



Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp



The development of memory maintenance: Children's use of phonological rehearsal and attentional refreshment in working memory tasks

Helen Tam^a, Christopher Jarrold^{a,*}, Alan D. Baddeley^b, Maura Sabatos-DeVito^c

^aDepartment of Experiment Psychology, University of Bristol, Bristol BS8 1TU, UK

^bDepartment of Psychology, University of York, Heslington, York YO10 5DD, UK

^cDepartment of Psychology, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA

ARTICLE INFO

Article history:

Received 8 September 2009

Revised 18 May 2010

Available online 23 June 2010

Keywords:

Working memory

Children

Rehearsal

Attentional refreshment

Phonological similarity

Verbal and nonverbal distraction

ABSTRACT

Past research suggests that children begin to phonologically rehearse at around 7 years of age. Less is known regarding the development of refreshment, an attention-based maintenance mechanism. Therefore, the use of these two maintenance methods by 6- and 8-year-olds was assessed using memory span tasks that varied in their opportunities for maintenance activity. Experiment 1 showed that nonverbal processing impaired both groups' performance to similar extents. Experiment 2 employed phonologically similar or dissimilar memory items and compared the effects of verbal versus nonverbal processing on recall. Both groups showed evidence of phonological maintenance under nonverbal processing but not under verbal processing. Furthermore, nonverbal processing again impaired recall. Verbal processing was also more detrimental to performance in 8-year-olds than in 6-year-olds. Together, the results suggest that nonverbal processing impairs recall by obstructing refreshment and that developmental change in maintenance between 6 and 8 years of age consists primarily of an increase in phonological rehearsal.

© 2010 Elsevier Inc. All rights reserved.

Introduction

Working memory can be defined as the ability to retain or “store” information in the face of concurrent distraction from a secondary processing task. Therefore, the construct is often (Conway et al.,

* Corresponding author.

E-mail addresses: c.jarrold@bristol.ac.uk, C.Jarrold@bris.ac.uk (C. Jarrold).

2005), although not exclusively (e.g., Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010; Oberauer, 2002), indexed by the “complex span” task in which participants are subjected to alternating processing and storage demands. Compared with simple span tasks, which involve only storage and so tap short-term memory, recall is often worse in complex span tasks (e.g., Duff & Logie, 2001; Hutton & Towse, 2001; La Pointe & Engle, 1990). In addition, complex span tasks are often stronger correlates than simple span tasks of higher level cognitive skills such as reasoning and intelligence (Conway, Cowan, Bunting, Theriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Hambrick, & Conway, 2005; Oberauer, Schulze, Wilhelm, & Süß, 2005). Importantly, this also holds for children, where the evidence suggests that complex span performance is particularly strongly related to academic abilities such as reading and mathematics (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Bull, Espy, & Wiebe, 2008; Swanson, 2008). Unsurprisingly, working memory performance develops with age in children (e.g., Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005; Swanson, 2008); therefore, understanding the causes of this development has clear educational implications (cf. Holmes, Gathercole, & Dunning, 2009). The aim of the current work was to investigate the developmental change during early to middle childhood of the maintenance activities that might be used to support working memory. More specifically, we examined the developmental improvement in children of articulatory rehearsal and attentional refreshment.

In the adult literature, there are, broadly speaking, two different explanations as to why the imposition of a processing demand within a working memory task leads to forgetting. One line of argument is that processing disrupts the maintenance of the to-be-remembered storage items, and without maintenance items inevitably decay (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Camos, Lagner, & Barrouillet, 2009; Towse & Hitch, 1995; cf. Conrad & Hull, 1966). Alternatively, processing may produce interference on the memoranda, causing forgetting (e.g., Lewandowsky, Geiger, & Oberauer, 2008; Oberauer & Lewandowsky, 2008). However, regardless of whether forgetting is due to decay or interference, it is clear that memory maintenance could serve to offset any forgetting that does occur in complex span tasks.

Indeed, in the time-based resource-sharing (TBRS) model developed by Barrouillet, Camos, and colleagues (see Barrouillet et al., 2004, 2007; Camos et al., 2009), the strength of item representations in memory decays over time, but participants are assumed to use temporal gaps within processing episodes to reinstantiate these memory traces, thereby increasing their activation (see Oberauer & Lewandowsky, 2010). In support of this model, recall performance on a complex span task has been found to be related to the pace of the processing operations. When the processing pace is slow, participants have relatively more free time in between processing operations to engage in memory maintenance activities. Correspondingly, participants show superior recall in these conditions even though this manipulation leads to an overall longer retention period within a trial (Barrouillet et al., 2004; Lépine, Bernardin, & Barrouillet, 2005).

Similarly, interference accounts often include some form of maintenance mechanism to account for the fact that performance improves as a result of slower rates of processing operations. Such findings are undoubtedly highly suggestive of the use of maintenance strategies, and Hudjetz and Oberauer (2007) went so far as to suggest that they saw “no alternative explanation for the benefit of slower processing rates” (p. 1681). Likewise, Oberauer and Lewandowsky (2008) included a mechanism for the strengthening of certain memory traces in their interference-based model of working memory to account for this effect. This implementation was based on Farrell and Lewandowsky’s (2002) SOB (serial-order-in-a-box) model of short-term memory in which forgetting is caused by the similarity of items at the point of encoding; new items that are similar to already encountered material are encoded into memory less strongly. In addition, Oberauer and Lewandowsky (2008) adjusted the model to allow for the reencoding after a burst of processing activity of just the most recently presented memorandum—a form of maintenance activity.

Although there is some consensus on the need for maintenance operations in working memory, there is debate as to the precise form that these operations take. Baddeley’s (1986) classic account assumed that verbal memoranda were maintained by a process of rehearsal, whereby subvocal repetition of the list of to-be-remembered items served to strengthen their representations in memory (cf. Conrad, 1964). Because rehearsal is speech based, although typically operating at the covert level rather than the overt level, it is assumed to be blocked by any other task, such as articulatory suppres-

sion (Murray, 1967), that recruits either speech planning or articulatory mechanisms. It is also a relatively slow activity because it is limited by the speed of subvocal articulation; consequently monosyllabic words might each take at least 400 ms to rehearse (Baddeley, Thomson, & Buchanan, 1975; Hulme, Maughan, & Brown, 1991; Thorn & Gathercole, 2001). In contrast, other authors have argued that memory maintenance might involve a more rapid and domain-general attentional process, often termed refreshment (Raye, Johnson, Mitchell, Reeder, & Greene, 2002) in which the activation of a single item's representation is boosted by reattending to it without any concomitant articulation. This process is assumed (e.g., Cowan et al., 1998) to share similarities with high-speed memory scanning (Sternberg, 1966), which appears to operate at a rate of approximately 30 ms per item. According to the TBRS model, because refreshment requires domain-general attentional resources, it is hindered whenever the processing in a working memory task makes attentional demands of the participant (Barrouillet et al., 2004, 2007) regardless of whether this processing is verbal or nonverbal in nature (Vergauwe, Barrouillet, & Camos, 2010).

A distinction between refreshment and rehearsal in the context of the study of working memory has been drawn by two recent reports. First, Hudjetz and Oberauer (2007) gave adult participants a "sentence span" task that required them to read a set of sentences and recall the final word of each one. These sentences were presented at either a slow or fast pace, and participants showed better recall under the slow pace condition than under the fast pace condition. Furthermore, this was true even when participants were required to read sentences at a continuous rate (by synchronizing their reading with a constantly paced tone) despite the fact that a subsequent experiment showed that continuous reading allows very little opportunity for subvocal rehearsal. Therefore, Hudjetz and Oberauer contended that the maintenance operations carried out by participants were not articulatory in nature and instead involved attentional refreshment. Second, Camos et al. (2009) presented adult participants with a series of complex span tasks in which letters needed to be remembered while interleaved processing operations were carried out. In one manipulation, the pace of the interleaved processing was varied, which the authors assumed would affect the amount of time available for attentional refreshment. In an orthogonal manipulation, the articulatory demand of the processing tasks was varied by requiring participants to make their response to each processing operation either verbally or nonverbally, with the former being assumed to block rehearsal. Camos and colleagues found some evidence that these manipulations had additive, rather than interactive, effects on working memory performance, leading them to conclude that these maintenance activities were separable, and are both implicated in adult working memory performance.

What is much less clear is whether the same holds in children and whether these two maintenance operations have different developmental trajectories. There is considerable developmental evidence that has been taken to suggest that the use of rehearsal begins at around 7 years of age. First, children under 7 years of age tend not to show lip movements, indicative of a primitive approach to subvocal rehearsal, during maintenance intervals (Flavell, Beach, & Chinsky, 1966). Second, assuming that faster articulation rate allows more items to be rehearsed, a positive correlation between articulation rate and memory span suggests that phonological rehearsal has taken place (Baddeley et al., 1975).¹ However, the correlation between speech rate and memory span is often not significant in children under 7 years of age (Ferguson, Bowey, & Tilley, 2002; Gathercole & Adams, 1993; Gathercole, Adams, & Hitch, 1994; Jarrold, Cowan, Hewes, & Riby, 2004; but see Jarrold, Hewes, & Baddeley, 2000).

