DEVELOPMENTAL NEUROPSYCHOLOGY, *19*(3), 273–293

Executive Functioning as a Predictor of Children's Mathematics Ability: Inhibition, Switching, and Working Memory

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Children's mathematical skills were considered in relation to executive functions. Using multiple measures—including the Wisconsin Card Sorting Task (WCST), dual-task performance, Stroop task, and counting span—it was found that mathematical ability was significantly correlated with all measures of executive functioning, with the exception of dual-task performance. Furthermore, regression analyses revealed that each executive function measure predicted unique variance in mathematics ability. These results are discussed in terms of a central executive with diverse functions (Shallice & Burgess, 1996) and with recent evidence from Miyake, et al. (2000) showing the unity and diversity among executive functions. It is proposed that the particular difficulties for children of lower mathematical ability are lack of inhibition and poor working memory, which result in problems with switching and evaluation of new strategies for dealing with a particular task. The practical and theoretical implications of these results are discussed, along with suggestions for task changes and longitudinal studies that would clarify theoretical and developmental issues related to executive functioning.

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The consideration of executive functioning in relation to children's skills has become a relatively common occurrence in recent years. Numerous populations have been studied, including children with learning disabilities, language and comprehension problems, mathematical difficulties, autism, attention deficit hyperactivity disorder (ADHD), and behavioral problems (e.g., Adams, Bourke, & Willis, 1998; Bull, Johnston, & Roy, 1999; Cornoldi, Barbieri, Gaiani, & Zocchi, 1999; Gathercole & Pickering, 2000a, 2000b; Hughes & Richards, 1998; Lehto, 1995; Lorsbach, Wilson, & Reimer, 1996; McLean & Hitch, 1999; Ozonoff & Jensen, 1999; Russell, Jarrold, & Henry, 1996; Swanson, 1993, 1999; Swanson, Ashbaker, & Lee, 1996). These studies have found that executive functioning is a good predictor of performance, with some studies showing this result even after controlling for other potential explanatory factors such as long-term memory retrieval, phonological processing, and speed of information processing. Indeed, Ozonoff and Jensen (1999) discuss the establishment of "executive profiles" for various developmental disorders. For example, children with autism typically show problems on executive tasks requiring flexibility and planning, but they perform normally on tasks involving inhibition. Children with ADHD show the opposite pattern of results, having difficulty on inhibition tasks, but not on tasks requiring flexibility.

However, many of these studies are relatively vague in what they assume the executive to be, treating it as a unitary system, rather than trying to theoretically understand how difficulties found on executive tasks might arise and what they might mean. Also, there have been few attempts to use these results to further our understanding of what has been a very under-researched area within working memory compared, for example, with articulatory and visual-spatial functions of the original model proposed by Baddeley and Hitch (1974). The articulatory loop and visual-spatial sketch pad are believed to be slave systems to the central executive. The articulatory loop is a time-based store used for the storage and rehearsal of verbal information. The visual-spatial sketch pad is assumed to have two subsystems. One of the subsystems is a passive visual component retaining material such as color and shape; the other is a spatial system responsible for retaining dynamic information about movement and spatial relations between objects (Logie, 1991; Quinn & McConnell, 1996).

An increasing number of studies have targeted the constructs hidden underneath the umbrella term "central executive", using converging research approaches: neurobiological (for a review, see Robbins, 1996), cognitive (Baddeley, 1996), neuropsychological (Burgess & Shallice, 1996), and developmental (Karmiloff-Smith, 1998). Baddeley (1996, 1998) sets the scene for beginning to understand how the central executive may be fractionated by using a variety of executive tasks to tap a number of functions that are generally agreed to be under the control of executive processes. These include the ability to coordinate the functions of the articulatory loop and visual-spatial sketch pad, possibly indicative of the ability to keep information updated in working memory. This is typically measured by dual-task performance, such as performing a span task and visual-spatial task simultaneously (Adams et al., 1998; Baddeley & Della Sala, 1996; Baddeley, Della Sala, Papagno, & Spinnler, 1997; Della Sala, Baddeley, Papagno, & Spinnler, 1995).

The ability to inhibit irrelevant information from entering working memory is also thought to be a component of executive functioning measured by tasks such as random generation (e.g., Baddeley, Emslie, Kolodny, & Duncan, 1998), trail making (see Lezak, 1995), and the Stroop task (Stroop, 1935). A number of stages are involved in the process leading from perceptual identification of the stimulus and response output in any Stroop task (Luo, 1999). Interference and hence slower performance on the incongruent condition of the task may be due to reduced attentional focus toward the relevant dimension (Pansky & Algom, 1999), increased automaticity of the irrelevant dimension, or to the faster speed of processing of the irrelevant dimension (for a review of these latter interpretations of interference, see MacLeod, 1991). Alternatively, higher interference may be due to difficulties with inhibition of the irrelevant dimension to select the correct response. As Salthouse and Meinz (1995) point out, greater interference may occur because of more effective automatic activation of the irrelevant dimension. Facilitation in the congruent condition should reveal any benefits of automatic activation.

Another function often ascribed to the central executive is the ability to switch between tasks or strategies as measured by complex tasks, such as the WCST (Heaton, Chelune, Talley, Kay, & Curtiss, 1993). However, there is much more interplay between processes for successful performance on this task. Also involved are evaluations of this strategy according to feedback, as well as online maintenance of the relevant dimension being used. This broad recruitment of different processes is supported by recent imaging studies, suggesting that a number of cortical areas are recruited when performing this task (Berman, et al., 1995), as well as other tasks of executive function (Collette et al., 1999). However, Miyake et al. (2000) found that performance on this task was best predicted by the ability to shift between strategies rather than by updating in working memory or inhibition.

Another feature of the central executive is the capacity for the temporary activation of long-term memory, whereby the executive is able to encode and retrieve information both from the slave systems and from temporarily activated components of long-term memory. This skill is measured through such tasks as the reading span task of Daneman and Carpenter (1980) and the counting span task of Case, Kurland, and Goldberg (1982). These tasks require the simultaneous processing and storage of information and do appear to allow the use of elaborate strategies to aid performance (Towse & Hitch, 1995; Towse, Hitch, & Hutton, 1998).

