Working Memory, Reading and Mathematical Skills in

Children with Developmental Coordination Disorder

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Abstract

The aim of the present study was investigate the relationship between working memory and reading and mathematical skills in 55 children diagnosed with developmental coordination disorder (DCD). The findings indicate a pervasive memory deficit in all memory measures. In particular, deficits observed in visuospatial short-term and working memory tasks were significantly worse than in the verbal short-term memory ones. On the basis of these deficits, the sample was divided into high and low visuospatial memory ability groups. The low visuospatial memory group performed significantly worse on the attainment measures compared to the high visuospatial memory group, even when the contribution of IQ was taken into account. When the sample was divided into high and low verbal working memory ability groups, verbal working memory skills made a unique contribution to attainment only when verbal IQ was taken into account, but not when performance IQ was statistically controlled. It is possible that the processing demands of the working memory tasks together with the active motor component reflected in the visuospatial memory tasks and performance IQ subtest both play a crucial role in learning in children with DCD.

Working Memory, Reading and Mathematical Skills in Children with Developmental

Coordination Disorder

The DSM IV introduced the term Developmental Coordination Disorder (DCD) to identify children who have "a marked impairment in the development of motor coordination…that significantly interferes with academic achievement or activities of daily living" (American Psychiatric Association, 1994, p.53). Developmental Coordination Disorder is believed to be an immaturity of parts of the cortical control processes that prevents messages from being properly transmitted to the body (e.g., Wilson, Maruff & Lum, 2003). Observable behaviors in children with Developmental Coordination Disorder include clumsiness, poor posture, confusion about which hand to use, difficulties throwing or catching a ball, reading and writing difficulties, and an inability to hold a pen or pencil properly. Findings from longitudinal studies indicate that children with motor deficits experience difficulties throughout their childhood and adolescence (Hellgren, Gillberg, Gillberg & Enerskog, 1993). It is not uncommon for this condition to persist into adulthood, resulting not only in perceptual and motor difficulties, but also in socio-emotional struggles (Cousins & Smyth, 2003). Estimated prevalence of Developmental Coordination Disorder in children aged between 5 and 11 years is about 6% (Mandich & Polatajko, 2003), with more males than females being affected.

Visual deficits are also characteristic of children with Developmental Coordination Disorder. In visual tasks that do not include a motor component such as length discrimination, gestalt completion, and visual integration, common failures include inaccuracies in estimating object size (e.g., Lord & Hulme, 1988), and difficulties in locating an object's position in space (Schoemaker et al., 2001). Visual tasks that do include some motor skills, such as Block Design and Object Assembly subtests from the WISC-III (Weschler, 1992) are often good discriminators of children with Developmental Coordination

Disorder from controls (see Alloway, in press, for a review of visual and motor deficits in children with Developmental Coordination Disorder).

There is substantial heterogeneity of cognitive profiles in children with Developmental Coordination Disorder. In particular, they can have co-morbid reading disabilities and general learning difficulties (Kaplan, Wilson, Dewey & Crawford, 1998; Piek & Dyck, 2004). However, very little work has actually investigated the working memory profiles of this group. In light of extensive evidence of a causal link between impairments of working memory and learning difficulties (e.g., Gathercole, Alloway, Willis & Adams, 2006; Swanson & Siegel, 2001), it is important to understand the working memory profiles associated with Developmental Coordination Disorder, and to establish how this affects learning.

Working memory is the term used to refer to a system responsible for temporarily storing and manipulating information needed in the execution of complex cognitive tasks, such as learning, reasoning, and comprehension. According to Baddeley's model (2000), working memory consists of four components (see also Baddeley & Hitch, 1974). The central executive is responsible for the high-level control and coordination of the flow of information through working memory, including the temporary activation of long-term memory. It has also been linked with control processes such as switching, updating, and inhibition (Baddeley, 1996). The central executive is supplemented by two slave systems specialized for storage of information within specific domains. The phonological loop provides temporary storage for linguistic material, and the visuospatial sketchpad stores information that can be represented in terms of visual or spatial structure. The fourth component is the episodic buffer, responsible for integrating information from different components of working memory and long-term memory into unitary episodic representations (Baddeley, 2000). This model of working memory has been supported by evidence from studies of children (e.g.,

Alloway, Gathercole, Willis & Adams, 2004; Alloway, Gathercole & Pickering, in press), adult participants, neuropsychological patients (see Baddeley, 1996; and Gathercole & Baddeley, 1993, for reviews), as well as neuroimaging investigations (see Vallar & Papagno, 2002, for a review).

The key feature of working memory is its capacity both to store and manipulate information. Working memory functions as a mental workspace that can be flexibly used to support everyday cognitive activities that require both processing and storage such as, for example, mental arithmetic. However, the capacity of working memory is limited, and the imposition of either excess storage or processing demands in the course of an ongoing cognitive activity will lead to catastrophic loss of information from this temporary memory system. Short-term memory refers to the capacity of storing units of information, and is typically assessed by serial recall tasks involving arbitrary verbal elements such as digits or words.

