Working memory deficits in children with reading difficulties: Memory span and dual task coordination

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\textbf{A B S T R A C T}

The current study investigated the cause of the reported problems in working memory in children with reading difficulties. Verbal and visuospatial simple and complex span tasks, and digit span and reaction times tasks performed singly and in combination, were administered to 46 children with single word reading difficulties and 45 typically developing children matched for age and nonverbal ability. Children with reading difficulties had pervasive deficits in the simple and complex span tasks and had poorer abilities to coordinate two cognitive demanding tasks. These findings indicate that working memory problems in children with reading difficulties may reflect a core deficit in the central executive.

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\textbf{Introduction}

Problems in reading single words accurately and fluently that persist throughout the school years and impair children's academic achievements are extremely common, affecting up to 6% of the school population (e.g., Yule, Rutter, Berger, & Thompson, 1974). The consensus is that deficits in processing the phonological structure of language are strongly associated with reading difficulties, although whether these processing deficits represent a core impairment (Vellutino, Fletcher, Snowling, & Scan-
ion, 2004) or are themselves a consequence of disruptions of more basic abilities such as analyzing fine-grained temporal structure (Goswami, 2011) is still to be resolved. In the current study, we build on evidence that children with reading difficulties experience difficulties in working memory (e.g., Swanson & Ashbaker, 2000) by investigating whether these problems represent a core deficit in working memory and, if so, what the nature of this deficit might be.

Working memory provides temporary maintenance of information necessary to support complex cognitive processing. Baddeley and Hitch (1974) advanced an influential multicomponent model of working memory consisting of two stores specialized for verbal and visuospatial material: the phonological loop and the visuospatial sketchpad. A third component is the central executive, an attentional control system with limited capacity responsible for the regulation of cognitive processes (Baddeley, 1996). More recently, Baddeley (2000) argued for a fourth component, the episodic buffer, capable of integrating information within and beyond working memory in multidimensional forms. Storage capacity is typically measured by simple span tasks that require only the passive retention of information, whereas working memory is typically measured by complex span tasks that involve simultaneous storage and processing of information. Latent factor studies of children (Alloway, Gathercole, & Pickering, 2006) and adults (Kane et al., 2004) have supported the original three-factor version of the model consisting of a domain-general factor that corresponds to the central executive plus distinct phonological and visuospatial stores. Complex span tasks that impose significant demands on storage and processing rely both on the central executive to support processing and on the relevant domain-specific store for temporary storage. Examples of such tasks include listening span, in which participants make semantic decisions about a series of spoken sentences and then recall the final words of each sentence (Daneman & Carpenter, 1980), and operation span, in which a series of mathematical calculations are made (e.g., 2 + 6/2) and then successive target items accompanying the calculations are recalled (Turner & Engle, 1989). Thus, for example, both the central executive and the phonological store will contribute to a verbal complex span task such as listening span.

Close links are well established between children's performance in working memory, as indexed by complex span tasks, and their reading disabilities, as indexed by performance on standardized tests of word decoding or comprehension 1 standard deviation or more below the levels expected on the basis of chronological age alone despite average performance on measures of intelligence (e.g., de Jong, 1998; Swanson, Zheng, & Jerman, 2009). This link is also identified when reading disabilities are indexed by significant discrepancies between IQ and word reading that are typically required for a diagnosis of dyslexia (e.g., Alloway, 2007; Jeffries & Everatt, 2004; Pickering, 2006b). For the current purposes, the term reading difficulties is used to include both overlapping methods of selecting children who are poor readers, although where differences associated with IQ appear to influence memory performance they are noted. Many studies have demonstrated that children with reading difficulties perform poorly both on tasks that involve phonological storage (e.g., Ackerman & Dykman, 1993; Mann, Liberman, & Shankweiler, 1980; Roedensys & Stokes, 2001) and on measures of verbal complex span (e.g., de Jong, 1998; Pickering, 2006b; Swanson, 1999; Swanson & Ashbaker, 2000). A key question is why these problems arise.