It is, as yet, unknown whether functions such as selective attention, dual-task performance, and the activation of long-term information, are performed by separate cognitive systems that can be selectively impaired, or whether they are subsystems of a single executive controller (Baddeley, 1996), possibly with dissociable components (Robbins, 1996; Shallice & Burgess, 1996). Baddeley (1996) acknowledges that many of the early notions of the central executive were based on the Supervisory Activating System (SAS) proposed by Norman & Shallice (1980; also see Shallice, 1982). This model involves a number of sources of action control. One is for well-learned habitual patterns that are triggered automatically for carrying out routine tasks; another is an attentional controller capable of overriding habitual response patterns when a new schema (or an adapted existing schema) needs to be initiated for dealing with novel situations. Shallice and Burgess (1996) elaborate somewhat on this earlier model and describe three stages of establishing a new temporary schema. Stage 1 involves generation of a strategy, which the authors suggest may be spontaneous or may arise through some kind of problem-solving process. They also suggest that this strategy generation may be aided by the formation and realization of intentions and by retrieval of related information from episodic memory that would help to deal with the novel situation. Stage 2 involves the maintenance of this temporarily activated schema in working memory. Finally, stage 3 monitors the effectiveness of the new schema for rejection or alteration of that schema.

Support for the idea that there may be some diversity between executive functions also comes from Miyake et al. (2000). Using confirmatory factor analysis, it was found that three target functions—inhibition, shifting between mental sets and strategies, and updating information in working memory—were distinguishable, although not completely independent. Miyake et al. went on to suggest that unity amongst executive functions may be accounted for by inhibition, as all executive functions involve some inhibitory processes to function properly (e.g., ignoring previous incoming information in a working memory task, changing to a new mental set, etc.). It is interesting to note that the authors also found no conclusive evidence to link dual-task performance to any of the functions they targeted, despite its frequent use as an executive measure (e.g., Baddeley, 1996). Further support for the notion that inhibition may be a unifying function in executive processes also comes from the hybrid model of executive functions proposed by Barkley (1997). Barkley's model proposes that behavioral inhibition permits the proficient performance of executive functions (e.g., working memory and self-regulation), which, in turn, influences the capacity to produce goal-directed behavior in novel situations.

Extensive testing of a group of participants who have previously been found to perform poorly on measures of executive functioning would provide evidence to support or refute the fractionation of executive functioning. The study reported here will involve children who are under- and overachieving in mathematics performance. Bull et al. (1999) found that children with poorer mathematical and basic arithmetical skills showed poorer performance of executive functioning (as measured by the WCST); however, their difficulty with this task was restricted to perseverative responding. Children of lower mathematical ability were significantly more likely to have difficulty shifting from one sorting set to another, hence making more perseverative responses. Rourke (1993) has reported similar results, when analysing the types of errors made by children with specific arithmetic difficulties. One type of error was difficulty switching between psychological sets (e.g., from addition to subtraction procedures). Bull et al. (1999) interpreted these findings as a problem with executive functioning, specifically inhibition. However, at this point, little more can be said about whether this represented a "general" executive problem (where children would show poorer performance on a whole range of executive measures) or whether this was a specific problem (with only one aspect of executive functioning). Of course, being able to answer this question would also tell us more about whether it is possible to conceptualize performance on these tasks in terms of distinguishable functions (e.g., inhibition, updating, and shifting) that may then be selectively impaired. Furthermore, although Shallice and Burgess (1996) and Miyake et al. (2000) have investigated fractionation exclusively in adult populations, this study addresses the issue of fractionation of executive functions in children.

Tasks were used that map onto the main functions of the central executive as proposed by Baddeley (1996), and which also have some correspondence to the functions targeted by Miyake et al. (2000). These include the WCST, which is believed to involve a selection of executive functions, but found by Miyake et al. to be best predicted by shifting ability. The Stroop task was used as a measure of inhibition; the counting span, a measure of memory updating; and dual-task performance, a measure of ability to coordinate the functions of the articulatory loop and the visual-spatial sketch pad.

The purpose of this study was twofold. First, we attempted to understand more fully how functions ascribed to the central executive are involved in the development of children's mathematical skills. Second, our study is a continuation of previous studies by Baddeley (1996), Shallice & Burgess (1996), and Miyake et al. (2000), which attempt to determine whether executive functioning should be theoretically viewed as a relatively distinct set of functions that may be selectively impaired and whether this model can be extended into childhood.

METHOD

Participants

Parental consent was obtained for 105 children to participate in the study. However, due to absences across the testing sessions, complete data are only available for 93 children; only data from these 93 children are included in the analysis. All children were in Primary 3 classes (mean age = 7 years, 4 months; *SD* = 3.8 months; and age ranges, from 6 years, 9 months, to 8 years, 3 months) from six schools in the Midlothian, Angus, and Kinross regions of Scotland. This sample consisted of 50 boys and 43 girls (all of White European origin); they attended a variety of schools, which ranged from small rural schools to large schools in urban areas representative of lower and middle class areas.

Children were initially screened for mathematics, reading, and general intelligence. Mathematics ability was assessed using the Group Mathematics Test (GMT; Young, 1970). In this task, children were required to answer questions (read by an experimenter) that were related to a picture of the test sheet. They were also required to complete both single- and multidigit addition and subtraction problems. Reading ability was assessed using the British Ability Scales (BAS) word-reading test (Elliott, Murray, & Pearson, 1979), and, in this case, children were required to read single words that became progressively more difficult, with testing being discontinued after 10 successive reading failures. Finally, an estimate of general intelligence was obtained by using the vocabulary and block design subtests of the Wechsler Intelligence Scale for Children–Revised (WISC–R) (Wechsler, 1977). These two subtests were chosen because they have high correlations with full scale IQ over a wide range and have a consistently high reliability (Sattler, 1982).

Tasks and Procedures

Children were then seen individually in 3 sessions, each of which was 20 to 30 min in length. All children completed the tasks in the same order. Testing was carried out in a small room away from the classroom area. Executive function tasks were completed in the following order: session 1, WCST; session 2, Stroop task and counting span; and session 3, dual-task.