Finally, phonologically confusable items are harder to recall than phonologically nonconfusable items (Conrad & Hull, 1964). Although this "phonological similarity effect" might itself arise from interitem confusion (Lewandowsky & Farrell, 2008; Nairne, 1990), the presence of such an effect when material is presented visually clearly shows that participants have recoded these items phonologically. Because this recoding involves subvocally naming the presented stimuli, some authors have suggested that it can be linked directly to phonological rehearsal (Gathercole, 1998; Howard &

¹ Similarly, if one assumes that the forgetting from immediate memory is time related (Baddeley, 1986), words that take longer to rehearse should suffer greater forgetting than words that can be rehearsed rapidly, providing a potential explanation for the word length effect in immediate serial recall (Baddeley et al., 1975). However, there is growing evidence that the word length effect may be caused by greater interference effects associated with long words as opposed to short words (Brown & Hulme, 1995; Campoy, 2008; Lewandowsky & Oberauer, 2008), casting doubt on the validity of this effect as a marker of phonological rehearsal.

Franklin, 1990; Vallar & Papagno, 1995). Again, a reliable phonological similarity effect for visually presented material is often not seen in children under 7 years of age (Halliday, Hitch, Lennon, & Pettipher, 1990; Hayes & Schulze, 1977; Hitch, Halliday, Schaafstal, & Heffernan, 1991; Hitch, Woodin, & Baker, 1989). Together, these three lines of evidence have led a number of authors to posit a qualitative difference in the rehearsal status of children over and under 7 years of age (Gathercole, 1998; Gathercole et al., 1994; Henry, 1991).

In contrast, there has been notably little research on the role of refreshment in children's working memory performance. Indeed, to our knowledge, only one previous study (Barrouillet et al., 2009, Experiment 3) has attempted to examine how children's working memory performance may be affected by refreshment opportunities within a task. In Barrouillet and colleagues' study, 5- and 7-year-olds were given a complex span task in which they needed to remember a series of pictured animals while naming colors that were presented during processing intervals. The duration of these intervals was fixed, but the pace of color presentation was either fast (four per interval) or slow (two per interval), with the assumption being that the former condition allowed fewer opportunities for refreshment than the latter condition. Barrouillet and colleagues found that 7-year-olds' recall was linearly related to processing pace, with better recall in the slow condition than in the fast condition. On the contrary, processing pace did not have any effect on the performance of 5-year-olds. This led the authors to suggest that the development of refreshment mirrors the development seen for rehearsal in other studies, with a marked change in the use of this maintenance activity at around 7 years of age. However, we note that because the processing involved in this study required an overt verbal response, the pace manipulation may well have tapped efficiency of phonological rehearsal in addition to refreshment.

Given this, and the scarcity of research concerning the role of these two maintenance mechanisms in children's working memory performance, a detailed investigation of the extent to which refreshment and phonological rehearsal are used by children in such paradigms is clearly needed. Two experiments were conducted to that effect. In the first experiment, 6- and 8-year-olds were given four memory span tasks that varied in the opportunities for memory maintenance in general. The extent to which both age groups spontaneously recoded information in a phonological form was also assessed to index the likelihood of individuals engaging in phonological rehearsal. The second experiment also investigated children's ability to engage in phonological recoding but more specifically examined the effects of two types of processing, verbal and nonverbal, on their maintenance of memory items. Verbal processing consisted of an activity that was assumed to block phonological rehearsal, whereas nonverbal processing involved an activity that was assumed to allow phonological rehearsal but block the attentional refreshment of memory representations.

Experiment 1

In the first experiment, we devised four memory span tasks, plus a phonological similarity effect (PSE) task, and administered these measures to 6- and 8-year-olds. Fig. 1 shows the structure of the four memory span tasks. At each span length, the number of storage items is identical across tasks, but the opportunity for memory maintenance differs. At the most basic level is the simple span task, where recall immediately follows presentation of the storage items. Next is the delayed span task, which was created by adding a delay between item presentation and recall. During this unfilled delay, we assume that participants can freely use phonological rehearsal and/or refreshment for memory maintenance provided that they are inclined to do so. The effective use of such mechanisms would result in a minimal decrease in the recall performance in the delayed span relative to the simple span task.

Next, the delay in the delayed span task was filled by a processing activity to create a task analogous to the classic Brown–Peterson task (Brown, 1958; Peterson & Peterson, 1959). Previous work (Barrouillet et al., 2007; Portrat, Camos, & Barrouillet, 2009; Vergauwe et al., 2010) has shown that nonverbal processing (spatial judgments) can impair recall despite the fact that the nonverbal activity imposes little similarity-based interference on verbal memory representations and also allows phonological rehearsal to take place (Hale, Bronik, & Fry, 1997; Hale, Myerson, Rhee, Weiss, & Abrams, 1996; Logie, Zucco, & Baddeley, 1990). Thus, nonverbal processing is likely to impair recall by disrupting refreshment-based memory maintenance. By incorporating a nonverbal processing activity, we could

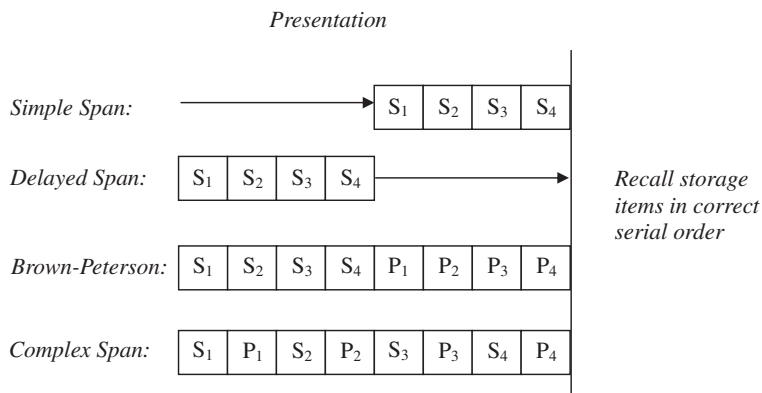


Fig. 1. Schematic representation of the trials presented in the four memory span tasks in Experiment 1: simple span, delayed span, Brown–Peterson, and complex span. “S” and “P” denote storage item and processing episode, respectively, and each subscript number indicates the storage item or processing episode number. Each trial depicted here is at a span length of four storage items.

assess whether nonverbal processing disrupts the refreshment mechanism in 6- and 8-year-olds, who in turn are thought to be on the cusp of developing the other method of maintenance—phonological rehearsal.

The last of our four memory span tasks was a variant of the complex span task. To create this task, the processing block used in the Brown–Peterson task was divided into equal intervals, which were then interleaved between storage items. In this way, the amounts of storage and processing demands were equivalent between the two tasks.

In addition to the four memory span tasks, participants were given a task measuring the size of the PSE shown for visually presented material to check whether the groups were indeed differentiable in their tendency to engage in phonological recoding and, by implication, phonological rehearsal. In the PSE task, memory items were presented pictorially for participants to encode and then recall. Some trials contained only phonologically similar items (e.g., *cat*, *man*, *mat*), whereas others contained only phonologically dissimilar items (e.g., *bird*, *drum*, *shoe*); a PSE is obtained when recall is significantly better for phonologically dissimilar trials than for phonologically similar trials. Based on previous evidence, we expected the PSE to be larger for 8-year-olds than for 6-year-olds and possibly nonsignificant in the younger group.

Similarly, we predicted that the two age groups would produce different patterns of recall performance across our four memory span measures. First, both phonological rehearsal and refreshment can be used during the unfilled delay in the delayed span task. Given that 8-year-olds are more likely to carry out phonological rehearsal and possibly refreshment (Barrouillet et al., 2009), recall decrements from simple to delayed span should be smaller for 8-year-olds than for 6-year-olds. Second, the addition of processing demands should disrupt memory maintenance (Barrouillet et al., 2007; Portrat et al., 2009; Vergauwe et al., 2010), but it remains unclear whether nonverbal processing per se would have a greater detrimental effect on recall in younger children than in older children. We assume that under nonverbal processing, phonological rehearsal can take place to some extent, but refreshment might be disrupted (Barrouillet et al., 2007; Camos et al., 2009). Given their apparently greater use of phonological rehearsal, 8-year-olds might be more able than 6-year-olds to withstand the disruptive effects of processing by carrying out some degree of phonological rehearsal (cf. Hale et al., 1997). Thus, the drop in performance (from delayed span to the Brown–Peterson task) may be less in 8-year-olds than in 6-year-olds. Finally, because the Brown–Peterson and complex span tasks contained equivalent total storage and processing demands, a comparison of performance on these two measures allows one to examine whether there is any switch cost involved in alternating between phases of storage and processing within working memory paradigms (complex span) relative to a situation in which the processing is presented in a single block (Brown–Peterson) (Liefvooghe, Barrouillet, Vandierendonck, & Camos, 2008) and, in this case, whether such an effect changes with age.

Methods

Participants

Participants were recruited from Year 1 and Year 3 classes across six local state primary schools (Bristol, UK). There were 117 5- and 6-year-olds (54 boys and 63 girls, mean age = 6 years 3 months, range = 5 years 8 months to 6 years 9 months) and 104 7- and 8-year-olds (40 boys and 64 girls, mean age = 8 years 3 months, range = 7 years 6 months to 8 years 9 months).