The capacities of verbal short-term and working memory vary widely between individuals, and independently from one another (e.g., Pickering, Gathercole & Peaker, 1998). Verbal short-term memory skills are much more weakly associated with general academic and cognitive performance than working memory skills (e.g., Daneman & Merikle, 1996). There is, however, a strong and highly specific link between verbal short-term memory and the learning of the sound patterns of new words in both the native language over the early childhood year, and in second language learning at all ages (e.g., Gathercole, Hitch, Service & Martin, 1997; Service & Craik, 1993; Service & Kohonen, 1995). Children with poor verbal short-term memory skills have specific impairments in the process of learning the phonological structures of new vocabulary items, and so acquire new vocabulary items at a much slower rate than other children (for review, see Baddeley, Gathercole & Papagno, 1998).

Verbal working memory skills are effective predictors of performance in many complex cognitive activities including reading (e.g., Swanson, 1994; de Jong, 1998), mathematics (e.g., Bull & Scerif, 2001; Mayringer & Wimmer, 2000; Siegel & Ryan, 1989), and language comprehension (e.g., Nation, Adams, Bowyer-Crain & Snowling, 1999; Signeuric, Ehrlich, Oakhill & Yuill, 2000), as well as attainments in National Curriculum assessments of English and mathematics (Alloway, Gathercole, Willis & Adams, 2005; Gathercole, Pickering, Knight & Stegmann, 2004). In particular, marked deficits of verbal working memory correspond with the severity of learning difficulty experienced by a child (Alloway, Gathercole, Adams, Willis, Eaglen & Lamont, 2005; Pickering & Gathercole, 2004). Recent research has also established that poor verbal working memory skills, but not general intelligence or verbal short-term memory, are uniquely linked with both reading and mathematical abilities (Gathercole et al., 2006). This asymmetry of associations provides a strong basis for identifying working memory as a specific and significant contributor to general learning difficulties.

Previous evidence has established that visuospatial short-term memory plays a role in mathematical skills, however findings have not been unanimous. Some researchers suggest that visuospatial memory supports number representation, such as place value and alignment in columns, in arithmetic (D'Amico & Guarnera, 2005; Geary, 1990; McLean & Hitch, 1999). However, other studies have found that visuospatial memory was no longer linked with mathematical ability once reading ability and IQ had been controlled (e.g., Bull, Johnson & Roy, 1999). One explanation for the contradictory findings is that visuospatial memory is linked with arithmetic rather than general mathematical skills as tested in Bull et al.'s study (1999).

There have been very few studies that have looked at the performance of children with Developmental Coordination Disorder on memory tasks (see Alloway, in press; Pickering,

2004). One aim of the present study is to investigate a larger cohort of children with Developmental Coordination Disorder in order to gain a more comprehensive understanding of their working memory profile. To this end, a sample of 55 children with Developmental Coordination Disorder was administered standardized tests of memory, performance in literacy and numeracy, and subtests of verbal and performance IQ. Of particular interest was whether there would be a degree of specificity in verbal and visuospatial memory impairments in this cohort.

An important issue is whether deficits of working memory impair learning in children with Developmental Coordination Disorder. There is some evidence that children with Developmental Coordination Disorder tend to perform poorly in literacy (e.g., Dewey, Kaplan, Crawford & Wilson, 2002; Iversen, Berg, Ellertsen & Tonnessen, 2005), but to our knowledge, there are no studies investigating Developmental Coordination Disorder and numeracy. On the basis that verbal working memory skills may be a critical determinant of the extent and severity of learning difficulties in children of low general abilities (e.g., Gathercole et al., 2006), the present study investigated whether there would be differential links between verbal and visuospatial memory impairments and learning in children with Developmental Coordination Disorder.

Method

Participants

There were 55 children (44 boys and 11 girls) from primary schools in the North-East England who participated in the study. They were referred by an occupational therapist that had identified them as experiencing motor difficulties using the DSM IV-R criteria and standardized motor assessments such as the Movement Assessment Battery for Children (M-ABC, Henderson & Sugden, 1992). Participants ranged in age from 5 to 11.4 years (mean 8.8 years, SD 19 months). Parental consent was obtained for each child participating in the study.

An additional motor skill screening measure was also completed for all participants. Classroom teachers filled in the Movement Assessment Battery Teacher Checklist (Henderson & Sugden, 1996) for each participating child, evaluating their motor skills in either a stable or changing environment while the participating child was either stationary or mobile. The checklist provides a useful means of assessing performance on a range of tasks relevant to the daily functioning, an impairment consistent with the DSM-IV criteria. Due to its moderate relationship with the Movement ABC test battery (Henderson & Sugden, 1992; r = .50), it is able effectively identify children with motor problems (see Schoemaker, Smits-Engelsman & Jongsmans, 2003; Wilson, 2005). Test-retest reliability of the Movement Assessment Battery Teacher Checklist is high (r = .89; Henderson & Sugden, 1992). The scores from this checklist confirmed the severity of the child's movement difficulties. Of the 55 children, 21 children had a marked degree of movement difficulties, and a further 21 children had pervasive movement difficulties that affected their daily physical interactions. The remaining children were identified by the teacher has being low risk for motor difficulties that affected them in the classroom setting.