WCST–Revised and Expanded (Heaton et al., 1993). In the WCST, three dimensions (color, shape, and number) are used for the classification of a series of cards. Four key cards are placed in front of the child, each with a different shape (triangle, star, cross, or circle), different numbers of shapes (one, two, three, or four), and different colors (red, green, yellow, or blue). The children are asked if they can see the three ways in which the cards are different, which appears to make the distinction more salient to the child (rather than being told how they differ by the experimenter). The child is instructed to pick up the first card and match it to one of the key cards by color, shape, or number. If the child matches the card by the correct sorting criteria (in the first instance, color), the experimenter say “that’s right”, and the child should continue sorting subsequent cards by the same dimension. If the matching dimension was incorrect, the experimenter responds “that’s wrong”, and the child should match the next card by a different dimension, in an attempt to identify the correct one. When the child has maintained the correct sorting dimension for 10 consecutive trials, the experimenter changes the matching criteria without explicitly telling the child. It is the child's task to use the feedback given by the experimenter to determine that a previous matching criteria that was correct is now incorrect and that a different matching criteria needs to be used. This procedure continues until the child completes six category changes or runs out of cards (total = 128 trials). Results obtained from the task pinpointed specific problems: initial conceptualization of the task (measured as the number of trials taken to successfully complete the first category), failure to maintain set (occurs when the child makes five or more correct responses and then makes an error), and ability to switch sorting criteria (measured as the percentage of trials on which the child makes a response that would have been correct using the previous sorting criteria, but is now incorrect). This includes correct responses that happen to match on this sorting dimension, but, when considered in conjunction with immediately surrounding nonambiguous errors, are, in fact, perseverative responses to the previous sorting criteria.

Stroop Task (see Salthouse & Meinz, 1995). Two different versions of the Stroop task were designed. The stimulus materials in each consisted of one page with two columns of 10 stimuli each. The characters were presented in 20-point new Gothic font (all capital letters for the color condition). In the color condition, children were asked to name the colors (i.e., red, blue, green, yellow) of the items. For the number version of the task, children were asked to name the quantity of items (one, two, three, or four). For both tasks, children were asked to respond as quickly as possible; they were timed with a stopwatch. The experimenter asked the children to correct any errors made. There were 3 conditions for each of the tasks. The first was a baseline condition, consisting of crosses (XXX), where children were required to name the color or quantity of the Xs. The second was a congruent condition where, for example, the word RED was printed in red, or the quantity corresponded to the printed number (e.g., 333). The third was an incongruent condition where, for example, the word RED was printed in green ink (the task being to name the color, not the word), or the quantity and the printed number did not correspond (e.g., 222—again, the task being to name the quantity, not the printed number. Conditions were counterbalanced by task (color and quantity), and type of condition (baseline, congruent, and incongruent). The total time to correctly name all of the items in each condition was measured. For each variant of the Stroop task, two scores were calculated. The first was an interference score, obtained by subtracting time required to complete the baseline condition from time required to complete the incongruent condition. The second, a facilitation score, was calculated by subtracting the time required to complete the congruent condition from the time required to complete the baseline condition. Hence, for both measures, a higher positive difference indicated greater interference in the incongruent condition or greater facilitation in the congruent condition.

Dual-task performance (Baddeley et al., 1997). This task was used to assess the ability to coordinate the functioning of the articulatory loop and the visuo-spatial sketch pad and to allow a comparison to single-task performance on measures of digit span and visual tracking. First, a baseline digit span was acquired. Children were presented with lists of digits read aloud by the experimenter, at a rate of one digit per second, starting from a span of three. The children were required to give immediate ordered recall. Two lists at each span length were given. If, at a particular span length, the child recalled both lists correctly, the span length was then increased by one digit. Span was taken as the maximum length at which the child performed both lists without error.

Second, the single-task digit span condition was carried out. The child was presented continuously with lists of digits, at their own spans, for a period of 2 min. The number of lists presented in 2 min varied, as this was dependent on the child's span; therefore, performance was measured by the percentage of correct sequences.

Next, the single-task tracking condition was carried out. Children were required to cross out 1 cm^2 boxes linked to form a path that was laid out on an A4 sheet of paper. Each sheet contained 80 boxes. Children were shown the starting point of the chain and asked to place a cross in each successive box as quickly as possible for a period of 2 min. The total number of crossed-out boxes was taken as the score.

Finally, the dual-task condition, where children were presented (for 2 min) with lists of sequences at their own span (while simultaneously being required to perform the tracking task), was carried out. Again, performance was measured as the percentage of completely correct sequences recalled and the number of boxes crossed out. The scoring procedure followed that presented by Baddeley et al. (1997). A mu score was calculated using the following formula:

$$mu \quad 1 \quad \frac{pm \quad pt}{2} \quad 100$$

where *pm* corresponds to the proportional loss of span performance under dual-task conditions (*pm* equals the percentage of correct digit recall under single-task conditions minus the percentage of correct digit recall under dual-task conditions). The proportion of single-task tracking lost in the dual-task condition is represented by *pt*; it is calculated as the number of boxes crossed in single task – number of boxes crossed in dual task divided by the number of boxes crossed in a single-task condition. A higher negative mu score represents a larger decrement in performance under dual-task conditions, compared to performance in the single-task condition. A positive mu score represents no decrement in performance.

Counting span. Stimuli for the counting span test consisted of plain white cards. On each card were between one and nine green spots and one and nine red spots; each spot had a radius of 8 mm. Red spots were presented as distractor items, in line with the task description provided by Case et al. (1982). Children were instructed to count the number of green spots on the card presented. After an initial practice session, children were presented with two cards that were facedown on the table. The experimenter then turned the first card over; after the child counted the green spots, this card was turned over and the next card was turned face up. After counting, this card was turned over. The experimenter pointed to the first card and then the second, asking the child to recall the number of spots counted on each card. Administration of the test continued until the child made errors on both attempts at a particular span length. Span was taken as the maximum number of counts recalled in the correct serial order.

RESULTS

Correlational Analyses

First, a correlational analysis was conducted to discover which of the measures of executive functioning were significantly correlated to mathematics ability. Because of the high correlation between mathematics ability and reading ability ($r = .61$, $p < .001$) and IQ ($r = .68$, $p < .001$), partial correlation coefficients were also calculated controlling for reading ability and IQ. The following measures were included in the correlational analysis: percentage of perseverative responses, number of trials to complete the first category, and failure to maintain set (from the WCST); maximum span length recalled correctly in serial order (from the counting span task); interference and facilitation scores for both the color-word and number-quantity variants (from the Stroop task); and a mu score, taking into account decrement in performance under dual-task conditions (from the dual task; see Table 1).

