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Executive functions and achievements in school: Shifting, updating, inhibition, and working memory

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Links have recently been established between measures of educational attainment and both verbal and visuo-spatial aspects of working memory. Relationships have also been identified between specific executive functions—shifting, updating, and inhibition—and scholastic achievement. In the present study, scholastic attainment, shifting, updating, inhibition, and verbal and visuo-spatial working memory were assessed in 11- and 12-year-old children. Exploratory factor analysis identified two executive factors: one associated with updating functions and one associated with inhibition. Updating abilities were closely linked with performance on both verbal and visuo-spatial working memory span tasks. Working memory was closely linked with attainment in English and mathematics, and inhibition was associated with achievement in English, mathematics, and science. Domain-specific associations existed between verbal working memory and attainment in English, and between visuo-spatial working memory and attainment in English, mathematics and science. Implications of the findings for the theoretical analysis of executive functioning, working memory and children's learning are discussed.

There is now substantial evidence that executive functioning plays an important role in learning during childhood (e.g., Bull, Johnson, & Roy, 1999; Bull & Scerif, 2001; Lehto, 1995; Lorsbach, Wilson, & Reimer, 1996; McLean & Hitch, 1999; Ozonoff & Jensen, 1999; Russell, Jarrold, & Henry, 1996; Swanson, 1993, 1999; Swanson, Ashbaker, & Lee, 1996). The impact of working memory on academic achievement is considerable. Between the ages of 7 and 14 years, children who score poorly on working memory measures linked with executive skills typically perform below expected standards in national curriculum assessments of English, mathematics, and science in England (Gathercole, Brown, & Pickering, 2003; Gathercole & Pickering, 2000a, 2000b; Gathercole, Pickering, Knight, & Stegmann, 2004; Jarvis & Gathercole, 2003).

The first step towards understanding the nature of the contribution made by executive aspects of working memory to the acquisition of complex skills and knowledge during childhood is to identify the component processes involved in relevant working memory measures. One of the leading theoretical accounts is the working memory model of Baddeley and Hitch (1974; see also, Baddeley, 2000). At the heart of the model is the central executive, responsible for the control and

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regulation of cognitive processes. A further component has recently been fractionated from the central executive; the episodic buffer is responsible for integrating information from the subcomponents of working memory and long-term memory (Baddeley, 2000). In 1986, Baddeley suggested that the model of the supervisory attentional system developed by Norman and Shallice (1980), a limited capacity system responsible for the control of action and attention, provides a useful account of some of the regulatory functions of the central executive (Baddeley, 1986). Baddeley has subsequently identified further functions of the central executive. These include the capacity for the temporary activation of long-term memory (Baddeley, 1998), coordination of multiple tasks (e.g., Baddeley, Della Sala, Papagno, & Spinnler, 1997), shifting between tasks or retrieval strategies (Baddeley, 1996), and the capacity to attend and inhibit in a selective manner (Baddeley, Emslie, Kolodny, & Duncan, 1998).

In a parallel analysis of executive functioning, Miyake et al. (2000) identified three key executive functions: shifting, updating, and inhibition. Shifting involves moving backwards and forwards between multiple tasks, operations, or mental sets (e.g., Monsell, 1996). Updating requires monitoring and coding of incoming information and appropriately revising the items held in working memory by replacing no-longer-relevant information with new, more relevant information (e.g., Morris & Jones, 1990). Inhibition in this context refers to the ability to deliberately inhibit dominant, automatic, or prepotent responses (e.g., Stroop, 1935). In an individual differences study of adult participants, Miyake et al. presented evidence that these three executive functions were separable (see also, Lehto, Juujarvi, Kooistra, & Pulkkinen, 2003; Oberauer, Süß, Wilhelm, & Wittmann, 2003).

Miyake et al. (2000) also tested participants on a measure of working memory—operation span—in which participants read aloud and verified arithmetic calculations and then attempted to recall unrelated words presented after the verification of each sum. Operation span scores were highly related to updating skills, but not to measures of either shifting or inhibitory control. On this basis it was concluded that there is a common working memory factor underlying operation span and updating. Other researchers, however, have identified shifting between the processing and storage components of working memory tasks as a crucial determinant of performance (e.g., Conway & Engle, 1996; Towse, Hitch, & Hutton, 1998), and some have focused on inhibitory processes (e.g., Cataldo & Cornoldi, 1998; Rosen & Engle, 1998; Whitney, Arnett, Driver, & Budd, 2001).

