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Executive Functions as Predictors of Math Learning Disabilities

Sylke W. M. Toll[1], Sanne H.G. Van der Ven[1], Evelyn H. Kroesbergen[1], and Johannes E.H. Van Luit[1]

Abstract

In the past years, an increasing number of studies have investigated executive functions as predictors of individual differences in mathematical abilities. The present longitudinal study was designed to investigate whether the executive functions shifting, inhibition, and working memory differ between low achieving and typically achieving children and whether these executive functions can be seen as precursors to math learning disabilities in children. Furthermore, the predictive value of working memory ability compared to preparatory mathematical abilities was examined. Two classifications were made based on (persistent) mathematical ability in first and second grade. Repeated measures analyses and discriminant analyses were used to investigate which functions predicted group membership best. Group differences in performance were found on one inhibition and three working memory tasks. The working memory tasks predicted math learning disabilities, even over and above the predictive value of preparatory mathematical abilities.

Keywords

executive functions, math learning disabilities, shifting, inhibition, working memory

Many children in elementary school experience problems in learning mathematical skills. The prevalence is estimated at 6% to 7% (Geary, 2004), or even 17.9% including combined reading and mathematical disabilities (Dirks, Spyer, Van Lieshout, & De Sonneville, 2008). Sometimes these problems are diagnosed only after some years of math education, during which these children's mathematical difficulties increase (Desoete, Roeyers, & De Clerq, 2004). An early identification of children at risk of developing mathematical difficulties would enable earlier treatment of these children. In addition, detailed knowledge of the type of difficulties these children experience would enable an intervention that is suited to the (im)possibilities of each individual child. One possible target for early identification of at-risk children, which we investigated in the current study, is executive functioning. Executive functions are the higher control functions that involve regulation of thinking and behavior. They are the routines responsible for monitoring and regulation of cognitive processes during complex cognitive tasks (Gilbert & Burgess, 2008; Miyake et al., 2000; Van der Sluis, De Jong, & Van der Leij, 2007; Zamarian et al., 2006).

In research of executive functions the multicomponent model of working memory proposed by Baddeley and Hitch (1974) has continued to be useful. The model comprised an attentional control system, the "central executive," aided by two subsidiary slave systems, the "phonological loop" and the "visuospatial sketchpad." Later, a third slave system was added to the model: the episodic buffer, which is assumed to be a limited-capacity temporary storage system that is capable of integrating information from a variety of sources (Baddeley, 2000). When analyzing the central executive, Baddeley (1996) and Baddeley and Della Sala (1996) specified three component functions: selective attention, switch attention, and the need to access and manipulate information in long-term memory. The three executive functions used in this study, shifting, inhibition, and working memory, are based on this specification of component functions. Shifting is defined as the ability to switch between sets, tasks, or strategies, in other words, the disengagement of an irrelevant task set and the subsequent initiation of a new, more appropriate set. Inhibition is the ability to suppress dominant, automatic, or prepotent responses in favor of more goal-appropriate responses. Working memory, or updating, is defined as the ability to monitor and code incoming information and to update the content of memory by replacing old items with newer, more relevant information

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(Miyake et al., 2000; Van der Sluis et al., 2007). The distinction in these three lower-level and relatively well-defined executive functions is often used (Miyake et al., 2000; Van der Sluis et al., 2007). The three functions have proved to be separable but dissociable components; they do not share the same underlying ability commonality but are also distinguishable (Miyake et al., 2000). The functions follow different developmental trajectories during childhood (Klenberg, Korkman, & Lahti-Nuuttila, 2001). Research has shown that working memory (Baddeley & Hitch, 1974) and updating show a large overlap. In a factor analysis, updating and working memory measures loaded on the same factor (St Clair-Thompson & Gathercole, 2006), probably because working memory tasks and updating tasks share the requirement to store information and to revise this in the light of new information (Van der Sluis et al., 2007). In the present study we included tests from both research traditions (one updating task and two working memory span task) and refer to these by the broader term *working memory* (WM).