The correlational analyses reveal that a number of executive function measures correlate significantly with mathematics ability. In support of previous research (Bull et al., 1999), the WCST percentage of perseverative responses is again found to be negatively correlated to mathematics ability—that is, children of higher mathematics ability made a lower percentage of perseverative responses. Counting span was also found to have a significant positive correlation with mathematics ability—that is, higher mathematics ability is related to a higher working memory span. The final measure related to mathematics ability is interference in the number–quantity Stroop task, which indicates that higher mathematics ability is associated with a lower amount of interference for irrelevant information. These relationships to mathematics ability remained significant after controlling for reading ability and IQ.

Many of the executive function measures were also found to be significantly correlated with one another. The amount of interference on the number–quantity Stroop task was found to be positively correlated with the percentage of

TABLE 1
Correlation Coefficients Between Executive Function Measures and Mathematics Ability (Below Principle Diagonal) and Partial Correlation Coefficients Controlling for Reading Ability and IQ (Above Principle Diagonal)

Executive Function Measures	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1 Mathematics	—	–.22*	*ns*	*ns*	.26*	*ns*	*ns*	–.27**	*ns*	*ns*
2 WCST % perseverative responses	–.43**	—	.21*	–.29**	*ns*	*ns*	*ns*	.41**	*ns*	*ns*
3 WCST trials to complete 1st category	*ns*	.25*	—	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
4 WCST failure to maintain set	*ns*	–.23*	*ns*	—	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
5 Counting span	.44**	*ns*	*ns*	*ns*	—	*ns*	*ns*	*ns*	*ns*	*ns*
6 Interference (color–word)	*ns*	*ns*	*ns*	*ns*	*ns*	—	*ns*	.27*	*ns*	*ns*
7 Facilitation (color–word)	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	—	*ns*	.22*	.21*
8 Interference (number–quantity)	–.46**	.51**	*ns*	*ns*	–.21*	.28**	*ns*	—	–.28**	*ns*
9 Facilitation (number–quantity)	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	.22*	–.26*	—	*ns*
10 Dual task	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	.22*	*ns*	*ns*	—

Note. For correlations, *df* = 91, except for correlations to dual task where *df* = 90. For partial correlations, *df* = 89, except for correlations to dual task where *df* = 88. WCST = Wisconsin Card Sorting Task.
*p < .05. **p < .01.

perseverative errors on the WCST, suggesting an underlying commonality, perhaps in the necessity to inhibit a learned strategy. Counting span is negatively correlated with amount of interference on the Stroop task, suggesting that children who show less interference on the Stroop task (i.e., those who are better able to inhibit the irrelevant information) have a higher working memory span. Facilitation on the number–quantity Stroop task is also found to be significantly positively correlated with performance on the dual task. This suggests that children who gained more facilitation from the irrelevant dimension in the Stroop task (i.e., number information) showed less decrement in performance under dual-task conditions.

Fixed-Order Multiple Regression Analyses

Specific links between predictor variables and mathematics ability were further tested in fixed-order multiple regression analyses to assess the amount of variance in mathematics ability predicted by each of the significantly related measure of executive functioning (WCST perseverative responses, Stroop interference, and counting span, referred to as perseveration, inhibition efficiency, and working memory, respectively). The outcomes of the regression analyses are summarized in Table 2. Models A_1, B_1, and C_1 show the amount of variance in mathematics ability predicted by each executive function measure. Working memory span, perseveration, and inhibition efficiency were each found to predict a significant amount of variance in mathematics ability (19%, 19%, and 21%, respectively). Models A_2, B_2, and C_2, show how much variance is shared with reading and IQ and how muchvariance is unique to each executive function measure. These analyses show that a large proportion of the variance for each executive function measure is shared with the variance predicted by IQ and reading ability (working memory span = 16%, perseveration = 17%, and inhibition efficiency = 18%). Therefore, each executive function measure is only contributing a small amount of unique variance to predicting mathematics ability, but these remained significant contributions over and above variance predicted by reading ability and IQ; working memory span accounted for 3% of additional variance in model A_2, perseveration accounted for 2% additional variance in model B_2, and inhibition efficiency accounted for 3% additional variance in model C_2.

Further regression analyses were conducted to examine the amount of unique variance predicted by each executive function measure after accounting for the variance predicted by the other executive function measures. Models A_3 to C_3 show that each executive function measure is predicting a significant amount of unique variance in mathematics ability, suggesting that the tests are relatively independent (working memory = 10%, perseveration = 4%, inhibition efficiency =

TABLE 2
Multiple Regression Analyses Predicting Mathematics Ability (Group Mathematics Test)

Model	*Order of Entry Into Regression Equation*	R^2	R^2 *Change*	F
A_1	1. Working memory span	.19	.19	21.22***
A_2	1. Reading and IQ	.56	.56	56.20***
	2. Working memory span	.59	.03	6.48*
A_3	1. Perseveration and inhibition efficiency	.27	.27	16.46***
	2. Working memory span	.37	.10	14.45***
A_4	1. Reading, IQ, perseveration, and inhibition efficiency	.60	.60	32.27***
	2. Working memory span	.62	.02	5.57*
B_1	1. Perseveration	.19	.19	21.06***
B_2	1. Reading and IQ	.56	.56	56.20***
	2. Perseveration	.58	.02	4.54*
B_3	1. Inhibition efficiency and working memory span	.33	.33	22.50***
	2. Perseveration	.37	.04	5.28*
B_4	1. Reading, IQ, inhibition efficiency and working memory span	.61	.61	34.95***
	2. Perseveration	.62	.01	1.22
C_1	1. Inhibition	.21	.21	24.84***
C_2	1. Reading and IQ	.56	.56	56.20***
	2. Inhibition efficiency	.59	.03	7.12**
C_3	1. Perseveration and and working memory span	.31	.31	20.56***
	2. Inhibition efficiency	.37	.06	8.07**
C_4	1. Reading, IQ, perseveration and working memory span	.60	.60	33.51***
	2. Inhibition efficiency	.62	.02	3.51 (= .06)

*$p < .05$. **$p < .01$. ***$p < .001$.