The purpose of the present study was to investigate the organization of executive functions including working memory in children. There is some evidence for discrete executive functions in children although both the number and nature of these functions have differed widely across studies (e.g., Lehto et al., 2003; Levin et al., 1996; Welsh, Pennington, & Groisser, 1991). There is also some evidence to suggest that there may be developmental differences in the organization of executive functions (e.g., Senn, Espy, & Kaufmann, 2004).

Multiple measures were taken of working memory. In the listening recall task, participants make judgements about the meaning of each of a series of sentences and then attempt to recall the final word of each sentence in sequence (Daneman & Carpenter, 1980). In backwards digit recall participants must recall a sequence of digit names in reverse order (e.g., Morra, 1994). Like operation span, these tasks both combine processing (linguistic analysis of each sentence, or reversing the digit sequence) with concurrent storage (of the sequence of final words, or of the digits). Recalling a sequence in reverse order is also assumed to increase task demands and therefore employ executive resources (Elliot, Smith, & McCulloch, 1997; Gathercole, 1999; Gathercole & Pickering, 2000a; Groeger, Field, & Hammond, 1999; Rosen & Engle, 1997).

In our study, measures of visuo-spatial as well as verbal working memory were included. Verbal and visuo-spatial working memory skills have been found to be dissociated in both children (Jarvis & Gathercole, 2003) and adults (Jurden, 1995;

Shah & Miyake, 1996). For example, Shah and Miyake found that the reading span task (Daneman & Carpenter, 1980) predicted verbal scholastic aptitude test scores more strongly than did a spatial working memory task. Conversely, spatial span but not reading span was significantly correlated with spatial ability. In an exploratory factor analysis spatial span and reading span also loaded on to distinct factors (see also, Friedman & Miyake, 2000; Handley, Capon, Copp, & Harper, 2002; Kane et al., 2004; Oberauer et al., 2003). A major goal of the present study was to investigate whether the two domains of complex memory span task share common or distinct links with other executive functions.

Our study was also designed to assess the extent to which the executive processes of shifting, working memory, and inhibition relate to learning abilities and achievements in childhood. Several studies have demonstrated a relationship between performance on working memory tasks and reading (e.g., De Jong, 1998; Siegel & Ryan, 1989; Swanson, 1993; Swanson & Sachse-Lee, 2001), comprehension (e.g., Daneman & Carpenter, 1980), and arithmetic (see DeStefano & LeFevre, 2004, for review). We have previously reported evidence of domain-specific links between working memory and learning, with strongest associations between verbal working memory and standardized attainments in English and between visuo-spatial working memory and attainments in mathematics and science (Jarvis & Gathercole, 2003). Inhibitory processes have been implicated in reading (e.g., De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; Gernsbacher, 1993), comprehension (Dempster & Corkhill, 1999), vocabulary learning (Dempster & Cooney, 1982), and mathematics (e.g., Espy et al., 2004). Shifting abilities have been associated with both writing skills (Hooper, Swartz, Wakely, de Kruif, & Montgomery, 2002) and arithmetic (e.g., Bull et al., 1999; Bull & Scerif, 2001). Furthermore, shifting, working memory, and inhibition each account for unique variance in mathematics scores (Bull & Scerif, 2001). The present study extended the approach taken by Bull and Scerif (2001) in order to explore whether distinct executive processes are uniquely linked with children's attainments in school-based assessments of English, mathematics, and science.

In summary, the study had three main goals. The first goal was to investigate the extent to which the three executive functions of shifting, updating, and inhibition are unitary or separable in children. This was examined by exploring the factor structure of the executive tasks. The second goal was to investigate the executive functions underlying performance on working memory span tasks. Miyake et al. (2000) found evidence suggesting that a common working memory factor underlies performance on updating tasks and the operation span task. In the present study, measures of both verbal and visuo-spatial working memory were included, to allow us to identify domain-general working memory skills. In order to address this issue the factor structure of the executive and working memory tasks was explored. The final goal of the study was to assess the extent to which executive functions contribute to children's learning achievements. This was investigated by analysing the relationships between executive factors and educational attainment in English, mathematics, and science. The domain specificity of links between working memory and attainment was also explored by examining associations between both verbal and nonverbal working memory and attainment.