A problem in measuring executive functions is the task impurity problem (Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Miyake et al., 2000; Van der Sluis et al., 2007). Because executive functions regulate other cognitive processes, assessments of executive functions imply that nonexecutive cognitive abilities are also measured (Hughes & Graham, 2002; Van der Sluis et al., 2007). In addition, executive tasks often require more than one executive function (Van der Sluis et al., 2007). One method to overcome this problem is the use of control tasks: Performance on an executive task is compared to performance on a control task, in which all nonexecutive aspects of the task are the same but the executive demands are much lower (Van der Sluis et al., 2007).

Executive functions have been hypothesized to underlie a range of higher-order cognitive abilities, including mathematics (Bull, Espy, & Wiebe, 2008; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Passolunghi, Vercelloni, & Schadee, 2007; St Clair-Thompson & Gathercole, 2006; Van der Sluis, De Jong, & Van der Leij, 2004, 2007). It is believed that shifting, inhibition, and WM each contribute differentially to mathematical performance. Shifting ability is believed to be involved in mathematical performance by supporting alternation between strategies and subsolutions in multistep mathematics problems (Andersson, 2008; Van der Sluis et al., 2007). Bull et al. (2008) found that the ability to shift between mental sets predicted mathematical achievement. In addition, a number of studies have reported poorer shifting abilities in children with mathematical disabilities (Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; McLean & Hitch, 1999; Zamarian et al., 2006). However, other studies did not find a relationship between shifting and mathematical abilities (Espy et al., 2004; Van der Sluis et al., 2004). Blair and Razza (2007) found no relation between shifting and mathematical abilities in 3- to 5-year-old children either, but did find a prominent relationship between inhibition and mathematical ability. This relationship has been found in more studies (e.g., Mazzocco & Kover, 2007; St Clair-Thompson & Gathercole, 2006) and has been explained by the suggestion that during mathematical problem solving immature strategies and task-irrelevant information must be inhibited. Indeed, a lack of inhibition has been reported in children with lower mathematical ability (Bull et al., 1999; Bull & Scerif, 2001). However, other studies did not find a direct relationship between inhibition and mathematics. Van der Sluis et al. (2004, 2007) found that children with mathematical problems experienced no difficulties with inhibition or shifting per se, but only with a complex executive task that required the combination of these two executive functions. In addition, Bull and Scerif (2001) found a relationship only between mathematics and an inhibition task in which numerical contents were present and no such relationship between mathematics and the regular Stroop task, in which the name of a color is printed in a not-denoted color that has to be named (Stroop, 1935).

Finally, WM is considered important for mathematical performance because information from long-term memory must be stored and manipulated during mathematical problem solving (Andersson, 2008). In addition, deficits in WM ability can disrupt the representation and articulation of numbers during the counting process (McLean & Hitch, 1999), which lead to secondary deficits in numerical processes (Zamarian et al., 2006). In their review, Raghubar, Barnes, and Hecht (2010) noted that many recent studies support the notion that WM is related to and important for mathematical outcomes. Indeed, many studies found a relationship between WM, or the related concept of updating, and mathematical or counting abilities (Bull et al., 2008; Kroesbergen et al., 2009; Mabbott & Bisanz, 2008; Passolunghi et al., 2007; Passolunghi, Mammarella, & Altoè, 2008; Schuchardt, Maehler, & Hasselhorn, 2008; Vukovic & Siegel, 2010).

Most of these results refer to single measurements. However, both executive functions and mathematics are skills that develop strongly during childhood and may influence each other mutually. Longitudinal studies are still scarce, but Welsh, Nix, Blair, Bierman, and Nelson (2010) showed that WM was related to later preparatory math performance in kindergarten, even when controlling for earlier numeracy skills. Van der Ven, Kroesbergen, Boom, and Leseman (in press) found that growth in WM was significantly related to growth in mathematics in children in Grades 1 and 2. Furthermore, De Smedt and colleagues (2009) found that WM was significantly related to mathematics achievement in Grades 1 and 2.