One possibility is that these impairments result from a core deficit in the phonological loop component of working memory, which underlies the deficits both in verbal storage and in more complex activities combining storage with processing. In line with this view, some authors have suggested that verbal working memory does not account for children's reading abilities beyond verbal short-term memory (Hutton & Towse, 2001). On balance, however, the weight of evidence points to an additional impairment in the executive control of working memory. For example, de Jong (1998) compared performance of a group of reading-disabled children and typical readers on measures for verbal working memory, verbal short-term memory, and processing speed. The verbal working memory deficits of the group with reading disabilities could not be explained by these children's verbal storage problems alone, a conclusion also reached by Swanson and Ashbaker (2000). In their study, the performance of poor readers in verbal complex span tasks shared specific links with word recognition and comprehension performance that were independent of the contribution of verbal short-term memory. On this basis, it was proposed that impaired reading abilities of these children reflected deficits in the central executive independent of their problems in verbal short-term memory. Other relevant evidence is provided by a longitudinal study of children identified as having very poor verbal short-term memory.
skills at 5 years of age (Gathercole, Tiffany, Briscoe, Thorn, & ALSPAC Team, 2005). Three years later, these children's vocabulary, language, and mathematics abilities were typical for their age, indicating that verbal storage deficits alone are not sufficient to cause enduring reading difficulties.

In line with Swanson and Ashbaker’s (2000) claims, a second possibility is that the poor performance in verbal complex span tasks of children with reading difficulties reflects their deficits in the central executive. Given the domain-general nature of the central executive (Alloway et al., 2006; Kane et al., 2004), a key prediction of this hypothesis is that the children's memory difficulties should extend to complex span tasks involving nonverbal as well as verbal material. Smith-Spark and Fisk (2007), Smith-Spark, Fisk, Fawcett, and Nicolson (2003), and Swanson, Ashbaker, and Lee (1996, Experiment 2) provided some support for this prediction, reporting that in addition to the expected verbal working memory deficits, the performance of individuals with reading difficulties was impaired in complex visuospatial (Smith-Spark & Fisk, 2007; Swanson et al., 1996), and spatial updating tasks when the number of updates required was increased (Smith-Spark et al., 2003). However, several other studies have reported intact performance on visuospatial complex span tasks. Swanson and colleagues (1996, Experiment 1), for example, failed to replicate their own findings in a different sample of children with reading difficulties, and visuospatial working memory deficits in children with reading difficulties have been reported to be eliminated when IQ is taken into account (Marzocchi et al., 2008; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005). A largely consistent outcome across many studies is an absence of detectable visuospatial short-term memory deficits in this population (Gould & Glencross, 1990; Liberman, Mann, Shankweiler, & Werfelman, 1982; Pickering, 2006b; Smith-Spark & Fisk, 2007; Smith-Spark et al., 2003), although it should be noted that Menghini, Finzi, Carlesimo, and Vicari (2011) reported short-term memory deficits in children with reading difficulties in tasks that require processing of visual–object and visual–spatial information.

In a recent meta-analysis conducted by Swanson and colleagues (2009) of 88 studies of working memory in children with and without reading difficulties, moderate to high effect sizes were found on measures of verbal short-term memory, verbal complex memory, visuospatial short-term memory, and visuospatial complex memory. However, children with reading difficulties were consistently disadvantaged relative to typical readers only on measures of verbal short-term memory and verbal complex memory when confounding factors such as IQ and reading level were taken into account. Swanson and colleagues argued that visuospatial memory performance in children with reading difficulties may fluctuate with task demands, resulting in inconsistent patterns of results. In Swanson and colleagues’ studies (e.g., Swanson, 2000; Swanson et al., 1996), visuospatial complex span tasks were presented under an initial condition (i.e., initial performance without cues), a gain condition (i.e., with cues to optimize performance), and a maintenance condition (i.e., without cues on the highest level of performance achieved under gain condition). Children with reading problems were consistently impaired under the maintenance condition (i.e., when the task demands were high), whereas the findings were mixed under the initial condition. One possible reason for the inconsistent findings under the initial condition concerns the absence of visuospatial tasks of both simple and complex memory span within a single study. Therefore, it is not possible to rule out the possibility that the level of visuospatial short-term memory abilities may have contributed to these inconsistencies. In addition, note that the visuospatial complex span tasks in previous studies were restricted to visual matrix or mapping and directions. The current study overcame these limitations by including other well-established measures of visuospatial complex span and comparing the same children on both verbal and visuospatial tests of simple and complex memory span.