Memory span tasks

As already noted, Fig. 1 shows the structure of the four memory tasks. On each task, there were five blocked trials for each span length, which ranged from 2 to 6 storage items. The same sets of 10, 15, 20, 25, and 30 items (for span lengths of 2, 3, 4, 5, and 6, respectively) were used for each task, albeit in a different randomized order within each span length. On each memory span task, the items (and trials) were presented in the same randomized order for all participants. All of the storage items were single-syllable concrete words, and all were shown to be acquired before 6 years of age (Morrison, Chappell, & Ellis, 1997). They were presented both auditorily and pictorially. The items were read in a male voice (from recordings), and the pictures were black-and-white line drawings adapted from Snodgrass and Vanderwart (1980), with 22 additional line drawings made for items not provided by those authors.

For the Brown–Peterson and complex span tasks, the nonverbal processing activity was a visual categorization (“coin-collecting”) task where participants needed to categorize (“collect”) “gold” and “silver” coins as quickly as possible by pressing the corresponding colored buttons on a response box attached to the keyboard. The coins were shown one at a time at one of eight different predetermined, evenly spaced locations on the screen. The sequence of coins was identical for a given trial across participants.

Children were tested individually in a quiet room. The tasks were presented using a Macintosh laptop computer. Participants were told to attend to the objects shown on the screen and to remember them in the right order. For the Brown–Peterson and complex span trials, participants were further instructed that gold and silver coins would appear on the screen after all of the pictures had been shown (in the Brown–Peterson task) or after each picture had been shown (in the complex span task). Participants were encouraged to collect as many coins as possible using the response box. For each task, they were also told to wait until prompted (by the appearance of a cartoon character on the screen) before telling the experimenter the objects they needed to remember in the correct order. In the delayed span task, participants were not instructed on what to do during the delay and, therefore, were free to engage in maintenance activities during this interval if they chose to do so.

On each trial, the pictorial form of each storage item was displayed for 1 s and the corresponding auditory form was presented simultaneously. A blank screen of 500 ms followed each storage item. In the simple span, delayed span, and Brown–Peterson tasks, the next storage item in the trial was presented following the blank. In the complex span task, each storage item and its subsequent 500-ms blank was followed by a 3-s processing interval. The processing activity in the Brown–Peterson task was given immediately after all of the storage items for that trial had been presented. The durations of the processing intervals in a Brown–Peterson trial, and of the delay intervals in a delayed span trial, were 6, 9, 12, 15, and 18 s for the span lengths of 2, 3, 4, 5, and 6 storage items, respectively (i.e., equivalent to the total duration of all processing intervals given on a complex span trial of the same span length).

During processing, a high-pitched sound and a low-pitched sound were used to signal correct and incorrect responses, respectively. Once a coin was collected by a participant (via button press), it disappeared from the screen and, after a brief interval (100 ms), the next coin was displayed. Thus, the processing activity was self-paced but continuous—in the sense that the next stimulus (coin) appeared virtually immediately once the participant had responded.

In all memory span tasks, participants were instructed to recall as many items as they could verbally in the correct order and to say “can’t remember” for forgotten items. Responses were recorded manually by the experimenter on a preprinted response sheet. Participants proceeded to the next span length if they produced perfect recall on at least 2 of the 5 trials of a given span length. The task was terminated if they failed to do so or if all of the trials (from span length of 2–6) had been presented.

PSE task

For the PSE task, seven phonologically similar items and seven phonologically dissimilar items were used to construct six phonologically similar trials and six phonologically dissimilar trials, respectively. No item was repeated for each trial, and each was presented pictorially without any accompanying verbal label as black-and-white line drawings. For 6-year-olds, all trials contained three items, whereas for 8-year-olds, all trials contained four items so as to increase task difficulty. In each age group, all participants received the same trials. Before the PSE task, participants were shown each of the items (as pictures) on the computer screen and were asked to name each one. This was to ensure that the participants would use the correct names for the items when recalling them later. Once participants had named all of the items correctly, the task began. During the task, the trials alternated between phonologically similar and phonologically dissimilar. On each trial, participants were told that they must remember the pictures by looking at them very carefully and without overtly naming them during their presentation. Each item was visually presented for 1 s, followed by a 500-ms blank. Once all items had been presented for the trial, a cartoon character reappeared immediately to signal verbal serial recall.

Order of presentation

Half of the children were given the experimental tasks in the following order: simple span, delayed span, PSE, Brown–Peterson, and complex span. The other half were given the tasks in the reverse order. Each child was tested in two sessions on separate days, with the simple span, delayed span, and PSE tasks comprising one session and the remaining tasks comprising the other session.

Results

Calculating recall scores

For each participant, a recall score on each of the memory tasks was calculated using the partial credit unit method recommended by Conway et al. (2005). Specifically, the proportion of items recalled (in their correct position) was first determined for each trial. The proportional scores from all trials were then summed to give a recall score. Table 1 shows the means and standard deviations of the recall scores for the two age groups on the four memory span tasks.

Overall analysis on recall

A preliminary analysis showed that there was no significant effect of order of task presentation on recall scores, $F(1, 217) = 0.05, p = .832$, and that task order did not interact significantly with either age group, $F(1, 217) = 0.05, p = .819$, or the combination of age group and task, $F(3, 651) = 1.15, p = .328$. Consequently, a 2 (Age Group: 6-year-olds/8-year-olds) $\times$ 4 (Task: simple span/delayed span/Brown–Peterson/complex span) mixed analysis of variance (ANOVA) was performed on the recall scores. This analysis revealed a reliable effect of age group, $F(1, 219) = 154.05, p < .001, MSE = 27.46, \eta^2_n = .413$, with older children ($M = 13.91$) outperforming younger children ($M = 9.53$) across the tasks. The task effect was also significant, $F(3, 657) = 334.87, p < .001, MSE = 4.26, \eta^2_n = .605$, as was the Age Group $\times$ Task interaction, $F(3, 594) = 8.49, p < .001, MSE = 4.26, \eta^2_n = .037$.

Table 1
Means and standard deviations of recall scores obtained in the four memory span tasks by 6- and 8-year-olds in Experiment 1.

Task	6-year-olds	8-year-olds	Marginal mean
Simple span	12.78 (2.60)	16.23 (2.90)	14.41 (3.24)
Delayed span	11.21 (2.65)	15.28 (2.88)	13.12 (3.43)
Brown–Peterson	7.37 (3.07)	12.03 (3.69)	9.56 (4.09)
Complex span	6.75 (3.14)	12.10 (4.24)	9.27 (4.56)
Marginal mean	9.53 (1.72)	13.87 (2.16)	

Note. Standard deviations are in parentheses.

To investigate the significant task effect and Age Group $\times$ Task interaction further, three other analyses were performed on the recall scores. In these, we report only task effects and Age Group $\times$ Task interactions because the age effect, although significant in all cases (with older children performing better than younger children), is not directly relevant to our research interests.

Simple span versus delayed span

The first analysis, an Age Group $\times$ Task (simple span/delayed span) mixed ANOVA, examined the effect of delay. The Age Group $\times$ Task interaction was significant, $F(1, 219) = 5.51$, $p < .02$, $MSE = 1.95$, $\eta_n^2 = .025$, as was the task main effect, $F(1, 219) = 90.28$, $p < .001$, $MSE = 1.95$, $\eta_n^2 = .292$. Post hoc analysis of simple main effects showed that both age groups achieved better recall in simple span than in delayed span, $F(1, 116) = 69.84$, $p < .001$, $MSE = 2.08$, $\eta_n^2 = .376$, and $F(1, 103) = 26.18$, $p < .001$, $MSE = 1.80$, $\eta_n^2 = .203$, for 6- and 8-year-olds, respectively. However, the decrease in delayed span, relative to simple span, was greater in the 6-year-olds (difference = 1.58) than in the 8-year-olds (difference = 0.95). When this difference was coded in proportional terms (by dividing the difference between each individual's performance on the simple and delayed span tasks by their performance on the simple span task [cf. Logie, Della Sala, Laiacina, Chambers, & Wynn, 1996]), the decrease in item recall from simple span to delayed span was again significantly greater for 6-year-olds than for 8-year-olds, $F(1, 219) = 9.74$, $p = .002$, $MSE = 0.02$, $\eta_n^2 = .043$.

Delayed span versus Brown–Peterson

The second analysis, an Age Group $\times$ Task (delayed span/Brown–Peterson) mixed ANOVA, examined the effect of processing on recall scores. The Age Group $\times$ Task interaction failed to reach significance, $F(1, 219) = 2.30$, $p = .13$, but there was a reliable task effect, $F(1, 219) = 344.91$, $p < .001$, $MSE = 4.01$, $\eta_n^2 = .612$, with poorer recall in the Brown–Peterson task ($M = 9.56$) than in the delayed span task ($M = 13.12$). This drop in recall from delayed span to Brown–Peterson was not different between the two age groups (differences = 3.84 for 6-year-olds and 3.26 for 8-year-olds).

Brown–Peterson versus complex span

Finally, an Age Group $\times$ Task (Brown–Peterson/complex span) mixed ANOVA compared recall on the Brown–Peterson task with that on the more conventional complex span measure. Here neither the Age Group $\times$ Task interaction, $F(1, 219) = 2.42$, $p = .12$, nor the task effect was significant, $F(1, 219) = 1.50$, $p = .22$.