Besides executive functions, preparatory mathematical abilities, such as the ability to subitize small quantities, to discern number patterns, to compare numerical magnitudes and estimate quantities, to count, and to perform simple number transformations (Gersten, Jordan, & Flojo, 2005), are often found as a strong predictor of later mathematical performance (e.g., Jordan, Glutting, & Ramineni, 2010; Locuniak & Jordan, 2008; Morgan, Farkas, & Wu, 2009; Stock, Desoete, & Roeyers, 2010).

The aim of the present study was to investigate whether executive functions can identify children with later mathematical difficulties and whether this predictive value adds to the predictive value of preparatory mathematical abilities in kindergarten. More specifically, it was investigated whether it is possible to predict poor mathematical abilities in first and second grade on the basis of the executive functions in first and the beginning of second grade. To answer this question, this study had two parts. First, the development of the executive functions of children at risk for mathematical difficulties was compared to that of typically developing children. The children with low mathematical ability were expected to obtain lower scores and possibly also diminished growth on the three executive function tasks than typically developing children.

Next, the predictive value of executive functions was investigated using discriminant analyses. To do this, two types of mathematical difficulties were defined: (a) mathematical difficulties at the end of second grade and (b) persistent mathematical difficulties throughout first and second grade. It was investigated how well executive functions could predict both types of mathematical difficulties separately. The first classification was used to investigate whether executive functions could predict later mathematical difficulties: executive function measures were obtained 1.5 years to 3 months before the mathematics measure. However, approximately one third of individuals who meet low achievement criteria at one time do not maintain low achievement over time (Vukovic & Siegel, 2010). Therefore, the second classification was created in which only those children with consistent low performance on four subsequent occasions were defined as having mathematical difficulties. Thus, the advantage of the first classification was to investigate the prediction of future achievements, whereas the second classification targeted only children with persistent mathematical difficulties. It was investigated how well executive functions alone could predict group membership correctly. In addition, it was investigated which executive function was the best predictor and in which early stage it was possible to predict these group classifications. Finally, it was investigated whether the inclusion of executive function measures could improve the predictions made by preparatory mathematical abilities alone. All three functions were expected to be predictors of mathematical difficulties.

Since longitudinal research considering executive functions and mathematical abilities is scarce, this study is a valuable addition to currently available literature. Especially because a distinction between persistent and single poor mathematical performance is made, this study contributes to identifying those children who are at serious risk for developing special needs in mathematical learning and to identifying targets of intervention for these children.

Method

Participants

At the beginning of the study, 227 children (120 boys, 107 girls) with a mean age of 6.5 years (*SD* = 4.3 months, range = 5.9–7.7 years) took part. Children came from 18 classes in 10 schools. School choice was based on three criteria: (a) a low number of children not speaking Dutch at home, (b) diversity in socioeconomic status (i.e., schools with high and low numbers of parents that completed less than 2 years of secondary education), and (c) use of the same mathematics teaching method. As the aim was to obtain a representative sample of children following regular education, there were no stringent exclusion criteria; however, three children were excluded because of failure to understand the task instructions (one child with Down's syndrome and two refugee children with insufficient mastery of the Dutch language).

During the course of the study, 15 more children (5.8%) dropped out because of moving (seven children), grade retention (three children), and accelerating a grade (five children). All analyses were performed with the 209 remaining children (108 boys, 101 girls, mean age at beginning of study = 6.14 years, *SD* = 4.5 months). Parental consent was obtained from all participating children.