In addition, each child completed two subtests from the Wechsler Intelligence Scale for Children - 3rd UK Edition (WISC-III[UK]; Wechsler, 1992): The V*ocabulary* test, a verbal IQ subtest and *Block Design*, a performance IQ subtest. This provided an index of general intelligence for verbal and performance IQ. Performance on these measures are summarized in Table 1. Over 60% of the sample achieved standard scores of less than 81 for the Block Design test, in contrast to just 35% for the Vocabulary test.

Procedure

Each child was tested individually in a quiet area of the school for a two sessions lasting up to 40 minutes. Measures of memory and learning were administered in a fixed sequence designed to vary task demands across successive tests.

Memory tests

There were twelve memory measures taken from the Automated Working Memory Assessment (AWMA, Alloway, Gathercole & Pickering, 2004), a standardized measure of memory. Test trials begin with one item and continue with additional items in each block until the child is unable to recall three out of six trials in a block. Test reliability of the AWMA was assessed in a subset of children (n=105) from the standardization study randomly selected across schools (see Alloway et al., in press), and are reported with the description of each test.

Verbal short-term memory. The child hears a sequence of digits, words and nonwords and has to recall each sequence in the correct order in the *digit recall, word recall* and *nonword recall* tasks, respectively. For children aged 4.5 and 11.5 years, test-retest reliability is .84, .76, .64 for digit recall, word recall and nonword recall respectively.

Verbal working memory. In the *listening recall* task, the child verifies a sentence and recalls the final word for each sentence. In the *counting recall* test, the child counts the number of red circles in a visual array and then recalls the tallies of circles in the arrays. In the *backwards digit recall*, the child recalls a sequence of spoken digits in the reverse order. For children aged 4.5 and 11.5 years, test-retest reliability is .81, .79, .64 for listening recall, counting recall and backward digit recall respectively.

Visuospatial short-term memory. In the *dot matrix* task, the child recalls the position of a red dot in a series of four by four matrices. In the *mazes memory* task, the child views a maze with a red path drawn through it for three seconds, and has to trace in the same path on a blank maze. In the *block recall* task, the child reproduces the sequence of blocks tapped at a rate of one block per second. For children aged 4.5 and 11.5 years, test-retest reliability is .83, .81, .83 for dot matrix, mazes memory and block recall, respectively.

Visuospatial working memory. In the *Odd-one-out* task, the child views three shapes, identifies the odd-one-out shape, and then recalls the location of each odd one out shape. In the *Mr. X* task, the child is presented with two Mr. X figures and has to identify whether they are holding the ball in the same hand. One Mr. X can be rotated. The child then has to recall the location of the ball in Mr. X's hand by pointing to one of eight compass points. In the *Spatial span* task, the child views two arbitrary shapes where one shape has a red dot on it, and has identifies whether the shapes are the same. The shape with the red dot may also be rotated. The child then has to recall the location of the red dot by pointing to one of three compass points. Test-retest reliability for children aged 4.5 and 11.5 years is .81, .77 and .82 for odd-one-out, Mr X and spatial span, respectively.

Learning: Literacy and Numeracy

The Wechsler Objective Reading Dimensions (WORD; Wechsler, 1993) provided assessments of reading (letters and single words), spelling (letters and single words) and reading comprehension (a passage read by the child followed by verbally presented questions). The Wechsler Objective Numerical Dimensions (WOND; Wechsler, 1996) assessed understanding of numerical operations and mathematical reasoning. The numerical operations subtest involves a paper and pencil test of addition, subtraction, division, multiplication, fractions, and algebra. The mathematical reasoning subtest includes questions on graph interpretation, shape identification, telling time, and word problems.

Results

Table 1 about here

Descriptive statistics for children with Developmental Coordination Disorder on measures of working memory, learning, and IQ subtests are shown in Table 1. The composite

scores were calculated by averaging standard scores of all three measures in each memory component. When comparing the children's performance to the test standardized score of 100, mean scores fell within one standard deviation of the mean (i.e., 15 points from the standardized norm of 100) in measures of the verbal short-term memory, with the exception of the digit recall task. Performance levels in verbal working memory measures were slightly lower, with mean standard scores at 85 or less in counting recall and backward digit recall. For the visuospatial short-term and working memory tasks, mean scores were considerably lower.

Group performance in the literacy and numeracy measures was also poor. The composite reading score fell slightly below age-expected levels, while the composite numeracy score fell in the low average range. With respect to the IQ subtests scores, although the Vocabulary score was low, it fell within one standard deviation from the mean. In contrast, the mean Block Design score was considerably lower, at almost 2 standard deviations from the mean.

In order to investigate the extent to which different children performed at low or average levels on these cognitive measures, standard scores were banded (<81, <86, <91, <96, >95) and the number of children obtaining scores in each band for each measure was calculated (see Table 1). Inspection of individual scores indicate that almost half of the Developmental Coordination Disorder sample achieved standard scores of less than 85 in the verbal short-term and working memory measures. With respect to the visuospatial memory measures, a slightly larger proportion of the sample performed more poorly—56% and 60% for visuospatial short-term and working memory, respectively. For the learning measures, more than half of the sample also obtained standard scores below 86: 56% for the composite literacy score and 51% for the composite numeracy score.