PSE

For the PSE task, the proportion of items recalled in their correct positions was first calculated across similar and dissimilar trials for each participant. The group means and standard deviations for the proportions are arranged by item type in Table 2. These scores were subjected to an Age Group $\times$ Item Type (similar/dissimilar) mixed ANOVA, although the main effect of age is not reported here because participants in the two age groups received different list lengths and so this comparison is uninformative. The Age Group $\times$ Item Type interaction was close to significant, $F(1, 219) = 3.40$, $p = .066$, $MSE = .022$, $\eta_n^2 = .015$. However, when the phonological similarity effect was coded in proportional terms (by dividing the difference between conditions by performance on the dissimilar condition), the gain in recall when items were phonologically dissimilar did not differ between age groups, $F(1, 219) = 2.48$, $p = .117$. Furthermore, an analysis of simple main effects showed that within each age

Table 2

Means and standard deviations for similar and dissimilar items recalled correctly in the PSE task by 6- and 8-year-olds in Experiment 1.

	6-year-olds	8-year-olds
Similar	.64 (.18)	.51 (.19)
Dissimilar	.71 (.22)	.63 (.22)

Note. Standard deviations are in parentheses.

group the PSE was reliable, with more dissimilar items than similar items being recalled, $F(1, 116) = 12.64$, $p = .001$, $MSE = 0.02$, $\eta^2 = .098$, and $F(1, 103) = 35.23$, $p < .001$, $MSE = 0.02$, $\eta^2 = .255$, for 6- and 8-year-olds, respectively.

Discussion

Experiment 1 showed that memory recall in both age groups was adversely affected by a delay imposed between item presentation and recall and by the addition of nonverbal processing during this delay. Alternating (nonverbal) processing and storage demands, as in the complex span task, did not induce further recall impairments in either group. The accompanying PSE task revealed that both 6- and 8-year-olds recoded visual information into a phonological form, suggesting that even 6-year-olds were able to spontaneously name information subvocally as is required for subsequent phonological rehearsal. There was some indication that the PSE was larger in 8-year-olds than in 6-year-olds, but the interaction between age and absolute size of the PSE was only close to significant ($p = .07$). This result is not completely inconsistent with previous studies suggesting an age difference in the size of PSE for visually presented materials (e.g., Hitch et al., 1989). However, the large sample sizes employed here provided the power to detect a small yet reliable PSE among younger children. In addition, when the PSE was coded in proportional terms, which has the advantage of controlling for individual differences in overall levels of performance (Beaman, Neath, & Surprenant, 2008; Logie et al., 1996) but is rarely done in developmental studies, there was no indication of a meaningful interaction between PSE size and age. Thus, although there is some evidence from this task that the degree of recoding increases with age, the development of this ability might not be as dramatic and stage-like as believed previously. We return to this point in the General discussion.

Although both age groups showed some evidence of recoding visual materials into phonological forms, the maintenance of these representations during an unfilled delay was not 100% successful, with both groups showing an overall decrease in performance from simple span to delayed span. This decrease, however, was greater for 6-year-olds than for 8-year-olds and remained so even when coded in proportional terms. Therefore, this difference may provide a clearer indication of a greater propensity for phonological recoding and rehearsal in the older children than in the younger children.

Compared with the decrease in recall performance due to unfilled delay, the impairment to recall caused by processing during the delay was far more catastrophic. Given that the processing employed in this experiment (visual categorization) was nonverbal in nature, it should be possible to maintain memory items through phonological rehearsal during processing. Because 8-year-olds have previously been suggested to use phonological rehearsal to a greater extent than 6-year-olds, it was expected that older children would be able to sustain a higher level of recall than younger children when faced with nonverbal processing. Contrary to this expectation, both age groups were impaired by nonverbal processing to similar extents. This suggests that nonverbal processing disrupted memory maintenance in some other way, possibly by preventing memory representations from being refreshed or reactivated, and that both age groups suffered equal amounts of disruption to the refreshment mechanism. Certainly, if one assumes that nonverbal processing still allows for rehearsal (cf. Jarrold, Tam, Baddeley, & Harvey, *in press*), the equivalent effect of this processing activity does suggest that refreshment was equally compromised in the two age groups.

A final result to note is that there was no evidence that either age group performed less well on the complex span than on the Brown–Peterson task. This implies that there are not substantial “switch costs” associated with complex span performance (cf. Tehan, Hendry, & Kocinski, 2001), although it is possible that any detrimental effects of switching in the complex span task are offset by the greater temporal distinctiveness of storage items within this procedure relative to the Brown–Peterson paradigm (see Brown, Neath, & Chater, 2007).

In summary, Experiment 1 failed to reveal any significant age difference in the use of the refreshment mechanism by the two age groups. Furthermore, the finding of a reliable PSE in our 6-year-olds was somewhat contrary to past findings showing a clearer age difference in this measure between 6- and 8-year-olds, with the PSE absent in the former group and present in the latter group (e.g., Gathercole, 1998; Hitch et al., 1989). These two separate findings from Experiment 1 were examined further in Experiment 2. First, we sought supporting evidence that the PSE exists in younger children

and examined whether or not there is a reliable age difference in the PSE size between 6- and 8-year-olds. We note that the results concerning the PSE from Experiment 1 might have been influenced by scaling artefacts because the 6-year-olds were given “easier” trials containing three items rather than four items per trial as received by the 8-year-olds. Although proportional coding of the effect should address scaling issues to some degree, both age groups in Experiment 2 were administered the PSE task with the same span procedure to provide a fairer indication of potential age differences in the PSE produced for visual materials.

Second, we reasoned that in Experiment 1, the recall decrement caused by nonverbal processing was due to a disruption in the refreshment of memory representations because phonological rehearsal should be unaffected by nonverbal processing. Although it might be argued that the coin-collecting task may have encouraged the use of subvocal naming of the two colored targets or the responses associated with them, the fact that participants simply needed to respond by pressing a button of the same color as the target means that the processing task involved a visual forced-choice response with a clear mapping between target and response. Nevertheless, to bolster this claim, a direct comparison between the effects of verbal and nonverbal processing on recall was needed. In Experiment 2, along with simple and delayed spans, two versions of the Brown–Peterson task were devised. In these, the same stimuli were presented during the processing intervals of the tasks, but participants were told to perform either verbal or nonverbal processing on the stimuli. Furthermore, the PSE materials were used as storage items in all of the memory span tasks in Experiment 2. In this way, the impact of verbal and nonverbal processing on the opportunities for phonological recoding, and by inference phonological rehearsal, could be clearly determined.

Experiment 2

The four tasks employed in Experiment 2 were simple span, delayed span, and two versions of the Brown–Peterson task: one with verbal processing (Brown–Peterson–verbal) and the other with nonverbal processing (Brown–Peterson–nonverbal). The complex span task was not included here because Experiment 1 showed that the additional requirement to switch between processing and storage demands did not have an effect on the recall of either age group. For the tasks retained here, their structures were as described in Experiment 1 (see Fig. 1). However, all four tasks in Experiment 2 involved trials containing either phonologically similar or phonologically dissimilar items. By embedding the PSE manipulation with the span tasks, we were able to remove the need to present different list lengths to the two age groups to examine the PSE, as was the case in Experiment 1. Past adult studies have examined the PSE in the context of memory span tasks to examine the claim that recall in working memory tasks is supported by the phonological loop (Lobley, Baddeley, & Gathercole, 2005; Tehan et al., 2001). In a similar vein, the PSE observed here for visually presented memoranda would indicate, first, the *tendency* of 6- and 8-year-olds to engage in phonological recoding of these materials and, second, the *conditions* under which these phonologically recoded representations were successfully maintained.

Methods

Participants

Participants were recruited from two local state primary schools. There were 64 children each from Year 1 (27 boys and 37 girls, mean age = 6 years 3 months, range = 5 years 9 months to 6 years 9 months) and from Year 3 (33 boys and 31 girls, mean age = 8 years 3 months, range = 7 years 9 months to 8 years 9 months).

Procedure

Within each age group, participants were divided into four subgroups, with each subgroup receiving a different experimental memory span task (simple span, delayed span, Brown–Peterson–verbal, or Brown–Peterson–nonverbal). To ensure that the subgroups were not different in terms of basic short-term memory capacity, children from both age groups were administered a digit span task in

the first test session, and these digit span scores were used to assign individuals within each age group to the four subgroups in a way that minimized the differences in both the mean and variation in verbal short-term memory ability across subgroups. In a second session, participants were given one of four memory span tasks. At each session, participants were tested individually in a quiet room. All tasks were programmed on a Macintosh laptop computer and presented via a touch-screen.

Digit span task

In the digit span task, digits from 1 to 9 were used to create four trials at each span length, ranging from two to seven digits. A practice trial containing two digits was also created, and this was presented before the test. No digit was repeated within a trial, and the trials were presented to all participants in the same fixed order. On each trial, each digit was presented visually and auditorily for 1 s with a 500-ms interstimulus interval (ISI). Children were instructed to remember the digits for later recall, which was prompted by the appearance of a cartoon character immediately after the digit sequence. Recall was verbal. Participants were told to say “can’t remember” in place of forgotten items. Responses were recorded manually as in Experiment 1. A span procedure was employed, with the task terminating when all trials at a particular span length were recalled unsuccessfully.