Two classifications were made, based on mathematical performance on four different time points, called measurements (halfway through and end of first grade and halfway through and end of second grade). The first classification into two groups was based on the test results of the latest measurement, at the end of second grade. This distinction was made as closely as possible to a 25% to 75% proportion of the total group of children: one group with the 25% lowest scoring children on the mathematical test (Grade 2 low, G2L) and one group with the 75% remaining children, the typically performing group (Grade 2 typical; G2T). Descriptive statistics of the groups are presented in Table 1. There was a significant association between gender and group classification, $\chi^2(1) = 6.35$, $p < .05$, $V = .17$, with the G2L group containing more females and the G2T group containing more males. This corresponds with results from other studies (e.g., Penner & Paret, 2008).

The second classification was based on the results of all four mathematical tests throughout first and second grade. The children were classified into three different groups: a persistent very low performing (PVL) group with test scores on each measurement below the 25th percentile (on each measurement belonging to the 25% lowest scoring children), a persistent below average (PBA) group with test scores not

Table 1. Descriptive Statistics of the Groups in the Two Classifications

			Gender				Age in Months	
			Male		Female			
Group	*n*	%	*n*	%	*n*	%	*M*	*SD*
First classification								
G2L	52	24.9	19	36.5	33	63.5	73.56	4.81
G2T	157	75.1	89	56.7	68	43.3	73.74	4.36
Second classification								
PVL	21	10.0	8	38.1	13	61.9	73.26	4.31
PBA	45	21.4	16	35.6	29	64.4	73.64	5.01
TA	143	68.4	84	58.7	59	41.3	73.73	4.34

Note: G2L = Grade 2 low; G2T = Grade 2 typical; PVL = persistently very low; PBA = persistently below average; TA = typically achieving.

low enough to qualify for the PVL group but always below the 50th percentile (on each measurement belonging to the 50% lowest scoring children), and a typically achieving (TA) group of the remaining children. Descriptive statistics of the three groups are presented in Table 1. The PVL group consists of 10% of the children, which corresponds with the prevalence of previous research (e.g., Dirks et al., 2008). Again, there was a similar significant association between gender and group classification, $\chi^2(2) = 9.35$, $p < .01$, $V = .21$.

Procedure

There were three measurements for executive functions: beginning (October) of first grade, halfway (March) through first grade, and beginning (October) of second grade. All executive function tasks were computer tasks that were administered individually, with the exception of the Simon Task and the Sorting Task, which the children completed in duos, each having their own laptop. Executive functions were measured in a fixed order in three 30-min sessions at each measurement. Tests were administered by trained (under) graduate students, as was preparatory mathematical ability, which was measured individually at the end (June) of kindergarten. Mathematical abilities were measured four times: halfway (January) through and end (June) of first and second grade; these tests were administered groupwise by the teacher.

Instruments

Mathematical Abilities

Preparatory mathematical abilities. Preparatory mathematical abilities were measured at the end of kindergarten (June) with the *Early Numeracy Test* (ENT; Van Luit, Van de Rijt, & Pennings, 1994). The ENT is a 40-item test for children between the ages of 4 and 7 years old. This test assesses counting skills and math prerequisites. The test consists of eight parts: concepts of comparison, classification, correspondence, seriation, using numerals, synchronized and shortened counting, resultative counting, and general understanding of numbers. Each component has 5 items. The reliability coefficient is .94. The raw score of a child is converted to a scaled score.

Mathematical abilities. Mathematical abilities in first and second grade were measured by four versions (first grade [halfway through and end] and second grade [halfway through and end]) of the criterion-based *Cito Mathematics Test* (CMT; Janssen, Scheltens, & Kraemer, 2005a). These are national Dutch tests with good psychometric properties that are commonly used in Dutch schools to monitor the progress of primary school children. Each test contains 50 (Grade 1), 52 (halfway Grade 2), or 54 (end Grade 2) items that are administered on two separate days. In Grades 1 and 2, five main domains are covered: (a) numbers and number relations, covering the structure of the number line and relations between numbers, (b) simple addition and subtraction, (c) simple multiplication and division, (d) complex math applications, often involving multiple mathematical manipulations, and (e) measuring (e.g., weight and length). Raw scores are converted into competence scores that increase throughout primary school, enabling the comparison of results of different versions (Janssen, Scheltens, & Kraemer, 2005b, 2005c). The reliability coefficients of the four versions are .92, .91, .93, and .93, respectively (Janssen, Verhelst, Engelen, & Scheltens, 2010).