6%). However, after accounting for the variance of reading, IQ, and the two remaining measures of executive function (models A_4 to C_4), it is again revealed that much of the predicted variance is shared with reading and IQ. Only working memory span contributed a significant amount of unique variance to predicting mathematics ability after taking into account the variance predicted by reading, IQ, perseveration, and inhibition efficiency (Model A_4). Perseveration and inhibition efficiency both failed to predict a significant amount of unique variance. Perseveration, a measure of a child's ability to inhibit a learned strategy, was found to have a strong correlation with inhibition efficiency ($r = .41, p < .01$). The inhibition efficiency measure (from the Stroop task) is a measure of a child's ability to inhibit an automatic response to the stimuli, but, given the blocked presentation of the stimuli in the three different conditions, it is also a measure, once again, of the child's ability to inhibit a learned response for dealing with the previous part of the task. The shared requirements of these tasks clearly limits the amount of unique variance that each task is able to predict when entered at a later stage of the regression equation, after the related task has already been entered.

DISCUSSION

This study began with two major goals. First, the authors attempted to elucidate the difficulties with executive functioning by children with lower mathematical skills. Second, the authors evaluated the notion that executive functions represent relatively diverse processes that may be selectively impaired. From Bull et al. (1999), it is known that children of lower mathematical ability showed problems with one form of executive functioning, poor inhibition of prepotent responding. Little was known as to whether these children would show a whole range of difficulties on other measures of executive functioning or whether they would show quite specific difficulties. These issues were examined using a recent theoretical model (Shallice & Burgess, 1996) and task analyses from Miyake et al. (2000).

With regard to the first goal, it has been shown that children of lower mathematical ability do indeed show difficulties on tasks that measure the ability to inhibit both prepotent information (Stroop interference) and learned strategies (WCST preseverative responses); these children also have difficulty maintaining information in working memory. To understand how these functions may influence mathematics performance, each will be considered in turn. The discussion of each task will also be related to the theoretical models described earlier.

Results from the WCST clearly show that the main difficulty for children of lower mathematical ability is with inhibiting a learned strategy and switching to a new strategy. These difficulties may correspond to stages 1 and 3 (strategy generation and evaluation) of the Shallice and Burgess (1996) model. It appears that strategy generation is not initially a problem because there is no significant correlation between trials to complete the first category and mathematics ability. The difficulty only becomes apparent once an established strategy must be inhibited in favor of a new strategy. The results also show that children of lower mathematical ability are able to maintain a strategy in memory once that strategy has been established. These findings suggest that, although the task is supposedly measuring central executive functioning per se, there are, in fact, components of the task that may map onto the dissociable processes suggested by the Shallice and Burgess model. This supports the notion of diverse executive functions, some functioning normally and others functioning deficiently.

The correlation between the numerical Stroop interference and mathematics ability is intriguing. The slower performance of lower ability mathematicians on the incongruent condition in the numerical variant of the task may be due to reduced attentional focus toward the numerosity dimension or to differences in the speed of counting or subitizing (Koontz & Berch, 1996; Pansky & Algom, 1999). If this is the case, we expect speed of performance on the baseline condition to be faster for those children of higher mathematical ability. Indeed this was found to be the case ($r = -.29$, $p < .01$). However, to some extent this has been controlled for by taking baseline performance into account when calculating interference and facilitation scores; therefore, any remaining differences must be accounted for by an alternative explanation. One explanation could be that children who show greater interference do so because of greater automaticity of the number identity dimension (Salthouse & Meinz, 1995). Facilitation should reveal any benefits of automatic activation. There was no significant correlation to indicate that mathematics ability was related to the amount of facilitation. Furthermore, the significant negative correlation between interference and facilitation indicates that a higher amount of interference was associated with a lower degree of facilitation, therefore ruling out the possibility that greater interference was due to more automatic activation of the irrelevant dimension. A remaining viable explanation for these results is poorer inhibition of prepotent responses, with more irrelevant information gaining access to working memory for children of lower mathematical ability. Indeed the correlational analysis did reveal that greater interference was related to lower working memory span. This supports previous findings that have examined children's reading and learning difficulties (Gernsbacher, 1993; Lorsbach et al, 1996). These studies have shown that less-skilled readers have no difficulty activating relevant information, but they do have difficulty suppressing activation of irrelevant information (De Beni, Palladino, Pazzaglia, & Cornoldi, 1998). Hasher and Zacks (1988) reported that breakdown of inhibitory mechanisms not only allows irrelevant information to enter working memory, but that it also allows this information to remain active for a longer period of time, hence having a detrimental effect on performance.

Although this interpretation adequately explains the findings from the number–quantity Stroop task, it does not explain why we did not find a significant correlation between mathematics ability and amount of interference on the color–word Stroop task. In line with previous research (for a review, see MacLeod, 1991), there was a high degree of interference from the irrelevant word dimension in the incongruent condition (average interference was 17.19 s and 11.34 s for the color–word and number–quantity conditions, respectively). The facilitation scores in the two variants of the Stroop task are significantly correlated, which supports that they are measuring the same ability. However, there is no significant correlation between interference scores in the task variants. Therefore, it may be appropriate to suggest that there is a domain-specific problem with inhibition of numerical information (see Swanson, 1993) or a reduced domain-specific working memory capacity (Dark & Benbow, 1994). However, before such a statement can be justified, it is necessary to ensure that future research include more varied stimuli in the tasks alongside the numerical stimuli, as presented in the tasks here.

The Stroop task may be considered in much more detail to understand further stages 1 and 3 of the Shallice and Burgess model—that is, strategy generation and strategy evaluation. In this study, children were given the same instructions for each condition of the task (e.g., name the color, not the word), so that, essentially, they were being instructed to use the same schema across conditions. The child is then able to evaluate its effectiveness and possibly adopt a more appropriate strategy—for example, word or number reading in the congruent condition. Explicitly manipulating the instructions given to the children could be useful in determining whether providing appropriate strategies decreases the interference effect. If higher interference in the low-ability groups is due to a problem with strategy generation, then instructing all children to use an efficient strategy could reduce individual differences. Providing a range of more or less efficient strategies for coping with the task may give an indication of the effectiveness of the monitoring process in the two ability groups.