In order to compare the severity of memory deficits, a repeated measures ANOVA was performed across the sample as a whole group (n=55). The analysis which was

performed on the four composite memory standard scores, revealed a significant difference in performance across the memory tasks, $F(3,162)=5.38$, $p=.001$. Post-hoc t-tests indicated that performance in both visuospatial short-term and working memory measures was significantly worse than in verbal short-term memory ones ($p<.0008$, in each case, adjusted for multiple comparisons).

Table 2 about here

Correlations among all memory and learning variables were conducted using the standard scores (see Table 2). The intercorrelations between measures purportedly tapping the different memory components were moderate to high, with rs ranging from .52 to .71 for the verbal short-term memory tasks, .34 to .49 for the verbal working memory tasks, .36 to .49 for the visuo-spatial short-term memory tasks, and .52 to .68 for the visuo-spatial working memory tasks ($p< .01$ probability level in each case).The within-construct coefficients were generally higher than between-construct coefficients suggesting good internal validity of the measures purportedly tapping four subcomponents of working memory. The intercorrelations between the learning measures were substantial in magnitude, with rs ranging from .74 to .97 for the literacy measures, and .85 to .97 for the numeracy measures.

Of additional interest was whether there would be a dissociation in the links between number-based and word-based memory tasks and literacy and numeracy skills. The difference in the strength of correlations between number-based memory tasks (e.g., digit recall, backward digit recall and counting recall) and literacy and numeracy skills and word-based memory tasks (e.g., word recall, nonword recall and listening recall) and literacy and numeracy skills was calculated based on the value of the coefficients and the sample size (Hinkle Wiersma, & Jurs, 1988). For example, $r=.42$ for word recall and the composite

literacy score was compared with $r=.26$ for digit recall and the composite literacy score. However, none of the pairs were significantly different ($p>.05$ in each case), suggesting that number-based memory tasks are not more strongly associated with numeracy skills compared to word-based memory tasks, nor are word-based memory tasks more strongly associated with literacy skills compared to numeracy skills.

Table 3 about here

It is worth noting that there is some variation in performance across subtests associated with each memory component, particularly with respect to the verbal short-term memory measures (see Table 1). Heterogeneous performance in other tasks such as learning measures in children with Developmental Coordination Disorder has been reported as well (e.g., Kaplan et al., 1998; Piek & Dyck, 2004). However, on the basis of good internal validity of the memory scores reported here (Table 2), as well as findings from a larger sample of typically developing children ($n=707$) establishing good construct validity between these measures (Alloway, Gathercole & Pickering, in press), subsequent analyses were based on composite memory scores. The correlation coefficients between all principal measures are shown in the lower triangle of Table 3. Measures within each area of cognitive function (i.e., tasks for working memory, learning, and IQ) shared correlations in the moderate to high range with rs ranging from .50 to .79, and were significant at the .001 probability level in each case. Correlation coefficients for the memory measures ranged from .50 (verbal and visuospatial short-term memory) to .65 (verbal working memory and visuospatial short-term and working memory). The coefficient for the learning measures was .79, and for the IQ subtests was. 52. Memory performance was significantly associated with the learning measures, with rs ranging from .38 (verbal short-term memory and numeracy) to .70 (verbal

working memory and numeracy). It is also worth noting that the memory measures were more highly correlated with Block Design than with Vocabulary (with the exception of verbal short-term memory).

The correlation coefficients between all principal measures with IQ subtests partialled out are shown in the upper triangle of Table 3. The interrelations between the memory measures remain high, with coefficients ranging from .46 (verbal and visuospatial short-term memory) to .60 (verbal and visuospatial short-term memory), as well as between the learning measures (r=.75). Correlation coefficients between the memory and learning measures were diminished only to a minor extent when external factors were taken into account, with rs ranging from .32 (verbal short-term memory and numeracy) to .59 (verbal working memory and numeracy).

Table 4 about here

The primary aim of the present study was to understand how the memory profile of children with Developmental Coordination Disorder affects their learning. In order to investigate this issue, the sample was divided on the basis of their visuospatial memory performance as the findings indicate that performance on visuospatial memory measures were significantly worse than on the verbal short-term memory tasks. Standard scores for visuospatial short-term and working memory were averaged and children were grouped on the basis of a composite visuospatial memory standard score less than 86 (n=35) or higher than 85 (n=20). Descriptive statistics for the two groups on measures of working memory, learning, and IQ subtests are shown in Table 4. The Developmental Coordination Disorder children with low visuospatial memory skills performed much worse in all areas of memory

and learning compared to the high visuospatial memory children. There is also a greater difference in performance on Block Design than in Vocabulary between the two groups.