Executive Functions

Executive function investigations should contain multiple tests per executive function (Miyake et al., 2000), especially when the reliability of the tasks is unknown. Therefore, inhibition and WM were measured with three computer tasks, and shifting was measured with two computer tasks. The instruction of all tasks was standardized. There was a practice item before each task in which feedback was provided. The shifting and inhibition tasks contained one or two control tasks and one executive function task. The total score on these tasks was the difference between the response time on the executive function task and the (mean) response time on the control tasks. For the WM tasks, the total score was the total number of correct responses on that task.

Shifting

Sorting Task. In this task, based on the inhibition task of Zelazo et al. (2003), the children had to alternate between two sorting rules: according to color and according to shape. The task was presented as a game in which a dog who likes blue and a frog who likes stars were introduced to the child. The child had to give the animal the stimuli that it liked while throwing away stimuli the animal did not like. The task contained two control blocks and a shifting block. In each block, the stimuli were 40 orange and blue stars and squares. In the first control task, only the dog, which loved blue things but hated orange, was introduced. When a blue picture appeared the children had to give the picture to the dog, which was shown on the lower-left side of the screen. When an orange picture appeared the children had to throw the picture in the waste bin, which was shown on the lower-right side of the screen. In the second control task, only the frog who loved star figures but hated squares was introduced. When a picture of a star appeared the children had to give the picture to the frog. When a picture of a square appeared the children had to throw the picture in the waste bin. The shifting task was a mixed block in which sometimes the dog and sometimes the frog appeared; the same 40 stimuli were shown again. The children had to give the picture to the animal or throw the picture in the waste bin. During the three tasks, after 700 ms a stimulus appeared. The children "gave" the picture to the animal by pressing the A button on the left side and the child "threw it away" by pressing the L button on the right side. No feedback was provided.

Animal Shifting. In this task, based on the Symbol Shifting task (Van der Sluis et al., 2007), the children had to name stimuli that were presented on the computer screen as quickly as possible. The eight stimuli consisted of four animal species (bird, fish, dog, and cat) and four fruit species (banana, pear, cherry, and strawberry). In the control task, 40 stimuli were presented one at a time. In the shifting task, two stimuli were presented simultaneously on the same screen. The children had to name only one of the stimuli, depending on the color of the screen background: the fruit when it was yellow, the animal when it was purple. Again, 40 stimuli were presented. All stimuli were preceded by a 700-ms fixation cross.

Inhibition

Animal Stroop. Inhibition ability was measured by the Animal Stroop task (Wright, Waterman, Prescott, & Murdoch-Eaton, 2003). In this task, animals were presented that are composed of the body of one animal and the head of another. The child had to name the animal body rather than the more salient animal head. The four stimuli, sheep, duck, cow, and pig, were presented one at a time, preceded by a 400-ms fixation cross. In the facilitation task, which contained 48 items, the children were asked to name the presented stimuli as fast as possible. The stimuli remained on the screen until the child responded. The control task consisted of bodies of the four stimuli presented with a human head (48 items). The inhibition task consisted of bodies of the four stimuli presented with another animals head (48 items). The children were asked to name the bodies of the animals as fast as possible. In both tasks the test assistant pushed the space bar at the time of the call. After this the assistant pushed the G key when the answer was correct and the F key when the answer was incorrect.