EXPERIMENT

Method

Participants

The participants were 51 children (27 boys and 24 girls) with a mean age of 11 years and 9 months ($SD = 3$ months; range $=$ 11 years 4 months to 12 years 3 months), attending a local education authority school in the north east of England. The pupils completed the executive tasks and working memory assessments during the first term of secondary school. The national curriculum tests (tests of academic achievement) had been completed approximately three months earlier during the final term of primary school.

Procedure

All participants completed a set of six executive tasks, composed of two tasks designed to tap each of the three functions of shifting, updating, and inhibition. The tasks were based on those employed by Miyake et al. (2000). All participants were also tested on four working memory span tasks, two of each requiring the storage and processing of verbal and visuo-spatial information. The schools supplied the attainment scores of each child on national curriculum tests in English, mathematics, and science.

Each child was tested in three sessions. Testing took place in a quiet room in school. The order of test administration was held constant. The shifting, updating, and inhibition tasks were administered first, followed by the two verbal and finally two visuo-spatial working memory span tasks.

Executive tasks. The following shifting tasks were administered. The plus–minus task (adapted from Jersild, 1927) consisted of three lists of 30 two-digit numbers. The numbers were prerandomized without replacement. On the first list participants were instructed to add 3 to each number. They were told to complete as many as possible within 2 minutes. Within the same time limit, on the second list the participants were instructed to subtract 3 from each number, and on the third list the participants were required to alternate between adding and subtracting 3 from the numbers. The cost of shifting was then calculated as the difference between the number of correct answers given in the alternating list and the average of those in the addition and subtraction lists within the given time periods.

The local–global task consisted of sets of figures in which the lines of a global figure—for example, a triangle—are composed of smaller local figures—for example, squares (Navon, 1977). On one list, participants were instructed to record the number of lines in the global figure—that is, one for a circle, two for an X, three for a triangle, and four for a square. They were instructed to complete as many as possible within 2 minutes. Within the same time limit, on the second list participants were instructed to record the number of lines in the local figure, and on the third list participants were required to alternate between recording the number of lines in the local figure and recording the number in the global figure. The cost of shifting was then calculated as the difference between the number of correct answers given in the alternating list and the average of those in the local and global lists within the given time periods.

The updating tasks were letter memory and the keep track task. In the letter memory task (adapted from Morris & Jones, 1990) letters were presented serially, for 2,000 ms each, in the centre of the computer screen. The number of letters presented (5, 7, 9, or 11) was varied randomly across trials. The task was to recall the last four letters presented in each list. Following the procedure used by Miyake et al. (2000), to ensure that the task required continuous updating, the instructions required the participants to rehearse the last four letters out loud throughout the task. After two practice trials participants performed 15 trials. The score given was the number of letters recalled incorrectly (so that consistent with the other executive tasks higher scores denoted worse performance). Split-half reliability for this task was calculated as .47.

In the keep track task (adapted from Yntema, 1963) participants were shown a number of target categories at the bottom of a computer screen. The target categories used here were animals, colours, clothes, countries, and sports. Fifteen words, including three exemplars from each category, were then presented serially in random order in the centre of the computer screen for 2,000 ms each. Participants were required to remember the last word presented in each of the target categories and then write these down at the end of each trial. Participants were not informed of the number of items in each category in order to minimize the possibility that they would monitor the number of instances rather than continuously updating information. Participants performed five trials with three target categories and five trials with four target categories. The score given was the number of words recalled incorrectly (again so that higher scores denoted worse performance). The split-half reliability estimate for this task was .43.

Stop signal and Stroop measures were used as inhibition tasks. The stop signal task (based on Logan, 1994) consisted of two blocks of trials. The first block was used to build up a prepotent categorization response. Participants were presented with a series of 24 monosyllabic words, matched for length and frequency, one at a time in the centre of the computer screen, for 1,000 ms each. They were instructed to verbally categorize each as an animal or nonanimal. They were given 2,000 ms to do so. In the second block of 48 trials the procedure was the same with the exception that participants were instructed not to respond—that is, to inhibit the categorization response when given a particular signal. The signal consisted of three asterisks presented below the word. Asterisks were presented on 16 of the trials. As recommended by Logan (1994) the instructions emphasized that participants should not slow down to wait for possible signals, and if slowing was detected the experimenter reminded them to continue responding as quickly as possible. The score given was the number of categorization responses given to the “stop” trials. Split-half reliability for the stop-signal task was .81.