The aim of the current study was to provide a strong test of the hypothesis that children with reading difficulties have a central executive deficit by combining two different methods for assessing executive capacity. First, we compared the performances of large samples of children with and without reading difficulties on the Automated Working Memory Assessment (AWMA; Alloway, 2007), a standardized test battery incorporating both verbal and visuospatial tests of simple and complex memory span. This allows the same children to be compared on standardized and co-normed measures of verbal and visuospatial memory span. The battery has high construct validity and has been shown to be highly effective in child populations in distinguishing the central executive, phonological loop, and visuospatial sketchpad components of the Baddeley and Hitch (1974) working memory model (Alloway et al., 2006). A domain-general deficit in the central executive would manifest itself in impair-
ments in both verbal and visuospatial complex span measures. In contrast, the impact of a phonological storage impairment would be restricted to verbal simple and complex span scores. The AWMA subtests provide particularly robust assessments of performance by providing up to six trials at each list length, with testing discontinued after errors have been made on three trials. In contrast to the tests used in the previous studies where only one trial was included in each sequence length (e.g., Swanson et al., 1996), this method allows for distractions and lapses of attention to occur during testing without having devastating consequences for the scores obtained by the children (Pickering, 2006a) and, as such, provides a more sensitive measure of performance.

Second, we investigated the dual task coordination abilities of children with reading difficulties. The ability to coordinate cognitive demanding tasks has been closely associated with the central executive (Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986; Della Sala, Baddeley, Papagno, & Spinnler, 1995), and dual task paradigms have been successfully used to investigate clinical populations. For example, patients with Alzheimer’s disease are disproportionately disrupted by combining tasks, and the degree of disruption increases as the disease progresses (Baddeley, Bressi, Della Sala, Logie, & Spinnler, 1991). These findings have been interpreted as reflecting a core central executive deficit. Whether children with reading difficulties have problems in dual task coordination is as yet unknown, but this experimental method holds clear promise as an alternative means of identifying the nature of working memory deficits in children with reading difficulties. The finding of a greater cost of combining two cognitively demanding tasks—digit recall and choice reaction times, employing the methodology developed by Baddeley and colleagues (1986)—would provide strong support for the hypothesis that central executive function is impaired in this population.

Method

Participants

A total of 689 children aged 8 to 10 years attending state primary schools in urban areas of the North East and South West of England participated in the screening phase of the study. Schools were selected on the basis of their willingness to participate. The participating schools on average had 24.4% of pupils eligible for free school meals (an index of poverty in England) and 19.0% of pupils with special educational needs (without statements). These proportions compare with 18.5% and 18.2% for free school meals and special educational needs, respectively, for primary schools across England in 2010 (Clarke, 2010). All children completed the single word reading subtest of the Wechsler Objective Reading Dimension (WORD; Wechsler, 1993) and the matrix reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). The matrix reasoning subtest was used to index children’s nonverbal reasoning ability. The single word reading subtest provided a measure of children’s ability to read single words in isolation. Children were presented with a list of progressively more difficult words, and the test stopped when children made four consecutive mistakes. The total number of words read correctly for each child was converted into a standard score with a population mean of 100 and a standard deviation of 15.

The selection criteria for the reading difficulties group were a standard score of 85 or below on the single word reading subtest of the WORD (i.e., ≤1 standard deviation below the population mean) and

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Means (and standard deviations) for chronological age and performance on the screening measures.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reading difficulties</td>
</tr>
<tr>
<td>Age (months)</td>
<td>113.76 (7.08)</td>
</tr>
<tr>
<td>Single word reading (WORD)</td>
<td>79.92 (5.12)</td>
</tr>
<tr>
<td>Matrix reasoning (WASI)</td>
<td>48.96 (6.03)</td>
</tr>
</tbody>
</table>

Note. Standard deviations are in parentheses.

a Standard score: \( M = 100, SD = 15 \).

b Standard score: \( M = 50, SD = 10 \).
a minimum t score of 40 on the matrix reasoning subtest of the WASI (i.e., \( \geq 1 \) standard deviation below the population mean). A total of 46 children (17 girls and 29 boys) met these criteria and were selected for participation. A comparison group of 45 children (24 girls and 21 boys) who were typical readers were recruited and conformed to the following criteria: standard scores \( \geq 95 \) in single word reading and t scores \( \geq 40 \) in matrix reasoning. These recruitment criteria correspond to those employed in previous research on children with reading difficulties (e.g., Gooch, Snowling, & Hulme, 2011). The proportion of children satisfying the criteria for reading difficulties in this screening sample was 6.6%, in line with levels of incidence in a population study reported by Yule and colleagues (1974). Children with reading difficulties and typical readers were matched individually within schools for their chronological ages (within 3 months) and standard matrix reasoning scores as closely as possible (within 4 points). As shown in Table 1, on the single word reading subtest of the WORD, children with reading difficulties performed significantly more poorly than typical readers (\( p < .001 \)), but the groups did not differ in age (\( p = .614 \)) or matrix reasoning scores (\( p = .883 \)). Teachers confirmed the absence of any other developmental disorders in children with reading difficulties and of significant educational problems in the group of typical readers. All children were native English speakers. Ethical approval for this study was granted by the ethics committee of the psychology department at the University of York. Informed parental consent was obtained and completed prior to participating.