Simon Task. Inhibition ability was measured also by the Simon Task, based on the original Simon Task (Simon, 1969). The Simon effect can be elicited with tasks where stimuli are presented at different locations on a screen, while this spatial aspect must be ignored. The task consisted of two conditions: one control task and one inhibition task. In the inhibition task half of the items were congruent and half of the items were incongruent. The children had to press the A button when a picture of a mouse appeared on the screen and press the L button when a picture of a dragon appeared on the screen. A cage appeared when the child pushed the right button. During the control task the 40 stimuli appeared in the center of the screen. During the inhibition task the stimuli appeared on one side of the screen. The mouse could appear on the left side (congruent) or the right side (incongruent). The dragon could appear on the left side (incongruent) or the right side (congruent). All stimuli were preceded by a 500-ms fixation cross.

Local Global. Inhibition ability was measured also by the Local Global task. In this task identical small geometrical shapes (circle, triangle, square) that together constituted a larger, different geometrical shape were presented. Sometimes the large, global shape had to be named, sometimes the small, local shapes. In general, people show a global preference: Reaction times are faster when the large image has to be named rather than the local shapes (Navon, 1977). The task consisted of three conditions: one control task and two inhibition tasks. In the control task, the children were asked to name 48 single, small geometrical shapes. The inhibition tasks each consisted of 48 larger stimuli that were constructed from the stimuli presented in the control task. All stimuli in these blocks were incongruent: The shape of the larger image was always different from the elements from which it was built. In the first inhibition task, the children had to name the large stimulus, whereas in the second inhibition task the children had to name the small image. The stimuli were preceded by a 400-ms fixation cross.

Working Memory

Keep Track. A computerized version of the Keep Track task (Miyake et al., 2000; Van der Sluis et al., 2007) was administered. During the task pictures belonging to five categories were presented in sets of 10: fruit (strawberry, banana, pear, cherry), animals (dog, cat, bird, fish), shapes (circle, square, triangle, heart), toys (scooter, blocks, teddy bear, car), and sky (sun, moon, stars, cloud). The task consisted of eight series with four different difficulty levels. Prior to a series the children were asked to pay special attention to one or more categories. The number of categories increased after two series, starting with one category and ending with four. First, the children were asked to name each presented picture. Second, the children were asked to name the last

Table 2. Descriptive Statistics of the Five Groups on the Eight Executive Tasks on the Three Measurements

					First Classification				Second Classification					
			Total		G2L		G2T		PVL		PBA		TA	
Function	Task	*ME*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Shifting	Sorting Task[a]	1	0.43	0.14	0.42	0.13	0.43	0.14	0.38	0.09	0.42	0.13	0.44	0.15
		2	0.42	0.16	0.41	0.17	0.13	0.16	0.39	0.19	0.41	0.16	0.44	0.16
		3	0.40	0.15	0.41	0.11	0.39	0.16	0.42	0.13	0.36	0.12	0.41	0.15
	Animal Shifting[a]	1	0.38	0.11	0.37	0.10	0.38	0.11	0.38	0.08	0.36	0.09	0.38	0.12
		2	0.34	0.11	0.33	0.11	0.34	0.11	0.32	0.09	0.33	0.12	0.34	0.11
		3	0.30	0.11	0.31	0.11	0.30	0.11	0.29	0.09	0.30	0.11	0.31	0.11
Inhibition	Animal Stroop[a]	1	0.24	0.09	0.22	0.08	0.25	0.09	0.21	0.09	0.23	0.09	0.25	0.09
		2	0.17	0.08	0.16	0.08	0.17	0.08	0.15	0.07	0.16	0.08	0.18	0.08
		3	0.17	0.07	0.15	0.08	0.17	0.07	0.16	0.08	0.15	0.08	0.17	0.07
	Simon Task[a]	1	0.41	0.14	0.44	0.14	0.40	0.14	0.45	0.11	0.43	0.15	0.39	0.14
		2	0.40	0.17	0.41	0.13	0.40	0.18	0.38	0.15	0.44	0.23	0.40	0.15
		3	0.39	0.15	0.41	0.18	0.38	0.14	0.44	0.19	0.40	0.16	0.38	0.15
	Local Global[a]	1	0.20	0.10	0.19	0.10	0.20	0.10	0.16	0.09	0.19	0.09	0.20	0.10
		2	0.19	0.10	0.18	0.09	0.19	0.10	0.19	0.09	0.17	0.08	0.20	0.10
		3	0.19	0.10	0.19	0.10	0.19	0.10	0.20	0.11	0.18	0.09	0.19	0.11
WM	Keep Track	1	11.73	3.03	10.40	2.7	12.17	3.00	9.14	2.63	11.60	2.77	12.15	2.98
		2	12.97	2.70	11.87	2.8	13.33	2.60	11.48	2.91	11.67	2.67	13.59	2.46
		3	13.92	2.87	12.40	2.9	14.43	2.67	11.71	2.63	12.73	2.82	14.62	2.64
	Odd One Out	1	6.79	2.44	6.10	2.6	7.02	2.36	5.86	2.52	6.11	2.49	7.14	2.35
		2	7.75	2.65	7.25	2.3	7.92	2.74	6.95	2.18	6.89	2.51	8.14	2.67
		3	8.40	2.63	7.35	2.3	8.75	2.64	6.81	1.94	7.51	2.52	8.91	2.60
	Digit Span Backward	1	3.76	1.68	3.23	1.5	3.93	1.71	3.19	1.25	3.53	1.53	3.91	1.76
		2	4.67	1.55	3.98	1.3	4.89	1.60	4.05	1.02	4.51	1.24	4.80	1.68
		3	4.97	1.57	4.79	1.3	5.03	1.65	4.76	1.38	4.56	1.24	5.13	1.67