In the Stroop task (Stroop, 1935) participants were presented with strings of asterisks, each printed in one of five colours (red, green, blue, orange, and yellow). Participants were asked to name the colours. They were given 2 minutes to complete as many as possible. Participants were then presented with colour words in incongruent colours—for example, BLUE in yellow ink, or RED in green ink. Again, participants were required to name the colour of the stimuli and to complete as many as possible within 2 minutes. The score given was the difference between the numbers of colours correctly named for the two types of stimulus.

Working memory span tasks. In the listening recall task (Working Memory Test Battery for Children; Pickering & Gathercole, 2001) participants hear a series of sentences and are asked to judge the veracity of each. At the end of each trial they are asked to recall the final word from each sentence. After two practice trials, each participant is given four trials with two sentences. After each four trials the number of sentences is increased by one. When two trials at any list length are incorrectly recalled, then the test ends. Each participant is given a score of the maximum list length at which they are correct on at least three out of four trials and an additional half a point if correct on two trials at the next list length. Test–retest reliability for listening recall is .38 for 9- to 11-year-old children (Pickering & Gathercole, 2001).

The backwards digit recall test (Working Memory Test Battery for Children; Pickering & Gathercole, 2001) requires each participant to recall a sequence of spoken digits (between one and nine) in reverse order. Testing begins with three trials at a list length of two digits. The number of digits then increases by one every three trials until two lists of a particular length are recalled incorrectly. The score given is the maximum list length at which three sequences are recalled correctly. Test–retest reliability for backwards digit recall is .71 for children aged 9 to 11 years (Pickering & Gathercole, 2001).

The odd-one-out task (based on the procedure used by Russell, Jarrold, & Henry, 1996) consisted of sets of three shapes. Two of the shapes were identical, and one was different. An example of the shapes used can be seen in Figure 1. The participant’s task was to indicate the odd one out. Each set of three shapes was shown for only two seconds (in which all children did identify

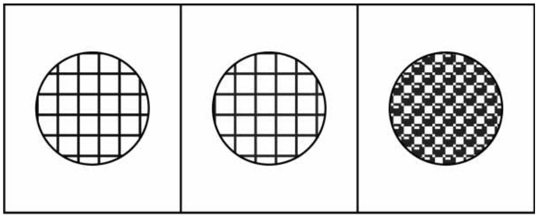

Figure 1. *Example of stimuli used in the odd-one-out task.*

the odd shape) and was then immediately followed by another set, to minimize the possibility that participants delayed the judgement of the odd one out to rehearse the spatial locations. Following each trial (in list lengths of two to seven) the participant was asked to recall the spatial locations of all the odd-one-out shapes, in their original order. The participant was given a score of the longest list length at which they were correct on at least two out of three trials. An extra half a point was awarded if the child made a correct response on one out of the three trials at the next list length. Test–retest reliability for the odd-one-out task is .81 (Alloway, Gathercole, & Pickering, 2004).

The spatial span task (Shah & Miyake, 1996) was modified for the purposes of the present study in order to eliminate any involvement of long-term memory or verbal working memory. The test stimuli were thus nonsense shapes presented either in a normal view or as a mirror image, in one of eight spatial orientations. An example of the shapes used can be seen in Figure 2. Each participant was required to state whether each shape presented was "normal" or a "mirror image" of an original shape that remained present on one side of the computer screen, while keeping track of the orientation of each shape. To ease the processing burden of locating the top of each shape prior to storing the location for later recall, the top of each shape was marked with a red dot. After each trial at list lengths of two to seven shapes, the participant was asked to recall the position of the top of each shape by pointing to one of eight given locations. Each shape was shown for only two seconds to minimize the possibility that participants delay the mental rotation in order to rehearse the orientations. The participant was given a score of the longest list length at which they were correct on at least two out of the three trials. They were given half a point extra if they were correct on one out of three trials at the next list length. Test–retest reliability for a simplified version of spatial span is .82 (Alloway et al., 2004).