Procedure

The tasks were administered individually in two sessions lasting less than 30 min each in a quiet room of the school. In the first session, four tasks from the AWMA (Alloway, 2007) were administered in a fixed order designed to vary task demands across successive tests (Alloway, Gathercole, Willis, & Adams, 2004). Then, the children received the dual task in a second session within 2 weeks.

Measures

Working memory

Four subtests from the AWMA (Alloway, 2007) were administered. All tests employed span procedures in which sequence lengths were increased until the point at which three or more errors were made within a block of trials. Verbal short-term memory was measured by digit recall, where the child hears a sequence of digits and needs to recall each sequence in the correct order. Verbal working memory was measured by backward digit recall, where the child needs to recall a sequence of spoken digits in reverse order. Visuospatial short-term memory was measured by dot matrix, where the child sees the position of a red dot in a series of 4 \( \times \) 4 matrices and needs to recall these positions in the correct serial order. Visuospatial working memory was measured using the spatial recall task. In this task, the child views two shapes where the shape on the right has a red dot on it. The child needs to determine whether the shape on the right is the same as or opposite of the shape on the left. The shape with the red dot is rotated. At the end of each trial, the child needs to recall the location of each red dot in the correct serial order. Performance was indexed by memory span scores. Standard scores were calculated for each test. Test–retest reliabilities for these tests are as follows: digit recall, .89; backward digit recall, .86; dot matrix, .85; spatial recall, .79.

Dual task coordination

The paradigm developed by Baddeley and colleagues (1986) was adapted for the purposes of this study. Participants performed a digit recall task and a choice reaction times task responding to the direction of arrows located on a screen both singly and in combination. Task difficulty levels in the dual task condition were set on an individual basis. Three conditions were administered. In the baseline condition, digit span and arrow reaction speed of each child were established. In digit recall, the child heard an auditory presentation of a list of digits, recorded by a female native English speaker, at a rate of one per second. The child needed to recall the digits orally in the serial order of presentation. The child first heard one digit, and the sequence length was increased by one digit after successful immediate serial recall of two of the three trials. This process continued until the child failed to recall at least two of the three trials at a given sequence length. Digit span for each child was calculated as
one item less than the sequence length at this discontinuation criterion applied. In the choice reaction times task, the child viewed arrows with different orientations presented singly in the center of a computer screen and pressed the key on the keyboard corresponding to the direction of the arrowhead. A total of 20 trials were completed on this task. Mean choice reaction time for correct responses was calculated for each child.

In the single task conditions, the child performed the task alone at a difficulty level set below individual assessed ability. In digit recall, the sequence length was calculated by subtracting 2 from the individual digit span. For instance, if the child’s digit span was 4, in this condition 2-digit sequences would be presented. Each trial lasted 90 s. The total number of digits presented for recall was similar across all children within the 90-s period. The total number of digits in the condition where the child was presented with a sequence of 1 digit is 33, with a sequence of 2 digits is 39, with a sequence of 3 digits is 39, and with a sequence of 4 or 5 digits is 40. The dependent variable was the percentage of digits recalled in the correct position. On the choice reaction times task, the maximum presentation time of each arrow on the screen was increased by 50% relative to the individual mean choice reaction time. Thus, for a mean choice reaction time of 800 ms, the presentation time of each arrow in this condition would be 1200 ms. Presentation of the next arrow occurred immediately following a key press. The trial lasted 90 s. The dependent variable was the percentage of correct responses. Presentation order of these two single tasks was counterbalanced across participants.