Memory span tasks

In a second session, each participant was given one of four memory span tasks. For all tasks, the storage items were monosyllabic concrete nouns that were presented as pictures without any accompanying verbal label. All nouns were acquired by 6 years of age, according to age of acquisition norms (Bird, Franklin, & Howard, 2001; Gilhooly & Logie, 1980; Morrison et al., 1997). The nouns formed two sets of nine items in each: a phonologically similar set and a phonologically dissimilar set. Each set was used to create four phonologically similar and four phonologically dissimilar trials at each span length level (from 2 to 6 storage items) and an additional practice trial containing two items. No item was repeated within a single trial, and the same trials were presented in the same fixed order across participants and across the four memory span tasks. Within each task, the phonologically similar and dissimilar trials were presented in separate blocks.

On each memory span task, storage items were presented visually for 1 s each with an ISI of 500 ms. The duration of the delay and processing interval (in the Brown–Peterson tasks and delayed span task, respectively) was determined by adding 2 s to the interval for every storage item presented. Thus, in those tasks, the duration of the delay/processing interval was 4, 6, 8, 10, and 12 s for trials containing 2, 3, 4, 5, and 6 storage items, respectively.

During the processing interval in the Brown–Peterson tasks, a red or green circle was presented. For the Brown–Peterson–verbal task, the circle was displayed at the center of the screen and the participant was to name the color of the circle as quickly as possible. Once the color was named, the next circle was presented (after an ISI of 200 ms) via a mouse-click by the experimenter. For the Brown–Peterson–nonverbal task, the circle was presented at one of eight predetermined locations on a touch-screen. The touch-screen was divided in half by a vertical line down the center, and two buttons were located on each side of the screen (left and right) near the bottom. Participants were instructed to touch the button that was on the same side as the circle as quickly as possible (the color of the circle was to be disregarded here). Once a response had been made, the next circle was presented (after an ISI of 200 ms).

The order of presentation of the phonologically similar and dissimilar blocks of each memory span task was counterbalanced across participants. Before each block was given, participants were shown each of the nine pictorially presented items used for that block and were asked to name them. Any incorrect naming was corrected at this point. This was followed by the practice trial and the test block. Participants were instructed to look at the pictures quietly and to try to remember them. Verbal recall was prompted by the appearance of a cartoon character at the end of the trial, and participants were to recall items serially and to say “can’t remember” for forgotten items. Responses were recorded by hand by the experimenter as in Experiment 1. A span procedure was again adopted for each test block, with testing terminating when all four trials within the same span length level were recalled incorrectly.

Results

For each participant, a digit span score and recall scores for phonologically similar and dissimilar items on the memory span task were calculated using the partial credit unit method as described in Experiment 1. The digit span score data showed that 6-year-olds ($M = 12.90$), on average, recalled fewer digits in the correct order than 8-year-olds ($M = 16.35$), $F(1, 126) = 71.07$, $p < .001$, $MSE = 5.35$, $\eta^2_n = .361$. Within each age group, the mean digit span scores of subgroups assigned to the four different memory span tasks did not differ significantly from each other ($F_s < 1$ for both 6- and 8-year-olds). The characteristics of each age group and subgroup can be found in Table 3.

Analysis of recall scores

The recall scores for similar and dissimilar items within each task condition, arranged by age group, are shown in Fig. 2. A 2 (Age Group: 6-year-olds/8-year-olds) $\times$ 4 (Task: simple span/delayed span/Brown–Peterson–verbal/Brown–Peterson–nonverbal) $\times$ 2 (Item Type: phonologically similar/dissimilar) mixed ANOVA was performed on the recall scores from the four experimental tasks. Both age group and task were between-participants factors, and item type was the within-participant factor. The overall three-way interaction among age group, task, and item type failed to reach significance, $F(3, 120) = 1.10$, $p = .35$. However, all other two-way interactions were significant and are discussed

Table 3

Numbers of participants, mean ages, and mean digit scores within each subgroup for 6- and 8-year-olds in Experiment 2.

	6-year-olds			8-year-olds		
	<i>n</i>	Age (years)	Digit score	<i>n</i>	Age (years)	Digit score
Simple span	16	6:03	12.80 (1.94)	16	8:02	16.31 (2.56)
Delayed span	15	6:02	12.93 (2.14)	16	8:03	16.42 (2.40)
Brown–Peterson–verbal	16	6:04	13.07 (2.11)	16	8:03	16.30 (2.50)
Brown–Peterson–nonverbal	17	6:02	12.81 (2.80)	16	8:03	16.35 (2.33)

Note. Standard deviations are in parentheses.

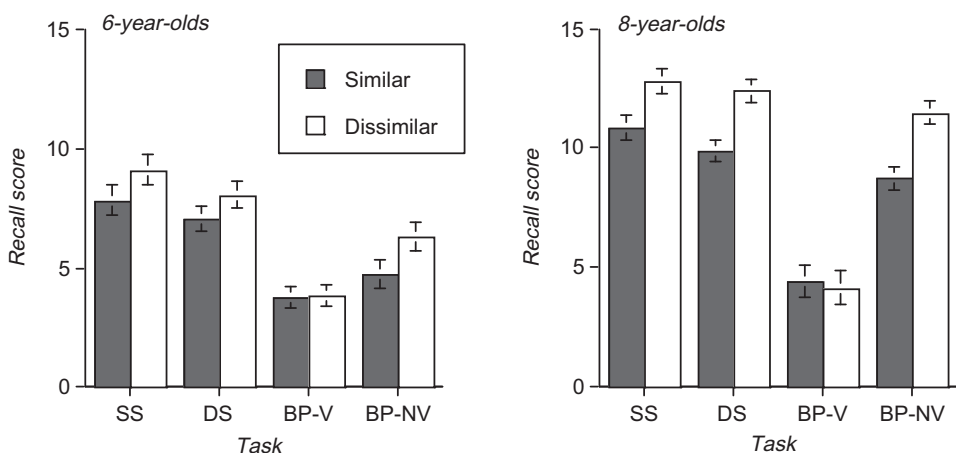


Fig. 2. Recall scores for similar and dissimilar items obtained for subgroups within the simple span (SS), delayed span (DS), Brown–Peterson–verbal (BP-V), and Brown–Peterson–nonverbal (BP-NV) conditions in Experiment 2. The left and right panels show the results for 6- and 8-year-olds, respectively. Error bars are 95% confidence intervals that account for between-participants variability (Bakeman & McArthur, 1996).

in detail below. Before that, the main effects are reported briefly here. The age group main effect was significant, with 8-year-olds ($M = 9.33$) achieving better recall than 6-year-olds ($M = 6.34$), $F(1, 120) = 60.16$, $p < .001$, $MSE = 9.35$, $\eta_n^2 = .334$. Recall scores also varied across memory span tasks, $F(3, 120) = 50.17$, $p < .001$, $MSE = 9.35$, $\eta_n^2 = .556$. This significant task main effect reflects the fact that both the Brown–Peterson–verbal ($M = 4.06$) and Brown–Peterson–nonverbal ($M = 7.75$) tasks yielded poorer recall than the delayed span task ($M = 9.43$), $F(1, 59) = 105.24$, $p < .001$, $MSE = 8.45$, $\eta_n^2 = .641$, and $F(1, 60) = 6.28$, $p < .02$, $MSE = 12.24$, $\eta_n^2 = .095$, respectively. Recall performance, however, did not differ significantly between the simple span ($M = 10.16$) and delayed span conditions, $F(1, 59) = 1.85$, $p = .18$. Finally, the item type main effect was significant, with better recall for dissimilar items ($M = 8.52$) than for similar items ($M = 7.15$), $F(1, 120) = 52.92$, $p < .001$, $MSE = 2.24$, $\eta_n^2 = .306$.

Age Group $\times$ Task interaction

The significant Age Group $\times$ Task interaction, $F(3, 120) = 5.46$, $p < .001$, $MSE = 9.35$, $\eta_n^2 = .120$, arose because the relative drop in performance on the Brown–Peterson–verbal task, compared with the other three tasks, was more substantial in 8-year-olds than in 6-year-olds. Consistent with this conclusion, the Age Group $\times$ Task interaction was eliminated if the same analysis included only simple span, delayed span, and Brown–Peterson–nonverbal conditions as levels of the task factor ($F < 1$). More specific comparisons against delayed span performance also revealed that the relative decrease in recall in the Brown–Peterson–verbal task was significantly greater for 8-year-olds (mean difference = 6.88) than for 6-year-olds (mean difference = 3.75), $F(1, 59) = 9.14$, $p < .01$, $MSE = 8.45$, $\eta_n^2 = .134$, whereas the decrease in the Brown–Peterson–nonverbal task (relative to the delayed span task) did not interact with age group ($F < 1$). Finally, the two age groups did not differ significantly in their performance on the Brown–Peterson–verbal task ($F < 1$).

Age Group $\times$ Item Type interaction

The significant Age Group $\times$ Item Type interaction, $F(1, 120) = 4.16$, $p < .05$, $MSE = 2.24$, $\eta_n^2 = .033$, was due to the magnitude of the PSE being clearly larger in 8-year-olds ($M = 1.74$) than in 6-year-olds ($M = 0.99$). However, analysis of simple main effects showed that both age groups independently produced a reliable PSE, with more dissimilar than similar items being recalled, $F(1, 63) = 13.44$, $p = .001$, $MSE = 2.33$, $\eta_n^2 = .176$, and $F(1, 63) = 34.46$, $p < .001$, $MSE = 2.82$, $\eta_n^2 = .354$, for 6- and 8-year-olds, respectively. In addition, when the size of the PSE was coded in proportional terms (see Experiment 1), the age difference in the effect was no longer significant, $F(1, 219) = 2.48$, $p = .117$.