In order to compare the specificity of deficits between Developmental Coordination Disorder children with high and low visuospatial memory, a MANOVA was performed on the subtests and composite score for the literacy and numeracy measures. The analyses were performed on standard scores, and the probability value associated with Hotelling's T-test is reported. The overall group term was significant, ($F=3.83$, $p=.002$), and the low visuospatial memory group showed significant deficits compared to the high visuospatial memory group in all areas of learning (alpha level was adjusted to .007 for multiple comparisons): the mathematical reasoning subtest, $F(1, 51)=19.05$, $p<.001$; the numerical operations subtest, $F(1, 51)=23.23$, $p<.001$; and composite numeracy score, $F(1, 51)=23.82$, $p<.001$; in the reading subtest, $F(1, 51)=14.97$, $p<.001$; the spelling subtest, $F(1, 51)=10.85$, $p=.002$; the reading comprehension subtest, $F(1, 51)=7.82$, $p=.007$; and composite literacy score, $F(1, 51)=12.96$, $p=.001$. These findings indicate that the low visuospatial memory group performed significantly worse on the learning measures compared to the high visuospatial memory group.

As a further analysis, taking into account the contribution of IQ, a MANCOVA was performed on the subtests and composite score for the literacy and numeracy measures, with the two IQ subtests as covariates. The analyses were performed on standard scores, and the probability value associated with Hotelling's T-test is reported. The overall group term was significant, ($F=2.48$, $p=.03$), with the low visuospatial memory group performing significantly worse compared to the high visuospatial memory group in the mathematical reasoning subtest, $F(1, 51)=11.55$, $p=.001$; the numerical operations subtest, $F(1, 51)=13.98$, $p<.001$; and composite numeracy score, $F(1, 51)=14.90$, $p<.001$; in the reading subtest, $F(1, 51)=9.46$, $p=.003$; the spelling subtest, $F(1, 51)=6.70$, $p=.01$; the reading comprehension

subtest, $F(1, 51)=4.70$, $p=.04$; and composite literacy score, $F(1, 51)=8.09$, $p=.006$. All pairwise comparisons were significant even when the alpha level was adjusted to .007 for multiple comparisons, except for the spelling and reading comprehension subtests. These findings indicate that even when the contribution of IQ was accounted for, the low visuospatial memory group performed significantly worse on the learning measures compared to the high visuospatial memory group.

Based on established links between verbal working memory skills and learning, the sample was also grouped on the basis of their verbal working memory performance. Descriptive statistics for the low (i.e., standard score less than 86, n=27) and high (i.e., standard score greater than 85, n=28) verbal working memory groups on measures of working memory, learning, and IQ subtests are shown in Table 3. The Developmental Coordination Disorder children with low verbal working memory skills perform much worse in all areas of memory and learning compared to the high verbal working memory children. Here also, there is also a greater difference in performance on Block Design than in Vocabulary between the two groups.

In order to compare the specificity of deficits between Developmental Coordination Disorder children with high and low verbal working memory, a MANOVA was performed on the subtests and composite score for the literacy and numeracy measures. The analyses were performed on standard scores, and the probability value associated with Hotelling's T-test is reported. The overall group term was significant, ($F=3.65$, $p=.003$), and the low verbal working memory group showed significant deficits compared to the high verbal working memory group in all areas of learning (alpha level was adjusted to .007 for multiple comparisons), except for the reading comprehension subtest: the mathematical reasoning subtest, $F(1, 51)=19.10$, $p<.001$; the numerical operations subtest, $F(1, 51)=20.12$, $p<.001$; and composite numeracy score, $F(1, 51)=22.10$, $p<.001$; in the reading subtest, $F(1,$

51)=13.83, $p<.001$; the spelling subtest, $F(1, 51)=12.46$, $p=.001$; the reading comprehension subtest, $F(1, 51)=7.72$, $p=.008$; and composite literacy score, $F(1, 51)=12.93$, $p=.001$. These findings indicate that low verbal working memory group performed significantly worse on the learning measures compared to the high visuospatial memory group.

In order to take into account the contribution of IQ, a MANCOVA was performed on all subtests and composite for the literacy and numeracy measures, with the two IQ subtests as covariates. The analyses were performed on standard scores, and the probability value associated with Hotelling's T-test is reported. The overall group term was not significant ($F=2.02$, $p=.07$). These findings indicate that the groupings based on verbal working memory performance did not have a significant effect on learning scores once the contribution of IQ scores was statistically controlled.

As there was a difference in group scores between the verbal and performance IQ subtests, two further MANCOVAs were performed on all subtests and composite for the literacy and numeracy measures. The first MANCOVA included only the Vocabulary subtest as a covariate. The analyses were performed on standard scores, and the probability value associated with Hotelling's T-test is reported. The overall group term was significant, ($F=3.06$, $p=.01$), with the low verbal working memory group showing significantly greater deficits compared to the high verbal working memory group in all areas of learning (alpha level was adjusted to .007 for multiple comparisons), except for the reading comprehension subtest: the mathematical reasoning subtest, $F(1, 51)=14.94$, $p<.001$; the numerical operations subtest, $F(1, 51)=16.14$, $p<.001$; and composite numeracy score, $F(1, 51)=17.72$, $p<.001$; in the reading subtest, $F(1, 51)=10.64$, $p=.002$; the spelling subtest, $F(1, 51)=9.89$, $p=.003$; the reading comprehension subtest, $F(1, 51)=4.99$, $p=.03$; and composite literacy score, $F(1, 51)=9.69$, $p=.003$. These findings indicate that low verbal working memory group

performed significantly worse on the learning measures compared to the high verbal memory group, even when performance on the Vocabulary subtest was accounted for.