In the dual task condition, the child needed to perform both the digit recall test and the arrow reaction times task for 90 s. The proportion of correct arrow responses and the proportion of digits recalled in the correct position were scored. Percentage changes in accuracy occurring between the single and dual tasks for digit recall and arrow reaction times tasks were calculated as \(\frac{\text{[(single task–dual task)/single task]} \times 100}{\text{2 (Baddeley, Della Sala, Gray, Papagno, & Spinnler, 1997; Logie, Cocchini, Della Sala, & Baddeley, 2004).}}\)

Results

Descriptive statistics for the principal measures, univariate \(F\) test values, and effect sizes are displayed in Table 2.

Table 2
Descriptive statistics for the principal measures.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Reading difficulties [mean (SD)] [n = 46]</th>
<th>Typical readers [mean (SD)] [n = 45]</th>
<th>(F)</th>
<th>(p)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated working memory assessment(^a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verbal STM</td>
<td>89.07 (15.80)</td>
<td>99.62 (15.86)</td>
<td>10.12</td>
<td>.002</td>
<td>0.67</td>
</tr>
<tr>
<td>Verbal WM</td>
<td>90.44 (10.65)</td>
<td>98.40 (11.89)</td>
<td>11.34</td>
<td>.001</td>
<td>0.71</td>
</tr>
<tr>
<td>Visuospatial STM</td>
<td>92.07 (13.99)</td>
<td>99.40 (10.25)</td>
<td>8.11</td>
<td>.005</td>
<td>0.60</td>
</tr>
<tr>
<td>Visuospatial WM</td>
<td>96.74 (14.00)</td>
<td>105.11 (12.56)</td>
<td>9.01</td>
<td>.003</td>
<td>0.63</td>
</tr>
<tr>
<td>Dual task performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digit span</td>
<td>3.89 (0.78)</td>
<td>4.44 (0.63)</td>
<td>12.82</td>
<td>.001</td>
<td>0.78</td>
</tr>
<tr>
<td>Arrow reaction time (ms)</td>
<td>888.23 (199.02)</td>
<td>828.54 (189.75)</td>
<td>2.61</td>
<td>.110</td>
<td>0.33</td>
</tr>
<tr>
<td>Single task (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digit recall</td>
<td>99.27 (2.56)</td>
<td>99.42 (1.68)</td>
<td>0.09</td>
<td>.756</td>
<td>0.07</td>
</tr>
<tr>
<td>Arrow reaction</td>
<td>76.02 (14.38)</td>
<td>81.01 (13.11)</td>
<td>2.98</td>
<td>.088</td>
<td>0.39</td>
</tr>
<tr>
<td>Dual task (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digit recall</td>
<td>85.66 (14.66)</td>
<td>92.52 (8.59)</td>
<td>7.36</td>
<td>.008</td>
<td>0.57</td>
</tr>
<tr>
<td>Arrow reaction</td>
<td>65.55 (17.06)</td>
<td>75.72 (15.70)</td>
<td>8.74</td>
<td>.004</td>
<td>0.63</td>
</tr>
<tr>
<td>Dual task decrement (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digit recall</td>
<td>13.64 (15.07)</td>
<td>6.95 (8.42)</td>
<td>6.79</td>
<td>.011</td>
<td>0.55</td>
</tr>
<tr>
<td>Arrow reaction</td>
<td>13.42 (16.86)</td>
<td>6.05 (15.75)</td>
<td>4.65</td>
<td>.034</td>
<td>0.45</td>
</tr>
<tr>
<td>Overall</td>
<td>13.54 (12.84)</td>
<td>6.50 (9.22)</td>
<td>8.98</td>
<td>.004</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Note. STM, short-term memory; WM, working memory.
\(^a\) Standard score: \(M = 100, SD = 15.\)
Working memory

Children with reading difficulties scored significantly less than typical readers on all memory measures: verbal short-term memory, $F(1,89) = 10.12, p = .002$, verbal working memory, $F(1,89) = 11.34, p = .001$, visuospatial short-term memory, $F(1,89) = 8.12, p = .005$, and visuospatial working memory, $F(1,89) = 9.01, p = .003$. An analysis of covariance (ANCOVA) established that group differences in verbal working memory, $F(1,89) = 5.90, p = .017$, and visuospatial working memory, $F(1,89) = 4.73, p = .032$, remained significant after relevant short-term memory was covaried.