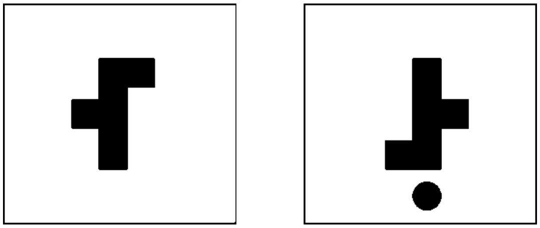

Figure 2. *Example of stimuli used in the spatial span task. (Note that the dot indicating the location to be remembered was presented in red.)*

Scholastic attainment tests. Attainment scores in English, mathematics, and science for each pupil were based on standardized tests taken in the summer term of the previous school year and were independent of teacher assessments of ability. At 11 years of age, English test scores incorporate measures of reading, writing, spelling, and handwriting. Two mathematics papers and a mental arithmetic test are used to generate a mathematics score, and there are two science papers. Each test has high reliability, with Cronbach's α for each subtest ranging from .86 to .89 (Qualifications and Curriculum Authority, 2001).

Results

Descriptive statistics

Descriptive statistics for the executive measures, working memory tasks, and children's attainment in school are provided in Table 1. Skew and kurtosis for all measures met criteria for multivariate normality (Kline, 1998). No univariate or multivariate outliers were identified.

Correlations

The correlation matrix including the executive measures, working memory tasks, and scholastic attainment is presented in Table 2. The upper triangle shows zero-order correlations, and the lower triangle shows partial correlations controlling for age in months. Only small reductions in correlation coefficients were observed when age was partialled out.

Several of the executive tasks were significantly correlated with one another. The highest correlations were between the two inhibitory tasks

Table 1. *Descriptive statistics for executive measures, working memory span tasks, and scholastic attainment scores*

Measure		*Mean*	*SD*
Shifting	Plus minus task	11.51	4.15
	Local global task	21.74	8.55
Updating	Letter memory (max. 60)	27.63	9.53
	Keep track task (max. 35)	15.12	5.96
Inhibition	Stroop task	12.06	6.77
	Stop signal task	5.78	4.60
Working memory tasks	Listening recall	2.84	0.42
	Backwards digit recall	3.73	0.85
	Odd-one-out task	3.54	0.56
	Spatial span task	2.57	0.47
Scholastic attainment score	English	59.70	14.22
	Mathematics	70.57	18.12
	Science	61.39	11.19

(Stroop and stop signal), $r(49) = .47, p < .01$, and the two updating tasks (letter memory and keep track), $r(49) = .38$, $p < .01$. The two shifting measures were not significantly correlated with one another, $r(49) = .13, p > .05$.

All four working memory span tasks were significantly correlated with one another. The highest correlations were between the pairs of verbal tasks (listening recall and backwards digit recall), $r(49) = .52$, $p < .01$, and visuo-spatial tasks (odd-one-out task and spatial span), $r(49) = .60, p < .01$.

Several executive measures correlated significantly with the working memory span tasks. Highest correlation coefficients were found between the updating and working memory span tasks, ranging from −.37 to −.66. Note that these coefficients have negative valences because higher scores reflect poorer performance on the executive tasks, but not on the working memory tasks.

Significant correlations were found between some of the executive tasks and attainments scores. The strongest associations were between the keep track scores and attainments in English, $r(49) = -.46$, $p < .01$, and maths, $r(49) = -.51$, $p < .01$. Several working memory measures were also significantly correlated with attainment scores: both listening recall and backwards digit recall with English scores, $r(49) = .50$, $p < .01$, and $r(49) = .39$, $p < .01$, respectively. The odd-one-out task was significantly correlated with both English, $r(49) = .56, p < .01$, and mathematics attainment, $r(49) = .47$, $p < .01$. Spatial span was significantly correlated with English scores, $r(49) = .45$, $p < .01$, mathematics scores, $r(49) = .44, p < .01$, and science scores, $r(49) = .31, p < .05$.

Executive and working memory measures

In order to explore relations between the shifting, updating, and inhibition tasks, scores on the executive measures were entered into a principal components analysis with varimax rotation. Factors with eigenvalues greater than 1 were retained. The factor loading scores for this analysis, PCA 1, are shown in Table 3. Two factors were identified, accounting for 56.7% of the variance in total. Factor loadings of .45 and above were used to guide interpretation of factor structure (Tabachnick & Fidell, 1996). Both updating tasks (letter memory and keep track) and one shifting measure (local−global task) loaded highly on Factor 1. Factor loadings for Factor 2 were high for both inhibition tasks (Stroop task, stop signal task), with an additional moderate loading of the plus minus shifting task.