Stimulus presentation may also affect the results. In this study, each separate condition was presented on a different card; therefore, those children who noticed matching information in the congruent condition might have realized that they could simply read the numbers or words for the whole card. If stimuli from all conditions were presented in a random order, one at a time, a continual strategy could not be used. Furthermore, it would be possible to record accuracy and response time for each single presentation. This would allow the separation of variance related to loss of instruction information from working memory, as measured by the number of errors (stage 2, maintenance), from variance related to strategy generation and evaluation, as measured by interference effects for correct responses only (stages 1 and 3). Furthermore, blocked stimuli could be used (e.g., five congruent stimuli followed by incongruent stimuli), when it is more likely that a temporary schema may be put into action. Preliminary results from a study comparing blocked versus random presentation of stimuli in the Stroop task reveal that children of lower mathematical ability do show greater interference in the blocked presentation than children of higher mathematical ability. However, when stimuli were randomly presented, and hence there is no necessity to inhibit a learned strategy, there were no differences in the amount of interference between children of high and low mathematics ability (Bull, Murphy, & McFarland, 2000). This clearly suggests that future studies should consider different inhibition requirements (e.g., inhibition of more automatic information vs. inhibition of learned strategies) when assessing how they may be related to other cognitive skills.

There was no significant correlation between mathematics ability and performance on the dual task. There was little change in performance on either the digit recall while performing the tracking task or on the tracking task while performing the digit recall. This might suggest that there are no differences between children with regard to the ability to focus attention on more than one task at a time, a result that conflicts with findings obtained with younger children (Adams et al, 1998). Therefore, the validity of the dual task as a measure of executive functioning must be considered.

Phillips (1997) lists a number of requirements for a task to be considered a true measure of executive functioning. A task should be novel in both content and form (so as to tap goal identification and strategy planning); it should be effortful, in that it may require online monitoring or inhibition; and it should have some element of maintenance in working memory. A novel task requires that a new temporary schema be set up to deal with that task, so as to inhibit some prepotent response that may have already been activated (strategy generation in terms of the Shallice & Burgess model). The dual task used in this study is, in no obvious respect, a truly novel task. It simply requires digit recall and placing crosses in boxes following a path, which children may relate to puzzles involving joining dots. It would seem that, in terms of the Shallice and Burgess model, the only process required here is one of maintenance of instructions for the task and recall of the digits. Indeed, a number of researchers now suggest that any dual task must involve some element of inhibition in the primary task (De Beni et al., 1998; Roberts & Pennington, 1996). Future studies should ensure that the dual task is more effortful. For example, the tracking task could be made more demanding by having children put a cross in a box, but to put a tick if they reach a circle along the path, requiring inhibition of the previous response. Future studies should also analyze errors made in following the path on the tracking task, rather than only measuring the number of crossed-out boxes. This could be easily attained by asking children to follow the path with a colored pen. Alternatively, the tracking task might be replaced by a more novel measure. For example, the Ruff Figural Fluency test (Ruff, Light, & Evans, 1987) has been shown to be a valid measure of executive functioning by Phillips (1997). This task requires generation of novel figures. It is novel because the task does not rely on long-term retrieval of automatic strategy, it is effortful because it requires online monitoring and inhibition of previously drawn figures, and it requires the maintenance of task instructions in memory.

There was a significant correlation between mathematics ability and counting span, with children of higher mathematics ability achieving a higher counting span. Counting span clearly involves some element of maintenance of information in working memory, which may be dependent on inhibiting previous information held in working memory and the use of rehearsal strategies to aid recall. In terms of the Shallice & Burgess (1996) model, this might be referred to as spontaneous strategy use, another component process of strategy generation, distinct from problem solving. Although no systematic measure was taken of which children used strategies, anecdotal evidence clearly suggests that some children used very obvious rehearsal strategies, whereas others did not. Furthermore, different strategies were used, even with the initial counting of numbers. Some children counted sequentially, others counted two dots at a time, and others reported the use of spatial arrangements of the dots. Previous research that has examined performance on similar span measures (reading and listening span) found that performance is very much dependent on the use of strategies (Carpenter & Just, 1989). Observation of correlation coefficients among tests also reveals that children who showed greater interference on the Stroop task had a lower working memory span. Our results are therefore supportive of previous studies showing that performance on a listening span task involves more than just processing capacity, with inhibitory processes and strategy generation playing an important role in group differences (Cataldo & Cornoldi, 1998; Cornoldi et al., 1999; Cornoldi, De Beni, & Pazzaglia, 1996; De Beni, Palladino, & Pazzaglia, 1995; De Beni et al., 1998; Pazzaglia, Cornoldi, & De Beni, 1995).

In terms of understanding how diverse these executive functions are, it appears that the results are generally supportive of the ideas proposed by Miyake et al. (2000); their model may be usefully applied to children. Results from the regression analyses reveal that there are independent and unique contributions from inhibition efficiency, working memory span, and perseveration in predicting mathematics performance, although much of this predicted variance was also shared with the variance predicted by reading ability and IQ. However, the significant correlation coefficients between the different measures suggest that there may indeed be some unity. This unity amongst executive functions may be accounted for by inhibition, as all executive functions involve some inhibitory processes to function properly (e.g., ignoring previous incoming information in a working memory task, changing to a new mental set, etc.) (Miyake et al., 2000). This may also offer support for the model proposed by Barkley (1997), in which behavioral inhibition permits the proficient performance of executive functions (such as working memory and self-regulation), which, in turn, influences the capacity to produce goal-directed behavior in novel situations.

It is clearly important that larger batteries of tests be administered for each of the functions targeted by Miyake et al. (2000) and that the findings be generalized to include stimuli that are not numerical. Using the techniques employed by

Miyake et al., it will be possible to understand the unity and diversity of these executive functions in children and to discover whether certain executive functions develop at different critical periods. Espy (1997) made such a suggestion with regard to different critical periods for the development of inhibition and shifting skills, although it has not yet been systematically examined.

The results may also have implications for models of nonverbal learning disabilities. Rourke (1993) identifies subgroups of children with learning difficulties and, in particular, he refers to a group of children with specific arithmetic difficulties as having nonverbal learning disabilities. This group shows a pattern of neuropsychological weaknesses consistent with difficulties in executive functioning. For example, children exhibited poor performance on visual-spatial organizational tasks, psychomotor and tactile-perceptual tasks, nonverbal problem solving, and concept formation. Furthermore, these children encountered increasing difficulties with tasks that became more novel and complex. Rourke (1993) discusses the types of errors made by children with specific arithmetic disabilities. In addition to errors in spatial organization, reading visual detail, procedural errors, and memory, these children were also found to have difficulties shifting psychological sets (children continued to use a practiced procedure—e.g., addition, to a new operation, such as subtraction). These children also exhibited difficulties judging the reasonableness of answers and generating reasonable plans of action when the requirements for a task were only slightly different from procedures already mastered by the child.