In the second MANCOVA with the Block Design subtest as the covariate, the overall group term was not significant (F=2.07, p=.07). These findings indicate that while verbal working memory skills make a unique contribution to learning in children with Developmental Coordination Disorder when verbal IQ is taken into account, skills underlying performance in Block Design also play an important role in the relationship between motor skills and learning.

Discussion

The present study provides a detailed investigation of the relationship between working memory and learning in children with Developmental Coordination Disorder. The deficits observed in measures of visuospatial short-term and working memory were significantly worse than in the verbal short-term memory ones. This was supported by the greater proportion of individual scores that fell below one standard deviation from the mean (standard scores <85) in visuospatial memory tasks. Literacy and numeracy skills were also poor, with moderate associations between learning skills and memory even after performance on the IQ subtests was accounted for. When the Developmental Coordination Disorder children were split into two groups on the basis of their visuospatial memory skills, there was a significant difference in learning skills. This effect remained when IQ skills were statistically controlled. When they were divided on the basis of verbal working memory skills, there was also a significant difference in learning outcomes but not when performance on the Block Design subtest was taken into account.

The finding that visuospatial memory skills were significantly poorer than verbal short-term memory skills is consistent with research indicating that visuospatial memory skills are linked with movement planning and control (e.g., Quinn, 1994, Smyth, Pearson & Pendleton,

1988). For example, Smyth et al. (1988) found that participants' retention of simple movements in sequence was comparable to their retention of verbal information, indicating that visuospatial memory parallels verbal memory. The marked deficits in the visuospatial memory tasks are also consistent with the suggestion that these tasks draw on resources that are distinct from those involved with verbal short-term memory tasks, indexing the phonological loop (Logie, Zucco & Baddeley, 1990).

The deficit in visuospatial memory tasks in the present study could be due to the dynamic nature of the stimuli presentation. Dynamic format involves the sequential presentation of the stimuli, for example, in the dot matrix task, the dots were presented successively in a new location on a grid. In a typically developing population, Pickering, Gathercole, Hall, and Lloyd (2001) found that performance was impaired on dynamic presentation formats of the visual and spatial tasks compared to static presentation formats. A related finding is that the level of motor involvement of a task also affects performance. A meta-analysis of 50 studies on Developmental Coordination Disorder children by Wilson and McKenzie (1998) established that effect sizes were higher for studies that involved active movement (e.g., Hulme, Biggerstaff, Moran & McKinlay, 1982) than passive movement (e.g., Laszlo & Bairstow, 1983). Other studies have also demonstrated that an active condition of a motor test, rather than a passive one, significantly discriminates Developmental Coordination Disorder children from a control group (e.g,. Piek & Coleman-Carman, 1995). In the present study, all six visuospatial memory tasks involved a motor component in the recall aspect of the task, i.e., the child pointed to the correct spatial locations (Dot Matrix, Block Design, Odd-one-out, Mr X, Spatial Span) or routes (Mazes Memory). Of the three verbal working memory tasks, the children performed worse on the Counting Recall task, which required them to point and count the circles on the computer screen, compared to the Listening Recall and Backward Digit Recall task which did not

involve any movement. However, it is important to note that visuospatial memory performance was not significantly worse than verbal working memory. It is possible that the combination of motor activity and added processing demands of the tasks proved difficult for children with Developmental Coordination Disorder.

With respect to memory and learning, the findings indicate that children with low visuospatial memory skills performed significantly worse than children with high visuospatial memory skills. The independence of the link between visuospatial memory and learning from the IQ subtests is consistent with evidence that memory skills are in fact dissociable from IQ in predicting learning ability (Cain, Oakhill & Bryant, 2004; Gathercole et al., 2006; Siegel & Ryan, 1989). Studies comparing memory and learning in children with learning difficulties and normal IQ have found that differences persist between these two groups even once performance IQ has been taken into account (e.g., Swanson & Sachse-Lee, 2001). The unique link between visuospatial memory skills and learning is also in-line with recent findings that visuospatial memory can reliably discriminate Developmental Coordination Disorder children from children with learning difficulties but normal motor functioning (Alloway & Temple, in press). Together, these findings suggest that visuospatial memory taps more than general ability and is not simply a reflection of motor involvement in a task. This provides a useful starting point in understanding how motor skills, memory and learning are linked in children with Developmental Coordination Disorder.