To establish whether children with reading difficulties had differential impairments in verbal and visuospatial memory tasks, two separate two-factor analyses of variance (ANOVA) were conducted on the short-term memory and working memory scores, each with reading group as a between-participant factor and task domain (verbal vs. visuospatial) as a within-participant factor. For short-term memory tasks, the main effect of group reflecting poorer performance of the children with reading difficulties was significant, $F(1,89) = 16.15, p < .001$. However, there was no significant effect of task domain, $F(1,89) = 0.50, p = .482$, nor was the interaction between group and task significant, $F(1,89) = 0.67, p = .415$. A corresponding analysis performed on the working memory measures showed a significant effect of group, $F(1,89) = 15.31, p < .001$, and task domain, $F(1,89) = 18.19, p < .001$, due to the lower scores of the children with reading difficulties and the higher scores on the visuospatial measure than on the verbal measure, respectively. However, the group by domain interaction was not significant, $F(1,89) = 0.02, p = .894$. In addition, there was a significant correlation between the measures of verbal working memory and visuospatial working memory in the reading difficulties group, $r(44) = .33, p = .013$, in line with the finding that the working memory deficits of these children appear to be domain general.

Dual task coordination

The single task performance of the digit span and arrow reaction times tasks for each group is summarized in Table 2. Typical readers had significant greater digit span than children with reading difficulties, $F(1,89) = 12.82, p = .001$, but did not differ in arrow reaction speed, $F(1,89) = 2.61, p = .110$. In both single task conditions, there was no significant group difference ($p > .05$ in both cases). The group of typical readers showed a decrement of 6% in dual task performance. The decrement for the reading difficulties group was approximately double this amount (13%) and significantly correlated with these children's own working memory composite score (i.e., the average of scores on verbal and visuospatial working memory tasks), $r(44) = -.28, p = .034$. An ANOVA performed on these percentage change scores yielded a significant group effect, $F(1,89) = 8.98, p = .004$. Although there was no significant group difference in both single task conditions, the children with reading difficulties were marginally less accurate in the arrow reaction times task than the typical readers with a moderate effect size. To ensure that the larger dual task decrement did not emerge as a result of having the children with reading difficulties complete a more difficult arrow reaction times task in the dual task condition, scores on the arrow reaction times task in the single task condition were entered as a covariate. The group difference remained significant ($p = .007$).

A two-factor ANOVA was conducted on scores for the digit recall and arrow reaction times task separately, with group (reading difficulties vs. typical readers) as a between-participant factor and type of task (single vs. dual) as a within-participant factor. There was a dual task decrement across both the digit recall and arrow reaction times tasks. In digit recall, the results showed a significant main effect of type of task, $F(1,89) = 65.13, p < .001$, and group, $F(1,89) = 7.28, p = .008$, as well as a significant interaction between type of task and group, $F(1,89) = 6.40, p = .010$. Given the marginal group difference on the arrow reaction times task, scores on this task were entered as a covariate in this two-factor ANOVA. The main effect of type of task ($p < .001$), the main effect of group ($p = .033$), and interaction between type of task and group ($p = .042$) all remained significant in the ANCOVA. In the arrow reaction times task, the main effect of type of task was significant, $F(1,89) = 40.12, p < .001$, the effect of group was significant, $F(1,89) = 6.73, p = .011$, and the interaction between type of task and group was significant, $F(1,89) = 4.34, p = .040$. Thus, in both tasks, there was a greater decrement under the dual task condition for children with reading difficulties than for typical readers.
To establish whether children with reading difficulties have a disproportionate decrement in either task, a two-factor ANOVA was conducted with group (reading difficulties vs. typical readers) as a between-participant factor and the decrement in each task as indexed by the performance difference between the single task condition and the dual task condition (digit recall vs. arrow reaction times) as a within-participant factor. This showed a significant group effect, $F(1,89) = 8.97, p = .004$, but there was no significant effect of type of task, $F(1,89) = 0.09, p = .770$, and no significant interaction between the two factors, $F(1,89) = 0.03, p = .857$.

Because the gender balance of the two groups differed, three separate ANOVAs were conducted with sex and group as independent variables and verbal working memory, visual working memory, and the dual task decrement as dependent variables. No significant main effects of gender or interactions between gender and group were found ($p > .05$ in all cases).