Table 2. *Correlations between executive measures, working memory tasks, and attainment*

Measure	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
1. Age	–	−.07	−.10	.05	.12	−.29*	.01	−.21	−.09	−.03	.12	.08	.12	.07
2. Plus minus task	–	–	.13	.16	.24	.25	.19	−.03	−.11	−.17	−.29*	−.28*	−.42**	−.34*
3. Local global task	–	.12	–	.32*	.32*	.11	.19	−.20	−.13	−.26	−.27	−.20	−.26	−.16
4. Letter memory	–	.16	.33*	–	.38**	−.08	.06	−.51**	−.49**	−.66**	−.52**	−.43**	−.33*	−.08
5. Keep track task	–	.25	.33*	.37**	–	−.03	.24	−.37**	−.37**	−.58**	−.51**	−.46**	−.51**	−.39**
6. Stroop task	–	.24	.08	−.07	.00	–	.47**	−.03	−.06	−.03	−.20	−.24	−.17	−.18
7. Stop signal task	–	.19	.19	.06	.24	.49**	–	−.04	.01	−.19	−.31*	−.24	−.31*	−.28*
8. Listening recall	–	−.04	−.23	−.51**	−.36*	−.10	−.04	–	.52**	.46**	.26	.50**	.21	.06
9. Backwards digit	–	−.12	−.14	−.48*	− .36*	−.09	−.01	.52**	–	.40**	.37**	.39**	.08	−.10
10. Odd-one-out	–	−.18	−.26	−.66**	−.58**	−.04	−.19	.46**	.40**	–	.60**	.56**	.47**	.22
11. Spatial span	–	−.28*	−.26	−.53**	−.53**	−.18	−.32*	.29*	.39**	.61**	–	.45**	.44**	.31*
12. English score	–	−.28	−.19	−.43**	−.47**	−.23	−.24	.53**	.40**	.56**	.44**	–	.53**	.35*
13. Maths score	–	−.42**	−.25	−.34*	−.54**	−.15	−.31*	.25	.09	.48**	.44**	.52**	–	.79**
14. Science score	–	−.34*	− .15	−.08	−.40**	−.17	−.28*	.08	−.09	.22	.31*	.34*	.79**	–

Note: Upper triangle shows first-order correlations, and lower triangles shows correlations controlling for age.
$^{*}p < .05$; $^{**}p < .01$.

Table 3. *Factor loading scores from principal component analysis of executive measures*

	Factor 1	*Factor 2*
Plus minus task	.32	**.48**
Local global task	**.65**	.19
Letter memory	**.78**	−.01
Keep track task	**.77**	.12
Stroop task	−.15	**.86**
Stop signal task	.16	**.79**

Note: Values in bold are in excess of .45.

As the two shifting measures failed to load on a single distinct factor they were excluded from further analysis. The relationships between updating and inhibition and the two domains of working memory were then explored. All eight measures (two each of updating, inhibition, verbal working memory, and visuo-spatial working memory) were entered in to a principal components analysis, PCA 2. Again, factors with eigenvalues in excess of 1 were retained. The resulting factor loadings are shown in Table 4. Two factors were identified, accounting for 61.8% of the variance in total. A clear split between executive functions was apparent in the factor structure, with the updating and working memory measures loading onto Factor 1 and the inhibition tasks onto Factor 2. In addition, the spatial span task scores showed a lower but moderate association with this factor (−.41). Using factor scores produced by this solution, a working memory score (updating and both verbal and visuo-spatial working memory) and an inhibition score were calculated for each participant.

Table 4. *Factor loading scores from principal component analysis of executive tasks and working memory measures*

	Factor 1	*Factor 2*
Letter memory	**−.82**	−.07
Keep track task	**−.70**	.18
Stroop task	.06	**.81**
Stop signal task	−.11	**.85**
Listening recall	**.71**	.08
Backwards digit recall	**.71**	.07
Odd-one-out task	**.83**	−.15
Spatial span	**.68**	−.41

Note: Values in bold are in excess of .45.