The dissociation in performance between the high and low verbal working memory groups in learning is consistent with the view that working memory provides a resource that allows the individual to integrate information retrieved from long-term memory with current inputs (Swanson & Saez, 2003). Thus, poor working memory skills result in pervasive learning difficulties because this system acts as a bottleneck for learning in many of the individual learning episodes required to increment the acquisition of knowledge (Gathercole,

2004). This view is supported by a recent observation study of children with verbal working memory impairments (Gathercole, Lamont & Alloway, in press). Children identified as having poor verbal working memory (i.e., standard scores <85) but normal nonverbal IQ in their first year of formal schooling were observed in the classroom one year later. Common failures for these children with working memory impairments included forgetting lengthy instructions and place-keeping errors (e.g., missing out letters or words in a sentence). One explanation for these failures is that the concurrent storage and processing demands of the activity were beyond the working memory capacities of these children. Although in isolation, it seems likely the child would be able to meet these storage requirements without difficulty, the added processing demands increased the working memory demands and so led to memory failure.

It is important to understand the relationship between verbal working memory, learning and performance IQ in Developmental Coordination Disorder children. It is possible that while verbal working memory skills are dissociable from verbal ability more generally (as indexed by the Vocabulary subtest in the present study), additional skills linked with the Block Design subtest could underlie the relationship between verbal working memory and learning in children with Developmental Coordination Disorder. Specifically, deficits on performance IQ measures in Developmental Coordination Disorder children have recently been explained in light of the motor components involved in tasks such as Block Design, rather than nonverbal intelligence *per se* (e.g., Coleman, Piek & Livesey, 2001). Correspondingly, Bonifacci (2004) found no relationship between motor abilities and nonverbal IQ when the IQ test did not involve motor skills (i.e., a matrices test). It seems likely that the processing demands of the working memory tasks together with the active motor component reflected in the visuospatial memory tasks and Block Design both play a crucial role in learning in children with Developmental Coordination Disorder.

What do these findings tell us about the role of memory and learning in children with Developmental Coordination Disorder? Looking first at their memory skills, it appears that these children struggle with visuospatial memory tasks because of their difficulties with movement planning (such as mentally rotating objects in the Mr X and Spatial Span tasks and tracking movement in the Dot Matrix, Block Recall and Mazes Memory tasks). It is also likely that they perform poorly on these measures as a result of the combined processing and storage demands of these tasks. This view is substantiated by the finding that their performance on verbal working memory tasks, also requiring simultaneous processing and storage of information, is poor. Which of these processes are linked to learning in children with Developmental Coordination Disorder? A recent intervention study sheds some light on this issue. Alloway and Warner (2006) found that a task-specific training program consisting of specific everyday functional actions (such as throwing, balancing and others) improved both motor skills and visuospatial working memory, however this effect did not transfer to literacy and numeracy. This confirms the suggestion that difficulties with movement planning underpin some aspects of performance on visuospatial memory tasks, and with training this can be improved. It also indicates that the combined processing and storage component of the visuospatial memory tasks is separate from motor skills and it is this that underlies learning skills in children with Developmental Coordination Disorder.

These findings have important implications for screening and supporting children with Developmental Coordination Disorder as marked visuospatial memory deficits will affect their capacity to learn. The combination of movement planning and processing-plus-storage skills tapped in visuospatial memory tasks allow them to provide the first step in identifying children with motor deficits (see also Alloway & Temple, in press). On the basis of their difficulties with processing and storing information, an intervention program that provides guidance for educators on ways of reducing excessive working memory loads in classroom

activities, and on developing children's own strategies for coping with memory failures would be useful to support children with Developmental Coordination Disorder as well (see Gathercole & Alloway, 2004, for further discussion). Ways of reducing memory loads include keeping task instructions brief and syntactically simple, providing external memory aids such as useful spellings and number lines, and frequently repeating key information. Effective management of working memory loads in structured learning activities may ameliorate the problems of learning that are associated with impairments of working memory. It is important to note that children with Developmental Coordination Disorder can also have co-morbid attentional and language problems (see Visser, 2003). However, as the present study focused on cognitive deficits associated with Developmental Coordination Disorder, in particular, the link between memory and learning, this represents an initial investigation that merits further study in order to understand in greater detail the implications of co-morbid disorders and learning.

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Table 1

Descriptive statistics of standard scores for working memory measures, attainment, and IQ,

and proportions of children obtaining bands of standard scores for each cognitive measure

Measures	Mean	SD	<81	<86	<91	<96	>95
Verbal STM: Composite score	88.78	17.35	.27	.42	.60	.73	1.00
Digit recall	82.55	17.82					
Word recall	90.24	20.55					
Nonword recall	93.62	22.35					
Verbal WM: Composite score	85.31	13.49	.38	.49	.73	.78	1.00
Listening recall	89.15	17.87					
Counting recall	81.44	16.46					
Backward digit recall	85.45	17.44					
Visuospatial STM: Composite score	82.87	13.67	.40	.56	.71	.87	1.00
Dot matrix	80.11	17.53					
Mazes memory	88.31	16.51					
Block recall	80.20	18.66					
Visuospatial WM: Composite score	82.20	14.34	.46	.60	.78	.80	1.00
Odd-one-out	85.84	15.70					
Mr X	83.18	15.87					
Spatial span	77.64	18.53					
Literacy: Composite score	84.27	17.52	.46	.56	.67	.76	1.00
Reading	87.95	16.02					
Spelling	86.42	14.40					