**Discussion**

Evidence from two distinct methodologies indicates that children with reading difficulties are impaired in activities that rely on the central executive. First, the children performed more poorly than the typical comparison group on memory tasks involving both verbal and visuospatial material, with their deficits on complex span tasks associated with the central executive remaining significant even after performance on the simple span tests of short-term memory was taken into account. Second, children with reading difficulties showed greater impairments in the ability to combine two different cognitive demanding tasks. Dual task coordination is also believed to rely on the limited resources of the central executive (Baddeley, 1996).

These data indicate that the reported working memory deficits in children with reading difficulties do not simply surface as a consequence of their well-documented problems in processing verbal material and are also consistent with Smith-Spark and Fisk's (2007) and Smith-Spark and colleagues' (2003) studies of adults with reading difficulties. It is worth noting that the current study differs from prior studies (e.g., Swanson et al., 1996) in that the same children were compared on standardized measures of verbal and visuospatial complex span, presumably providing a more reliable basis to compare the performance difference across groups relative to when nonstandardized measures were used. It is also important to note that the group difference on both the verbal and visuospatial complex span tasks remained after adjustment was made for relevant simple span task performance, which rules out an explanation in terms of a primary storage deficit that in turn leads to disrupted performance on more complex memory span tasks in children with reading difficulties. This aspect of the current findings is also consistent with Gathercole and colleagues' (2005) finding that verbal short-term memory deficits alone do not lead to a pervasive pattern of learning difficulties in children with poor phonological skills and with previous results from studies of poor readers (de Jong, 1998; Swanson & Ashbaker, 2000). It is acknowledged that some researchers have argued that forward and backward digit span tasks both tap short-term memory (Rosen & Engle, 1997), although the more common view is that the backward digit span task also relies on executive resources (e.g., Alloway et al., 2006). In the current data, it should be noted that the deficit of the children with reading difficulties on the backward digit recall measure persisted even after forward digit span was taken into account and, therefore, is most parsimoniously explained in terms of differences in the central executive rather than the verbal storage component.

At odds with many previous studies (Gould & Glencross, 1990; Liberman et al., 1982; Pickering, 2006b; Smith-Spark & Fisk, 2007; Smith-Spark et al., 2003), children with reading difficulties were found to be equivalently impaired in tasks requiring serial recall of visuospatial and verbal material. The dot matrix task was used to tap visuospatial short-term memory in the current study. In this task, the child sees the position of a red dot in a series of 4 × 4 matrices and needs to recall these positions in the correct order by tapping the computer screen. On the basis of findings that in typically developing children of comparable ages this task is not linked with verbal storage abilities (Alloway et al., 2006), it seems unlikely that the poor performance of the reading difficulties group reflects problems with verbal mediation. One possibility is that these children’s inferior visuospatial short-term memory performance may be a consequence of their visual attention deficits. Although the current study does...
not address this issue, it is notable that in a recent study by Menghini and colleagues (2011), visuospatial short-term memory problems in children with reading difficulties were found to persist even after their visual processing skills were taken into account.

The larger decrements of the children with reading difficulties than the typical comparison group when combining a digit recall task with a visual choice reaction times task are particularly notable because this difference does not seem to arise from general cognitive resource limitations in the group with reading difficulties. The difficulty levels of the two tasks when performed both singly and in combination were matched across the two groups, whose members also scored equivalently on a standardized measure of fluid cognitive abilities, matrix reasoning. An impairment in dual task coordination that is dissociated with general cognitive ability is consistent with Logie and colleagues’ (2004) claims that it taps the limited capacity resources of the central executive quite specifically and so in this case with the hypothesis that children with reading difficulties have deficits in the central executive.

In summary, the unique contributions of the current study are to provide a more powerful test of the hypothesis that children with reading difficulties have a central executive deficit by combining two different methods for assessing executive capacity in a large sample of children with reading difficulties. In line with previous findings (e.g., Swanson et al., 1996, 2009), the children with low reading abilities participating in this study had substantial deficits in complex span tasks involving either verbal or visuospatial material. The novel finding is that they also exhibited deficits in coordinating two cognitively demanding activities. These difficulties do not appear to reflect more general cognitive limitations because they were matched on a measure of nonverbal reasoning widely associated with fluid intelligence (Raven, 2000). Equally, the dual task coordination problems of the reading difficulties group were unlikely to arise from deficits in the component tasks because difficulty levels of the tasks were matched across groups. Instead, the findings are consistent with the hypothesis that the flexible cognitive resources of the central executive component of working memory responsible for the regulation of cognitive processes and for the coordination of cognitive demanding tasks are impaired in this population.

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Reference