Task $\times$ Item Type interaction

The significant Task $\times$ Item Type interaction, $F(3, 120) = 7.20$, $p < .001$, $MSE = 2.24$, $\eta_n^2 = .153$, reflected the fact that the PSE was significant in the simple span ($M = 1.62$), delayed span ($M = 1.78$), and Brown–Peterson–nonverbal ($M = 2.16$) tasks (analysis of simple main effects showed that in these tasks recall was significantly greater for dissimilar items than for similar items, lowest $F = 16.69$, all $ps < .001$) but was not reliably observed in the Brown–Peterson–verbal task ($M = -0.10$, $F < 1$). Indeed, when data from the Brown–Peterson–verbal condition were removed from the analysis, the Task $\times$ Item Type interaction ceased to be significant ($F < 1$). In addition, when the PSE was coded in proportional terms, there was a significant effect of task on this measure, $F(3, 124) = 7.33$, $p < .001$, $MSE = 0.42$, $\eta_n^2 = .151$, which was no longer significant when the Brown–Peterson–verbal task was removed from the analysis, $F(2, 93) = 1.18$, $p = .312$.

Discussion

The results from Experiment 2 supported the conclusions established in Experiment 1 in two major respects. First, a reliable PSE was again observed in both age groups, although in this instance the effect was significantly larger for 8-year-olds than for 6-year-olds when considered in absolute terms (the comparison of proportionalized scores was again nonsignificant). Thus, both 8- and 6-year-olds showed a tendency to recode and then maintain visually presented stimuli in a phonological form, and there was some, albeit not overwhelming, evidence that this tendency was stronger for older children than for younger children.

Second, Experiment 2 replicated Experiment 1 in showing the detrimental effect of nonverbal processing on recall; performance was superior in the delayed span task than in the Brown–Peterson–nonverbal task. This indicates that the nonverbal processing employed here was sufficiently demanding to capture attention and presumably to disrupt refreshment as a result. Certainly, it would be hard to argue that the processing operations caused forgetting as a result of interference with the verbal memoranda given that nonverbal processing simply required participants to touch the side of the screen on which the target appeared. Furthermore, the presence of a PSE in the Brown–Peterson–nonverbal task suggests that phonological recoding and maintenance, presumably via rehearsal, was still possible in the face of nonverbal distractor activity for both 6- and 8-year-olds.

Unlike Experiment 1, however, Experiment 2 did not provide evidence that an unfilled delay caused significant impairment in recall or that the decrease in performance from simple span to delayed span was different between the two age groups. We note that the sample size in Experiment 1 was nearly twice that in Experiment 2 and that task type was manipulated within-group in the former experiment and between-groups in the latter experiment. Furthermore, at each span length, the delay interval was longer in Experiment 1 (3 s per storage item was added to the interval) than in Experiment 2 (2 s per storage item). Together, these methodological differences might have allowed the small task effect and the Age Group $\times$ Task interaction to be detected in the first experiment but not in the second experiment.

General discussion

In two experiments, memory recall by 6- and 8-year-olds was examined using memory span tasks that differed in the extents to which maintenance, by phonological rehearsal and/or refreshment, could be carried out. These age groups were selected because previous research has led to the accepted view that one of these maintenance methods, phonological rehearsal, develops at around 7 years of age. In Experiment 1, both age groups suffered a substantial decrement in recall in a Brown–Peterson task, where a nonverbal processing activity was performed during the retention interval. In a separate PSE task, the two age groups independently produced reliable phonological similarity effects, although there was a slight suggestion that the size of this effect was larger among 8-year-olds. Experiment 2 incorporated the PSE stimuli into the memory span tasks and assessed the effect of nonverbal and verbal processing on the opportunity for phonological rehearsal and, subsequently, recall performance. Replicating results from Experiment 1, Experiment 2 showed that in both age groups nonverbal processing impaired recall but that the PSE was still clearly observed in this condition. In contrast, the PSE was eradicated by verbal processing. This finding was accompanied by a drastic decrease in recall, particularly for 8-year-olds, whose performance became statistically equivalent to that of 6-year-olds. In both experiments, therefore, verbal processing appears to have prevented phonological rehearsal in our participants; an effect that was particularly damaging to the recall of 8-year-olds.

It is, of course, possible that the form of verbal processing employed in Experiment 2 blocked both rehearsal and attentional refreshment. According to the TBRS model, the resources that support refreshment are also recruited by any processing that requires attentional retrieval (Barrouillet et al., 2004, 2007). The processing employed in the Brown–Peterson–verbal task in Experiment 2 required participants to name the color of a presented target, and although this might not have been particularly attentionally demanding, it does involve the retrieval of the color name from long-term memory. In that sense, the forced-choice decision involved in the task is arguably comparable to that required in the nonverbal processing task employed in Experiment 1. Future research could address this issue further by combining the verbal and nonverbal processing tasks employed in Experiment 2, for example, by asking participants to name the color of a target while also judging its spatial location (cf. Oberauer & Lewandowsky, 2008). However, given the low levels of recall seen in children of this age on the Brown–Peterson–verbal task in Experiment 2 (see Fig. 2), there may be relatively little room to see an additional decrement from combining these two types of processing. In addition, the key point to emphasize here is that regardless of whether the verbal processing employed in Experiment 2 blocked refreshment or not, the greater decrement caused by verbal processing, as opposed to nonverbal processing, in that experiment can be readily explained by the fact that verbal processing

blocks rehearsal by virtue of engaging participants in irrelevant articulation (cf. Baddeley, 1986; Hudjetz & Oberauer, 2007).

Our findings suggest, therefore, that phonological recoding and maintenance via rehearsal play a greater role in the working memory performance of older children than of their younger counterparts. This conclusion might at first appear to agree with the past proposal of a qualitative change in the use of phonological rehearsal at 7 years of age (e.g., Gathercole, 1998). However, both experiments conducted here indicated quite clearly that, as a group, children under 7 years of age showed some tendency to recode visually presented stimuli into phonological forms, an ability that is thought to be directly linked to subvocal rehearsal. Thus, the current data suggest that the developmental change in the use of phonological recoding and, by implication, rehearsal is likely to be *quantitative*, rather than *qualitative*, between 6 and 8 years of age.

One potential counter to this claim follows from the fact that when phonological recoding was assessed in both experiments, participants were given a pretest in which they were asked to name the pictures used to depict the similar and dissimilar storage items. This is standard practice in this area (e.g., Halliday et al., 1990; Hitch et al., 1989, 1991) because one needs to ensure that participants identify each item correctly so as to ensure that the similarity manipulation is effective, and it should be emphasized that when the stimuli were presented for recall they were only ever presented visually. However, it is possible that this pretest phase encouraged more recoding of these items in the memory phase of the task than might otherwise have been spontaneously observed, particularly among younger children. It is worth noting that studies using exactly this procedure have previously been cited as evidence for quantitative evidence of a change in rehearsal with age. In addition, there is other evidence in the literature to suggest that children age 6 years or under may already engage in phonological recoding and rehearsal even if not to an extent that is regularly detectable. For example, Ford and Silber (1994) found that the phonological similarity effect for visually presented material in children age 6 years or under, although significantly smaller than that in children age 6 years or over, was nonetheless reliable (see also Al-Namlah, Fernyhough, & Meins, 2006). Indeed, it may well be that the generally lower levels of overall performance seen among younger children make phonological similarity effects somewhat harder to detect than those in older children (cf. Beaman et al., 2008; Logie et al., 1996), a suggestion supported by the fact that significant and close to significant interactions between the absolute size of the PSE and age in both experiments were nonsignificant when the size of the PSE was coded proportionally. Certainly, one would not want to argue that children under 7 years of age never recode visual images given that children much younger than this can clearly name pictured objects when asked to do so. Nevertheless, the view that recoding and rehearsal do not begin until around 7 years of age is widely held, and the current data clearly cast serious doubt on this assumption.

In contrast to evidence consistent with a quantitative increase in phonological rehearsal use between 6 and 8 years of age, the current data suggest little development in the use of the refreshment mechanism between these two ages. In the two experiments here, both 6- and 8-year-olds showed similar degrees of decrement in recall under concurrent nonverbal processing despite the fact that phonological recoding (as gauged by the PSE) clearly occurred in this condition. On the one hand, this finding points to the existence of a refreshment-based maintenance mechanism that can be disrupted by nonverbal processing while leaving phonological rehearsal unhindered (Hudjetz & Oberauer, 2007; see also Camos et al., 2009; Mora, Camos, & Oberauer, 2008). On the other hand, our conclusion regarding the developmental course of the refreshment mechanism is contrary to that claimed by Barrouillet et al. (2009). As described in the Introduction, Barrouillet and colleagues found that 7-year-olds showed better recall when the processing pace in a working memory task was slow rather than fast, whereas 5-year-olds were not susceptible to this effect. The authors attributed this finding to the use of refreshment as a method of memory maintenance by 7-year-olds but not by 5-year-olds. In view of the current data, we would instead argue that the 7-year-olds in Barrouillet and colleagues' study not only were carrying out refreshment but also were engaged in phonological rehearsal to a greater extent than the 5-year-old participants. This interpretation would be consistent with the claim that refreshment efficiency does not develop as rapidly as rehearsal between 6 and 8 years of age and our finding of a comparable effect of nonverbal processing on recall in these two age groups.