Executive functions, working memory, and scholastic attainment

In order to identify unique associations between the executive factors and scholastic attainment scores, a series of partial correlation coefficients were computed using the factor scores from PCA 2. The resulting coefficients are shown in Table 5. In the first set of analyses, correlations between the executive constructs and attainment were computed in which the other construct was partialled out in each case. Working memory was associated with unique variance in attainment in English scores, $r(49) = .62$, $p < .01$, and mathematics scores, $r(49) = .45$, $p < .01$. Inhibition accounted for a small amount of unique variance in each curricular domain, for English, $r(49) = .31$, $p < .05$, for mathematics, $r(49) = .36$, $p < .05$, and for science, $r(49) = .34$, $p < .05$.

A further set of analyses was performed in order to examine possible links between domain-specific aspects of working memory and the attainment measures. Composite scores were calculated for verbal working memory and for visuo-spatial working memory by averaging the z scores on the associated tasks. The verbal and visuo-spatial composite scores were significantly correlated with one another, $r(49) = .48$, $p < .01$. Partial

Table 5. *Partial correlation coefficients between executive functions, working memory, and scholastic attainment*

	Executive function		*Working memory domain*	
	Working memory	*Inhibition*	*Verbal*	*Visuo-spatial*
Function partialled out	*Inhibition*[a]	*Working memory*[a]	*Visuo-spatial*[a]	*Verbal*[a]
English	.62**	.31*	.33*	.42**
Mathematics	.45**	.36*	−.10	.50**
Science	.19	.34*	−.19	.35*

[a] Function partialled out.
*$p < .05$; **$p < .01$.

correlations between each working memory score and attainment measures were then computed, eliminating the variance associated with the other working memory score in each case. Significant partial correlations were found between verbal working memory and English scores, $r(49) = .33$, $p < .05$, and between visuo-spatial working memory and scores in all areas of assessment: English, $r(49) = .42$, $p < .01$, mathematics, $r(49) = .50$, $p < .01$, and science, $r(49) = .35$, $p < .05$.

Discussion

This study casts further light on the relationship between executive functions and learning achievements in children, with three principal findings. First, abilities to update the contents of working memory and to inhibit information were unrelated in this sample of 11- and 12-year-old children. This extends previous evidence from studies of adults that inhibition is dissociable from other executive functions to children, and it is consistent with the view that there are several diverse executive functions (e.g., Espy, 1997; Klenberg, Korkman, & Lahti-Nuuttila, 2001; Miyake et al., 2000). Unlike the Miyake et al. study with adult participants, the present study failed to identify a third distinct executive factor: shifting. This disparity across the two studies may reflect a fundamental difference in the organization of executive function between children and adults. Consistent with this view, Senn et al. (2004) suggested that mental flexibility may be less differentiated from working memory and inhibition in young children than in older participants. Alternatively, the disparity could result from limitations associated with the paradigm used for the shifting tasks (see Emerson & Miyake, 2003; Rogers & Monsell, 1995). Contrasting conditions in which the same task is repeated with a condition in which it is necessary to switch between two tasks confounds switch costs and mixing costs—that is, costs associated with switching from one task to another and costs of mixing two tasks in a trial sequence rather than always performing the same task (Miyake, Emerson, Padilla, & Ahn, 2004). Furthermore, the reliability of the shifting measures is unknown. For these reasons, no strong conclusions concerning the relationships between shifting and either other executive functions or learning can be drawn from the present data.

A second finding was that verbal and visuo-spatial measures of complex working memory share a common association with updating skills, but are not linked with inhibitory processes. This finding reinforces Miyake et al.'s (2000) report of strong and specific links between updating and one verbal working memory measure: operation span. Our results establish that the association between updating and complex memory span extends both to other verbal measures and also to visuo-spatial working memory assessments, and they are consistent with claims that performance on these tasks is constrained by the ability to monitor incoming information and update the contents of working memory (Conway & Engle, 1996; Engle, Tuholski, Laughlin, & Conway, 1999; Lehto, 1996; Miyake et al., 2000; Towse et al., 1998). It is worthy of note that updating was closely linked with nonverbal working memory measures even though the stimulus demands of the updating tasks were largely verbal in nature. Updating therefore appears to reflect a genuinely domain-general facility crucial for both verbal and visuo-spatial complex memory tasks. The dissociability of the verbal and visuo-spatial memory factors must therefore arise from additional domain-specific components to the tasks, possibly reflecting in part at least the contributions of modality-specific storage systems (Baddeley & Logie, 1999).