Rourke and Conway (1997) also pointed out that early neuropsychological assessment can reveal patterns of assets and deficits that may be predictive of later academic performance, including arithmetic. In line with this, the findings from this study are now being considered with regard to children's uses of counting strategies. This is being done by examining children's varied uses of counting strategies in simple arithmetic and perseveration of ineffective strategy use (Bull & Scerif, 2001). It might also be the case that, at different levels of skill acquisition, executive functioning becomes more or less important. For example, once children are able to retrieve well-practiced strategies or arithmetic facts directly from long-term memory, there may be less need for the establishment of temporary new schemas, and so executive processes may not play such an important role once a skill becomes more automatic. This underscores the need for longitudinal studies that target developmental changes and constancy in strategy use and executive functioning. Longitudinal studies would allow us to determine whether an early delay in executive functioning results in a developmental lag in learning skills, such as mathematics. If this is found to be the case, consideration should also be given to methods by which such difficulties may be circumvented—for example, through raising a child's awareness of his or her own behavior and the monitoring of those behaviours, or through changes to teaching materials that might, for example, restrict the amount of irrelevant information presented or the number of task changes required.

ACKNOWLEDGMENTS

Funding for this study was provided by the Nuffield Foundation (NUF–URB99).

We thank the children and staff of all participating schools: Blairingone Primary School, Kinross; Cornbank, Cuiken, Loanhead, and Paradykes Primary Schools; Midlothian and Monikie Primary School, Angus. We also thank three anonymous reviewers for their constructive comments on a previous draft of this article, and to John Crawford for statistical advice.

REFERENCES

Adams, A.-M., Bourke, L., & Willis, C. (1998, September). *Working memory: Implications for individual differences in language development.* Poster session presented at the annual meeting of the British Psychological Society Developmental Section, Lancaster, England.

Baddeley, A. D. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology, 49A,* 5–28.

Baddeley, A. D. (1998). The central executive: A concept and some misconceptions. *Journal of the International Neuropsychological Society, 4,* 523–526.

Baddeley, A. D., & Della Sala, S. (1996). Working memory and executive control. *Philosophical Transactions of the Royal Society of London, 351,* 1397–1404.

Baddeley, A. D., Della Sala, S., Papagno, C., & Spinnler, H. (1997). Dual-task performance in dysexecutive and nondysexecutive patients with a frontal lesion. *Neuropsychology, 11,* 187–194.

Baddeley, A. D., Emslie, H., Kolodny, J., & Duncan, J. (1998). Random generation and the executive control of working memory. *Quarterly Journal of Experimental Psychology, 51A,* 819–852.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: advances in research and theory* (Vol. 8, pp. 47–90). New York: Academic Press.

Barkley, R. A. (1997). Behavioural inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121,* 65–94.

Berman, K. F., Ostrem, J. L., Randolph, C., Gold, T., Goldberg, T. E., Coppola, R., Carson, R. E., Herscovitch, P., & Weinberger, D. R. (1995). Physiological activation of a cortical network during performance on the Wisconsin Card Sorting Test: A positron emission tomography study. *Neuropsychologia, 33,* 1027–1046.

Bull, R., Johnston, R. S., & Roy, J. A. (1999). Exploring the roles of the visual-spatial sketch pad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. *Developmental Neuropsychology, 15,* 421–442.

Bull, R., Murphy, S. L., & McFarland, S. E. (2000, September). *Assessing inhibition using two presentation formats of the Stroop task: Links to intellectual development.* Poster session presented at the annual meeting of the British Psychological Society Developmental Section, Bristol, England.

Bull, R., & Scerif, G. (2001). *Strategy generation and evaluation in children's solutions of simple arithmetic problems: The role of executive processes.*

Burgess, P. W., & Shallice, T. (1996). Response suppression, initiation and strategy use following frontal lobe lesions. *Neuropsychologia, 34,* 263–276.

Carpenter, P. A., & Just, M. A. (1989). The role of working memory in language comprehension. In D. Klahr & K. Kotovsky (Eds.), *Complex information processing: The impact of Herbert A. Simon* (pp. 31–68). Hillside, NJ: Lawrence Erlbaum Associates, Inc.

Case, R., Kurland, M., & Goldberg, J. (1982). Operation efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology, 33,* 386–404.

Cataldo, M.G., & Cornoldi, C. (1998). Self-monitoring in poor and good reading comprehenders and their strategy use. *British Journal of Developmental Psychology, 16,* 155–165.

Collette, F., Salmon, E., Van der Linden, M., Chicherio, C., Belleville, S., Degueldre, C., Delfiore, G., & Franck, G. (1999). Regional brain activity during tasks devoted to the central executive of working memory. *Cognitive Brain Research, 7,* 411–417.

Cornoldi, C., Barbieri, A., Gaiani, C., & Zocchi, S. (1999). Strategic memory deficits in attention deficit disorder with hyperactivity participants (ADHD): The role of executive processes. *Developmental Neuropsychology, 15,* 53–71.

Cornoldi, C., De Beni, R., & Pazzaglia, F. (1996). Profiles of reading comprehension difficulties: An analysis of single cases. In C. Cornoldi & J. Oakhill, (Eds.), *Reading comprehension difficulties: Processes and intervention* (113–136). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behaviour, 19,* 450–466.

Dark, V. J., & Benbow, C. P. (1994). Type of stimulus mediates the relationship between working memory performance and type of precocity. *Intelligence, 19,* 337–357.

De Beni, R., Palladino, P., & Pazzaglia, F. (1995). Influenza nella memoria di lavoro e delle abilita' cognitive e sintattiche nella difficolta' di comprensione della lettura [Working memory and metacognitive and syntactic abilities implied in specific reading comprehension disabilities]. *Giornale Italiano di Psicologia, 22,* 615–640.

De Beni, R., Palladino, P., Pazzaglia, F., & Cornoldi, C. (1998). Increases in intrusion errors and working memory deficit of poor comprehenders. *Quarterly Journal of Experimental Psychology, 51A,* 305–320.

Della Sala, S., Baddeley, A., Papagno, C., & Spinnler, H. (1995). Dual-task paradigm: A means to examine the central executive. In K. J. Grafman and F. Boller (Eds.), *Structure and functions of the human prefrontal cortex* (pp. 161–190). New York: Annals of the New York Academy of Sciences.