However, an alternative reading of this aspect of the current data follows from the fact that [Barrouillet et al. \(2009\)](#) found that although 5-year-olds showed no effect of varying the number of colors to be named in a processing interval, they were affected by the imposition of a processing load relative to a baseline condition. Specifically, the drop in performance from a delayed span task to the condition in which participants named two colors in the corresponding processing interval was comparable in the two age groups. Barrouillet and colleagues' interpretation of this pattern among 5-year-olds was that although these individuals were not engaging in refreshment, they were prevented from "passively paying attention" to the memoranda by the general "distraction" produced by any processing load. Therefore, it is possible that the comparable effect of nonverbal processing seen in the two age groups assessed in the current study reflects a greater susceptibility to the interfering effects of processing among younger individuals than among older ones coupled with a comparably greater disruption of refreshment among older children than among younger children.

One concern with this suggestion is that it is not entirely clear how the disruption of passive attention due to interference in younger individuals differs conceptually from the prevention of active maintenance via rehearsal in older participants; put another way, how does paying passive attention offset the decay of representations assumed by the TBRS model if not by some process such as refreshment? In addition, we would argue that it is unlikely that these opposing effects would balance out exactly and that this account is, therefore, less parsimonious than the suggestion that the 5-year-olds in [Barrouillet et al.'s \(2009\)](#) study suffered from disruption to refreshment from the imposition of a processing load, whereas the 7-year-olds also experienced additional disruption of rehearsal as indicated by the effect of pace of processing on their performance. The advantage of our methodological approach is that by separately examining the effects of verbal and nonverbal processing on the development of working memory, we can more clearly isolate the disruptive effects of processing on rehearsal and refreshment than one can by simply manipulating the amount of processing from a single domain. The fact that our data showed that nonverbal processing did not disrupt phonological recoding and rehearsal, but nonetheless impaired recall to similar extents for both 6- and 8-year-olds, does suggest that the ability to refresh memoranda is in place by 6 years of age and that this ability does not develop considerably within this particular age range.

Of course, this raises the question of why refreshment develops less noticeably than rehearsal within this age range. If [Barrouillet et al. \(2009\)](#) are correct in suggesting that refreshment reflects the allocation of attention to the memoranda, this may well reflect a relatively primitive and automatic process. Certainly, by 6 years of age, children are capable of shifting their attention ([Manly et al., 2001](#)), and although the ease and speed with which attention is deployed no doubt improve when measured over a sufficiently large age range, it may be that the rate of this improvement in the context of immediate memory is different from that seen for rehearsal. Support for this suggestion comes from [Cowan et al.'s \(1998\)](#) study in which estimates of "rehearsal" and "retrieval" (with the latter corresponding closely to the notion of refreshment employed here) were indexed from children's short-term memory performance by measuring pause and word durations within response outputs. Cowan and colleagues found that these two measures explained separate variance in the memory span of 7–11-year-olds (see also [Jarrold et al., 2000](#)) and showed no evidence of intercorrelation. In other words, the developmental processing underlying refreshment and rehearsal may well be separable, allowing the two processes to develop at different rates (cf. [Bayliss et al., 2005](#)).

At the same time, it should be noted that [Cowan et al.'s \(1998\)](#) data indicated that both rehearsal and retrieval (or refreshment) factors mediated age-related changes in memory span, and we do not wish to claim that the efficiency of refreshment does not improve at all with age. Rather, we would argue that the 6–8-year period represents a time window in which rehearsal efficiency is undergoing a more marked developmental improvement. This is certainly consistent with previous evidence of a large change in the size of the phonological similarity effect for visually presented material at around 7 years of age that is often attributed to the onset of an explicit rehearsal strategy at this age (e.g., [Flavell et al., 1966](#)). As noted, our data are more consistent with the suggestion of quantitative changes in rehearsal efficiency, which might be better explained in terms of relatively rapid increases in the speech rate at this point of development rather than the abrupt onset of strategy use. However, these are somewhat speculative suggestions that would ideally need to be verified in future research that examines the

developmental changes in rehearsal and refreshment efficiency across a broader age range than assessed here.

Conclusion

The two experiments conducted here indicated that nonverbal processing within a Brown–Peterson task paradigm impaired recall to similar degrees in both 6- and 8-year-olds, probably by disrupting a refreshment-based maintenance mechanism. In contrast, verbal processing disrupted phonological recoding and rehearsal in both age groups but did so to a greater extent in older children than in younger children. Overall, this study provided evidence that two separate maintenance mechanisms are already in place by 6 years of age, although their courses of development appear to differ. The findings presented here, therefore, highlight the need to consider how the processing component within working memory measures can affect the workings of phonological rehearsal and attentional refreshment in children at various points of development. The blocking of phonological rehearsal would be expected to have a larger impact in older children who have a greater reliance on this method of memory maintenance. In contrast, the disruption to refreshment would appear to have more similar effects across children between 6 and 8 years of age.

Acknowledgments

This research was supported by a grant from the Economic and Social Research Council (UK) awarded to Chris Jarrold and Alan Baddeley (RES-062-23-1048). We thank the staff and pupils at Ashley Down Junior School, Ashton Gate Primary School, Broomhill Infants and Junior Schools, Cheddar Grove Primary School, and St. Anne's Infant School for their participation in this work.

References

- Al-Namlah, A. S., Fernyhough, C., & Meins, E. (2006). Sociocultural influences on the development of verbal mediation: Private speech and phonological recoding in Saudi Arabian and British samples. *Developmental Psychology*, 42, 117–131.
- Baddeley, A. D. (1986). *Working memory*. Oxford, UK: Oxford University Press.
- Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning & Verbal Behavior*, 14, 575–589.
- Bakeman, R., & McArthur, D. (1996). Picturing repeated measures: Comments on Loftus, Morrison, and others. *Behavior Research Methods, Instruments, & Computers*, 28, 584–589.
- Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, 133, 83–100.
- Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 33, 570–585.
- Barrouillet, P., Gavens, N., Vergauwe, E., Gaillard, V., & Camos, V. (2009). Working memory span development: A time-based resource-sharing model account. *Developmental Psychology*, 45, 477–490.
- Bayliss, D. M., Jarrold, C., Baddeley, A. D., Gunn, D. M., & Leigh, E. (2005). Mapping the developmental constraints on working memory span performance. *Developmental Psychology*, 41, 579–597.
- Bayliss, D. M., Jarrold, C., Gunn, D. M., & Baddeley, A. D. (2003). The complexities of complex span: Explaining individual differences in working memory in children and adults. *Journal of Experimental Psychology: General*, 132, 71–92.
- Beaman, C. P., Neath, I., & Surprenant, A. M. (2008). Modeling distributions of immediate memory effects: No strategies needed? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 34, 219–229.
- Bird, H., Franklin, S., & Howard, D. (2001). Age of acquisition and imageability ratings for a large set of words, including verbs and function words. *Behavior Research Methods, Instruments, & Computers*, 33, 73–79.
- Brown, J. (1958). Some tests of the decay theories of immediate memory. *Quarterly Journal of Experimental Psychology*, 10, 12–21.
- Brown, G. D. A., & Hulme, C. (1995). Modeling item length effects in memory span: No rehearsal needed? *Journal of Memory and Language*, 34, 594–621.
- Brown, G. D. A., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review*, 114, 539–576.
- Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology*, 33, 205–228.
- Camos, V., Lagner, P., & Barrouillet, P. (2009). Two maintenance mechanisms of verbal information in working memory. *Journal of Memory and Language*, 61, 457–469.
- Campoy, G. (2008). The effect of word length on short-term memory: Is rehearsal necessary? *Quarterly Journal of Experimental Psychology*, 61, 724–734.
- Conrad, R. (1964). Acoustic confusions in immediate memory. *British Journal of Psychology*, 55, 75–84.
- Conrad, R., & Hull, A. J. (1964). Information, acoustic confusion, and memory span. *British Journal of Psychology*, 55, 429–432.
- Conrad, R., & Hull, A. J. (1966). The role of the interpolated task in short-term retention. *Quarterly Journal of Experimental Psychology*, 18, 266–269.

