; e.g. Bunting, Conway, & Heitz, 2004). However, this type of interference does not appear relevant to the present study because

we did not require that the participant distinguish between associations contributing to the same fan. In future work, it could be useful to require that the serial position of the name be recalled, to determine whether the serial positions of names presented at the same location would be confused with one another. We would expect a strong developmental trend due to the increasing ability to overcome such interference.

The pattern of correlations and regressions provides further information relevant to an understanding of the verbal-to-spatial mapping task and of working memory tasks generally. The verbal-to-spatial task correlates well with other working memory tasks (Table 3). Regressions (Table 4) showed that the mapping task conditions taken together subsumed 37% of the variance in counting span and 34% of the variance in running span, two measures that correlate well with cognitive aptitude measures, as shown, for example, by Cowan et al. (2005). When the mapping task scores were entered first into these regressions, they left non-significant variance in counting or running span to be accounted for by a combination of age group, spatial span, and name span. Yet, when these other variables were entered first into the regressions, there still was 5% of the variance in counting span and in running span uniquely accounted for by mapping task performance. This shows that a special component of working memory can be indexed by the ability to make associations between very different elements. This finding also is reinforced by neuroimaging results (Prabhakaran et al., 2000) indicating prefrontal cortical activity specifically related to cross-code associations in working memory.

The study is relevant to a large literature on working memory and individual differences. Working-memory tasks that combine processing and storage are highly predictive of a wide range of aptitudes (Conway et al., 2002, in press; Daneman & Merikle, 1996; Engle et al., 1999; Kane et al., 2004; Kyllonen & Christal, 1990) but we do not know why this is so. It had been assumed that, to correlate highly with aptitudes, a “successful” task must include separate, simultaneous storage and high-level processing components that must be coordinated. However, several recent studies show that this need not be the case. It is true that this factor does appear critical for some abnormal populations, as in Alzheimer’s disease (Logie, Cocchini, Della Sala, & Baddeley, 2004). However, recent evidence indicates that, instead, in normal individuals it may be requiring mnemonic processing on a rigid and demanding schedule across time that is critical for correlations with aptitudes (Conlin et al., 2005; Cowan et al., 2005; Friedman & Miyake, 2004; Lépine et al., 2005; Mukunda & Hall, 1992). For example, Cowan et al. found good correlations between aptitudes and a running memory span task in which digits were acoustically presented at a rapid, 4/s rate in a list that ended at an unpredictable point, and Lépine et al.

found good correlations between aptitudes and a task in which numbers to be remembered were interspersed with letters to be read aloud, which were presented at a fairly rapid rate of 1350 ms/letter. The verbal-to-spatial mapping task also requires memory encoding on a fairly strict time scale, so it may be another promising task for which strong correlations with aptitudes might be expected. The verbal-to-spatial mapping span correlates well with counting span and running span and accounts for variance in these tasks beyond a combination of the component tasks (spatial and name spans). Of course, in future research, it will be necessary to determine whether it is just the verbal-to-spatial association ability that correlates with aptitudes within adults, or also the sophisticated mnemonic processes that are capable of supplementing the basic capability.

We have introduced the verbal-to-spatial mapping task as a promising alternative to the typically used working-memory tasks. It may be theoretically preferable in that (1) it minimizes the need for complex, non-mnemonic processing such as reading, arithmetic, or counting; (2) it does not involve a dual task; and (3) it does not require very fast presentation; yet (4) it correlates well with the more standard tasks. We have shown how verbal-spatial associative information can be separated from another strategy, the parallel use of verbal and spatial information, based on performance on two versions of the task. Clearly, additional followup work on the mapping task is needed. Nevertheless, it has helped to demonstrate developmental changes in working memory that are qualitative as well as quantitative, as rehearsal plays an increasing role across age groups.

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