Elliott, C. D., Murray, D. J., & Pearson, L. S. (1979). *British Ability Scales.* Windsor, England: NFER-Nelson.

Espy, K. A. (1997). The shape school: Assessing executive function in preschool children. *Developmental Neuropsychology, 13,* 495–499.

Gathercole, S. E., & Pickering, S. J. (2000a). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. *British Journal of Educational Psychology, 70,* 177–194.

Gathercole, S. E., & Pickering, S. J. (2000b). Assessment of working memory in six- and seven-year old children. *Journal of Educational Psychology, 92,* 377–390.

Gernsbacher, M. A. (1993). Less skilled readers have less efficient suppression mechanisms. *Psychological Science, 4,* 294–298.

Hasher, L., & Zacks, R. T. (1988). Working, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). San Diego, CA: Academic Press.

Heaton, R. K., Chelune, G. J., Talley, J. L., Kay, G. G., & Curtiss, G. (1993). *Wisconsin Card Sorting Test Manual: Revised and Expanded.* New York: Psychological Assessment Resources.

Hughes, C., & Richards, S. (1998, September). *Executive dysfunction in hard-to-manage preschoolers: Longitudinal findings.* Poster session presented at the annual meeting of the British Psychological Society Developmental Section, Lancaster, England.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences, 2,* 389–398.

Koontz, K. L., & Berch, D. B. (1996). Identifying simple numerical stimuli: Processing inefficiencies exhibited by arithmetic learning disabled children. *Mathematical Cognition, 2,* 1–23.

Lehto, J. (1995). Working memory and school achievement in the Ninth Form. *Educational Psychology, 15,* 271–281.

Lezak, M. D. (1995). *Neuropsychological assessment* (3rd ed.). New York: Oxford University Press.

Logie, R. H. (1991). Visuo-spatial working memory: Visual working memory or visual buffer? In C. Cornoldi & M. McDaniel (Eds.), *Imagery and cognition* (pp. 77–102). Berlin: Springer-Verlag.

Lorsbach, T. C., Wilson, S., & Reimer, J. F. (1996). Memory for relevant and irrelevant information: Evidence for deficient inhibitory processes in language/learning disabled children. *Contemporary Educational Psychology, 21,* 447–466.

Luo, C. R. (1999). Semantic competition as the basis of Stroop interference: Evidence from colour word matching tasks. *Psychological Science, 10,* 35–40.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109,* 163–203.

McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetic learning difficulties. *Journal of Experimental Child Psychology, 74,* 240–260.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex frontal lobe tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49–100.

Norman, D. A., & Shallice, T. (1980). *Attention to action: Willed and automatic control of behaviour.* University of Salifornia at San Diego, CHIP Report 99.

Ozonoff, S., & Jensen, J. (1999). Brief report: Specific executive function profiles in three neurodevelopmental disorders. *Journal of Autism and Developmental Disorders, 29*(2), 171–177.

Pansky, A., & Algom, D. (1999). Stroop and Garner effects in comparative judgements of numerals: The role of attention. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 39–58.

Pazzaglia, F., Cornoldi, C., & De Beni, R. (1995). Knowledge about reading and self evaluation in reading disabled children. *Advances in Learning and Behavioural Disabilities, 9,* 91–117.

Phillips, L. (1997). Do "frontal tests" measure executive function? Issues of assessment and evidence from fluency tests. In P. M. A. Rabbitt (Ed.), *Methodology of Frontal and Executive Functions* (pp. 191–214). Hove, England: Psychology Press.

Quinn, J. G., & McConnell, J. (1996). Irrelevant pictures in visual working memory. *Quarterly Journal of Experimental Psychology, 49A,* 200–215.

Robbins, T. W. (1996). Dissociating executive functions of the prefrontal cortex. *Philosophical Transactions of the Royal Society of London, 351B,* 1463–1471.

Roberts, R. J., & Pennington, B. F. (1996). An interactive framework for examining prefrontal cognitive processes. *Developmental Neuropsychology, 12,* 105–126.

Rourke, B. P. (1993). Arithmetic disabilities, specific and otherwise: A neuropsychological perspective. *Journal of Learning Disabilities, 26,* 214–226.

Rourke, B. P., & Conway, J. A. (1997). Disabilities of arithmetic and mathematical reasoning: Perspectives from neurology and neuropsychology. *Journal of Learning Disabilities, 30,* 34–46.

Ruff, R. M., Light, R. H., & Evans, R.W. (1987). The Ruff figural fluency test: A normative study. *Developmental Neuropsychology, 3,* 37–51.

Russell, J., Jarrold, C., & Henry, L. (1996). Working memory in children with autism and with moderate learning difficulties. *Journal of Child Psychology and Psychiatry, 37,* 673–686.

Salthouse, T. A., & Meinz, E. J. (1995). Aging, inhibition, working memory, and speed. *Journal of Gerontology, 50B,* 297–306.

Sattler, J. M. (1982). *Assessment of children's intelligence and special abilities.* Boston: Allyn & Bacon.

Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal Society of London, B298,* 199–209.

Shallice, T., & Burgess, P. (1996). The domain of supervisory processes and temporal organisation of behaviour. *Philosophical Transactions of the Royal Society of London, 131,* 1405–1412.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643–662.

Swanson, H. L. (1993). Working memory in learning disability subgroups. *Journal of Experimental Child Psychology, 56,* 87–114.

Swanson, H. L. (1999). Reading comprehension and working memory in learning-disabled readers: Is the phonological loop more important than the executive system? *Journal of Experimental Child Psychology, 72,* 1–31.

Swanson, H. L., Ashbaker, M. H., & Lee, C. (1996). Learning disabled readers working memory as a function of processing demands. *Journal of Experimental Child Psychology, 61,* 242–275.

Towse, J. N., & Hitch, G. J. (1995). Is there a relationship between task demands and storage space in tests of working memory capacity? *Quarterly Journal of Experimental Psychology, 48A,* 108–124.

Towse, J. N., Hitch, G. J., & Hutton, U. (1998). A reevaluation of working memory capacity in children. *Journal of Memory and Language, 39,* 195–217.

Wechsler, D. (1977). *Wechsler Intelligence Scale for Children–Revised.* Windsor, England: NFER-Nelson.

Young, D. (1970). *Group Mathematics Test.* Kent: Hodder and Stoughton.