- Conway, A. R. A., Cowan, N., Bunting, M. F., Theriault, D. J., & Minkoff, S. R. B. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence*, 30, 163–183.
- Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review*, 12, 769–786.
- Cowan, N., Morey, C. C., AuBuchon, A. M., Zwilling, C. E., & Gilchrist, A. L. (2010). Seven-year-olds allocate attention like adults unless working memory is overloaded. *Developmental Science*, 13, 120–133.
- Cowan, N., Wood, N. L., Wood, P. K., Keller, T. A., Nugent, L. D., & Keller, C. V. (1998). Two separate verbal processing rates contributing to short-term memory span. *Journal of Experimental Psychology: General*, 127, 141–160.
- Duff, S. C., & Logie, R. H. (2001). Processing and storage in working memory span. *Quarterly Journal of Experimental Psychology A*, 54, 31–48.
- Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General*, 128, 309–311.
- Farrell, S., & Lewandowsky, S. (2002). An endogenous distributed model of ordering in serial recall. *Psychonomic Bulletin and Review*, 9, 59–79.
- Ferguson, A. N., Bowey, J. A., & Tilley, A. (2002). The association between auditory memory span and speech rate in children from kindergarten to sixth grade. *Journal of Experimental Child Psychology*, 81, 141–156.
- Flavell, J. H., Beach, D. R., & Chinsky, J. M. (1966). Spontaneous verbal rehearsal in a memory task as a function of age. *Child Development*, 37, 283–299.
- Ford, S., & Silber, K. P. (1994). Working memory in children: A developmental approach to the phonological coding of pictorial material. *British Journal of Developmental Psychology*, 12, 165–175.
- Gathercole, S. E. (1998). The development of memory. *Journal of Child Psychology and Psychiatry*, 39, 3–27.
- Gathercole, S. E., & Adams, A. (1993). Phonological working memory in very young children. *Developmental Psychology*, 20, 770–778.
- Gathercole, S. E., Adams, A., & Hitch, G. J. (1994). Do young children rehearse? An individual-differences analysis. *Memory & Cognition*, 22, 201–207.
- Gilhooly, K. J., & Logie, R. H. (1980). Age of acquisition, imagery, concreteness, familiarity, and ambiguity measures for 1,944 words. *Behavior Research, Methods, & Instrumentation*, 12, 395–427.
- Hale, S., Bronik, M. D., & Fry, A. F. (1997). Verbal and spatial working memory and school-age children: Developmental differences in susceptibility to interference. *Developmental Psychology*, 33, 364–371.
- Hale, S., Myerson, J., Rhee, S. H., Weiss, C. S., & Abrams, R. A. (1996). Selective interference with the maintenance of location information in working memory. *Neuropsychology*, 10, 228–240.
- Halliday, M. S., Hitch, G. J., Lennon, B., & Pettipher, C. (1990). Verbal short-term memory in children: The role of the articulatory loop. *European Journal of Cognitive Psychology*, 2, 23–38.
- Hayes, D. S., & Schulze, S. A. (1977). Visual encoding in preschoolers' serial retention. *Child Development*, 48, 1066–1070.
- Henry, L. A. (1991). The effects of word length and phonemic similarity in young children's short-term memory. *Quarterly Journal of Experimental Psychology A*, 43, 35–52.
- Hitch, G. J., Halliday, M. S., Schaafstal, A. M., & Heffernan, T. M. (1991). Speech, inner speech, and the development of short-term memory effects of picture-labeling on recall. *Journal of Experimental Child Psychology*, 51, 220–234.
- Hitch, G. J., Woodin, M. E., & Baker, S. (1989). Visual and phonological components of working memory in children. *Memory & Cognition*, 17, 175–185.
- Holmes, J., Gathercole, S. E., & Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental Science*, 12, F9–F15.
- Howard, D., & Franklin, S. (1990). Memory without rehearsal. In G. Vallar & T. Shallice (Eds.), *Neuropsychological impairments in short-term memory* (pp. 287–318). Cambridge, UK: Cambridge University Press.
- Hudjetz, A., & Oberauer, K. (2007). The effects of processing time and processing rate on forgetting in working memory: Testing four models of the complex span paradigm. *Memory & Cognition*, 35, 1675–1684.
- Hulme, C., Maughan, S., & Brown, G. D. A. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language*, 30, 685–701.
- Hutton, U. M. Z., & Towse, J. N. (2001). Short-term memory and working memory as indices of children's cognitive skills. *Memory*, 9, 383–394.
- Jarrold, C., Cowan, N., Hewes, A. K., & Riby, D. M. (2004). Speech timing and verbal short-term memory: Evidence for contrasting deficits in Down syndrome and Williams syndrome. *Journal of Memory and Language*, 51, 365–380.
- Jarrold, C., Tam, H., Baddeley, A. D., & Harvey, C. E. (in press). The nature and the position of processing determines why forgetting occurs in working memory tasks. *Psychonomic Bulletin & Review*.
- Jarrold, C., Hewes, A. K., & Baddeley, A. (2000). Two separate speech measures constrain verbal short-term memory in children. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 26, 1626–1637.
- Kane, M. J., Hambrick, D. Z., & Conway, A. R. A. (2005). Working memory capacity and fluid intelligence are strongly related constructs: Comment on Ackerman, Beier, and Boyle (2005). *Psychological Bulletin*, 131, 66–71.
- La Pointe, L. B., & Engle, R. W. (1990). Simple and complex word spans as measures of working memory capacity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 1118–1133.
- Lépine, R., Bernardin, S., & Barrouillet, P. (2005). Attention switching and working memory spans. *European Journal of Cognitive Psychology*, 17, 329–345.
- Lewandowsky, S., & Farrell, S. (2008). Phonological similarity in serial recall: Constraints on theories of memory. *Journal of Memory and Language*, 58, 429–448.
- Lewandowsky, S., Geiger, S. M., & Oberauer, K. (2008). Interference-based forgetting in verbal short-term memory. *Journal of Memory and Language*, 59, 200–222.
- Lewandowsky, S., & Oberauer, K. (2008). The word length effect provides no evidence for decay in short-term memory. *Psychonomic Bulletin & Review*, 15, 875–888.
- Liefoghe, B., Barrouillet, P., Vandierendonck, A., & Camos, V. (2008). Working memory costs of task switching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 34, 478–494.

- Lobley, K. J., Baddeley, A. D., & Gathercole, S. E. (2005). Phonological similarity effects in verbal complex span. *Quarterly Journal of Experimental Psychology*, 58, 1462–1478.
- Logie, R. H., Della Sala, S., Laiacina, M., Chambers, P., & Wynn, V. (1996). Group aggregates and individual reliability: The case of verbal short-term memory. *Memory & Cognition*, 24, 305–321.
- Logie, R. H., Zucco, G. M., & Baddeley, A. D. (1990). Interference in visual short-term memory. *Acta Psychologica*, 75, 55–74.
- Manly, T., Anderson, V., Nimmo-Smith, I., Turner, A., Watson, P., & Robertson, I. H. (2001). The differential assessment of children's attention: The Test of Everyday Attention for Children (TEA-Ch), normative sample, and ADHD performance. *Journal of Child Psychology and Psychiatry*, 42, 1065–1081.
- Mora, G., Camos, V., & Oberauer, K. (2008). How do articulatory rehearsal and attentional refreshing interact with phonological similarity in the complex span paradigm? In *Poster session presented at the fourth European working memory workshop*, Bristol, UK.
- Morrison, C. M., Chappell, T. D., & Ellis, A. W. (1997). Age of acquisition norms for a large set of object names and their relation to adult estimates and other variables. *Quarterly Journal of Experimental Psychology A*, 50, 528–559.
- Murray, D. J. (1967). The role of speech responses in short-term memory. *Canadian Journal of Psychology*, 21, 263–276.
- Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition*, 18, 251–269.
- Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28, 411–421.
- Oberauer, K., & Lewandowsky, S. (2010). Modelling working memory: A computational implementation of the time-based resource-sharing theory, submitted for publication.
- Oberauer, K., & Lewandowsky, S. (2008). Forgetting in immediate serial recall: Decay, temporal distinctiveness, or interference? *Psychological Review*, 115, 544–576.
- Oberauer, K., Schulze, R., Wilhelm, O., & Süß, H.-M. (2005). Working memory and intelligence—Their correlation and their relation: Comment on Ackerman, Beier, and Boyle (2005). *Psychological Bulletin*, 131, 61–65.
- Peterson, L. R., & Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology*, 58, 193–198.
- Portrat, S., Camos, V., & Barrouillet, P. (2009). Working memory in children: A time-constrained functioning similar to adults. *Journal of Experimental Child Psychology*, 102, 368–374.
- Raye, C. L., Johnson, M. K., Mitchell, K. J., Reeder, J. A., & Greene, E. J. (2002). Neuroimaging a single thought: Dorsolateral PFC activity associated with refreshing just-activated information. *NeuroImage*, 15, 447–453.
- Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory*, 6, 174–215.
- Sternberg, S. (1966). High-speed scanning in human memory. *Science*, 153, 652–654.
- Swanson, H. L. (2008). Working memory and intelligence in children: What develops? *Journal of Educational Psychology*, 100, 581–602.
- Tehan, G., Hendry, L., & Kocinski, D. (2001). Word length and phonological similarity effects in simple, complex, and delayed serial recall tasks: Implications for working memory. *Memory*, 9, 333–348.
- Thorn, A. S. C., & Gathercole, S. E. (2001). Language differences in verbal short-term memory do not exclusively originate in the process of subvocal rehearsal. *Psychonomic Bulletin and Review*, 8, 357–364.
- Towse, J. N., & Hitch, G. J. (1995). Is there a relationship between task demand and storage space in tests of working memory capacity? *Quarterly Journal of Experimental Psychology A*, 48, 108–124.
- Vallar, G., & Papagno, C. (1995). Neuropsychological impairments of short-term memory. In A. D. Baddeley, B. A. Wilson, & F. Watts (Eds.), *Handbook of memory disorders* (pp. 135–165). Chichester, UK: John Wiley.
- Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource? *Psychological Science*, 21, 384–390.