The third aim of the present study was to explore links between executive functioning and learning achievements at 11 years of age. The results are consistent with findings of independent contributions of discrete executive functions to children's attainment in mathematics (Bull & Scerif, 2001) and extend these findings to standardized assessments in English, mathematics, and science. The results are also consistent with previous findings of associations between working memory span tasks and national curriculum test scores at 7, 11, and 14 years of age

(Gathercole & Pickering, 2000a, 2000b; Gathercole et al., 2004; Jarvis & Gathercole, 2003). It is notable that when controlling for inhibition, working memory remained closely associated with English scores. This provides support for the view that working memory plays a causal role in children's developing skills and knowledge, particularly in the domain of literacy (see also, De Jong, 1998, Gathercole & Pickering, 2000a, 2000b; Siegel & Ryan, 1989; Swanson & Alexander, 1997). This finding may have emerged due to working memory being employed for all or some of the skills assessed by the English tests: reading (e.g., Swanson, Saez, Gerber, & Leafstedt, 2004), writing (see Berninger & Swanson, 1994; Swanson & Berninger, 1995, for a review), and spelling (e.g., Carramazza, Miceli, Villa, & Romani, 1987; Margolin, 1984). Working memory was also closely related to achievement in mathematics, consistent with the view that working memory capacity constrains mental arithmetic and mathematics performance (see DeStefano & LeFevre, 2004, for review). Competence in curriculum-based mathematics tests involves mastering a number of skills such as counting and mental arithmetic, measurement abilities (e.g., perimeter, area, and time), and space abilities (manipulation or evaluation of geometric forms), all of which may require working memory resources (e.g., Geary, 2004; Maybery & Do, 2003; Swanson, 2004).

When controlling for working memory, inhibition was significantly associated with attainment in each curricular area, indicating that inhibitory skills support general academic learning rather than the acquisition of skills and knowledge in specific domains (e.g., Dempster & Corkhill, 1999). It should, however, be noted that the magnitude of the associations between attainments and working memory was considerably higher than the links found between attainments and inhibitory skills.

Although verbal and visuo-spatial working memory scores were highly associated with one another they did account for unique variance in academic attainments. Verbal working memory was found to account for a small but significant mount of unique variance in English scores (see also, Jarvis & Gathercole, 2003), whereas visuo-spatial working memory was closely related to attainment in English, mathematics, and science. This latter finding contrasts with our own previous study with the same age group (Jarvis & Gathercole, 2003), in which visuo-spatial working memory was found to be uniquely linked with achievements in mathematics and science only. It is possible that the present findings of more pervasive links between visuo-spatial working memory and attainments may arise from the greater dependency of this component of working memory on general executive resources than of verbal working memory (see Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000; Shah & Miyake, 1996, for related arguments). At present it is sufficient to note that in English and mathematics at least, the strongest associations with scholastic attainment are found with domain-general rather than domain-specific aspects of working memory.

This study adds to existing evidence that executive functions of working memory and inhibition play a role in learning. There are a number of possible reasons why this is the case. Children with poor working memory function (as indexed by poor verbal complex memory span performance) have been found to make frequent errors in a range of learning activities including remembering and carrying out instructions, keeping track of places in tasks, writing while formulating text, and carrying out mental arithmetic, (Gathercole, Lamont, & Alloway, in press). Several of these common classroom activities require the simultaneous processing and storage of information. Several also clearly involve processes such as shifting, updating, and inhibition. For example, a task such as writing a sentence has a complex hierarchical structure that requires shifting between lower levels of processing (identifying the component letters in individual words and writing them) and higher levels of activity such as maintaining the surface form of the planned sentence and identifying the next word in the sequence. Keeping track of place in the sentence requires updating of previous representations of how far the child has progressed in the task. Reading a sentence also requires inhibition of irrelevant information (Gernsbacher, 1993). This theoretical analysis has potentially important implications for educational practice. In particular it predicts that structuring learning activities in ways that prevent working memory overload, for example by reducing processing difficulty and storage loads as appropriate and encouraging the use of external memory aids, will enhance learning activities in children with poor working memory function.

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