Reading comprehension	86.87	15.91					
Numeracy: Composite score	86.31	19.31	.46	.51	.58	.73	1.00
Mathematical reasoning	90.98	18.65					
Numerical operations	85.45	14.57					
Verbal IQ subtest: Vocabulary	86.73	16.08	.35	.52	.65	.72	1.00
Performance IQ subtest: Block design	76.27	21.48	.61	.67	.72	.80	1.00

Note: STM=short-term memory; WM=working memory

Table 2

Correlations between all measures of short-term and working memory and attainment

Measures	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1. Digit recall	1.00																		
2. Word recall	.52	1.00																	
3. Nonword recall	.55	.71	1.00																
4. Listening recall	.31	.45	.35	1.00															
5. Counting recall	.37	.41	.49	.45	1.00														
6. Backward digit recall	.36	.33	.34	.34	.49	1.00													
7. Dot matrix	.44	.30	.22	.31	.40	.49	1.00												
8. Mazes memory	.32	.43	.43	.37	.56	.46	.36	1.00											
9. Block recall	.34	.27	.29	.24	.35	.43	.49	.36	1.00										
10. Odd-one-out	.45	.60	.46	.47	.47	.44	.48	.42	.37	1.00									
11. Mr X	.31	.49	.50	.39	.45	.32	.40	.52	.35	.52	1.00								
12. Spatial span	.27	.43	.56	.44	.49	.41	.33	.52	.31	.59	.68	1.00							
13. Literacy: Composite	.26	.42	.42	.36	.41	.51	.51	.34	.39	.45	.36	.46	1.00						

14. Reading	.25	.39	.44	.39	.41	.48	.45	.30	.36	.46	.33	.45	.97	1.00					
15. Spelling	.27	.38	.39	.34	.37	.45	.45	.26	.36	.42	.24	.36	.92	.87	1.00				
16. Reading comprehension	.21	.40	.33	.27	.37	.51	.52	.38	.36	.37	.43	.46	.92	.84	.74	1.00			
17. Numeracy: Composite	.31	.35	.32	.44	.60	.60	.62	.47	.43	.47	.39	.52	.79	.76	.67	.78	1.00		
18. Mathematical reasoning	.36	.35	.34	.39	.57	.62	.59	.44	.41	.43	.37	.50	.77	.72	.65	.77	.97	1.00	
19. Numerical operations	.23	.34	.28	.44	.57	.52	.61	.48	.48	.48	.40	.49	.76	.73	.66	.73	.94	.85	1.00

Note: All coefficients between .27 and .34 are significant at the .05 level; all coefficients > .34 are significant at the .01 level.

Table 3

Correlations between measures of working memory, attainment and IQ in the lower triangle;

partial correlations with IQ accounted for in the upper triangle

Measures	1	2	3	4	5	6	7	8
1.Verbal STM	--	.55**	.46**	.60**	.37**	.32*	--	--
2. Verbal WM	.57**	--	.56**	.59**	.44**	.59**	--	--
3. Visuospatial STM	.50**	.65**	--	.54**	.42**	.53**	--	--
4. Visuospatial WM	.62**	.65**	.61**	--	.41**	.45**	--	--
5. WORD	.43**	.55**	.53*	.49**	--	.75**	--	--
6. WOND	.38**	.70**	.65*	.54**	.79**	--	--	--
7. Verbal IQ: Vocabulary	.26	.31*	.33*	.26	.36**	.42**	--	--
8. Performance IQ: Block Design	.18	.46**	.45**	.32*	.38**	.57**	.52**	--

Note: STM=short-term memory; WM=working memory

*p<.05

**p<.01

Table 4

Descriptive statistics of standard scores for working memory measures, attainment, and IQ, on the basis of groups divided by memory performance

	Groups based on visuospatial composite memory score				Groups based on verbal working memory score			
	<86 (n=35)		>85 (n=20)		<86 (n=27)		>85 (n=28)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Verbal STM	80.89	12.36	102.60	16.31	81.56	12.91	95.75	18.41
Verbal WM	79.43	9.97	95.60	12.82	74.59	7.12	95.64	9.47
Visuospatial STM	75.42	9.46	95.92	9.48	75.20	9.74	90.27	12.92
Visuospatial WM	74.03	9.33	96.50	9.49	73.78	10.30	90.32	13.02
Numeracy: Composite score	78.26	14.62	100.40	18.67	75.74	13.52	96.50	18.71
Mathematical reasoning	83.80	15.11	103.55	17.85	81.30	13.63	100.32	18.23
Numerical operations	79.43	10.56	96.00	14.82	77.74	10.39	92.89	14.28
Literacy: Composite score	78.46	13.61	94.45	19.22	76.44	12.01	91.82	18.83
Reading	82.31	12.39	97.80	17.15	80.59	10.35	95.04	17.44
Spelling	81.94	11.69	94.25	15.85	80.04	11.52	92.57	14.58
Reading comprehension	82.60	13.99	94.35	16.63	81.15	11.88	92.39	17.49
Vocabulary subtest	84.71	13.00	90.25	20.29	82.96	12.95	90.36	18.10
Block design subtest	70.71	20.26	86.00	20.49	67.41	17.45	84.82	21.79

Note: STM=short-term memory; WM=working memory