Note: G2L = Grade 2 low; G2T = Grade 2 typical; PVL = persistently very low; PBA = persistently below average; TA = typically achieving; ME = measurement; WM = working memory.

[a] The lower the score, the better the shifting or inhibition ability.

presented picture of the category to which they had to pay special attention. During the task a white picture at the bottom of the screen helped the children remember the category of attention. In each series the children could gave one, two, three, or four correct answers. The sum of the correct answers was the final score.

Odd One Out. An adaptation of the Dutch version of Odd One Out from the *Automated Updating Assessment* test battery WM (Alloway, 2007) was administered. Three boxes with shapes were presented next to each other. One of the shapes was different from the other two. The child pointed at the different shape. Then three new shapes appeared. At the end of each trial three empty boxes appeared and the child had to point at the locations of the previously shown different shapes in the same order in which they appeared. An answer was considered correct if each location was recalled correctly in the right order. The task started with only one item; after three correct answers of the same length the sequence increased by one. When two mistakes were made in trials of the same length, the task was discontinued. The number of correct responses was used as a final score.

Digit Span Backward. This task was adapted also from the *Automated Updating Assessment* (Alloway, 2007). The children were asked to repeat a recorded digits sequence backward. The task started with two digits. After completing three right items of a certain length, an extra digit was added. After completing two wrong items in the same series, the task was ended. The number of trials recalled correctly was used as a final score.

Outlier Analysis

The scores on the shifting and inhibition tasks represent response times. Response time can be considered a valid score only if the number of errors is limited (Huizinga, Dolan, & Van der Molen, 2006; Van der Sluis et al., 2007). The response time scores on the shifting and inhibition tasks were removed if the accuracy on the task was less than 55% correct, a standard based on the study of Huizinga et al. (2006). Therefore, 12 Animal Shifting scores (7 from the first measurement, 4 from the second measurement, and 1 from the third measurement), one Simon Task score (second measurement), and two Sorting Task scores (one from the first measurement and one from the second measurement) were removed.

Results

The overall mean scores and the mean scores of the five groups on the eight executive function tasks on the three measurements are presented in Table 2. For further analysis,

Table 3. Results of Repeated Measures ANOVAs on Three Working Memory Tasks

	Difference in Time				Difference Between Groups			
Task	*F*	*df*	*p*	η^2	*F*	*df*	*p*	η^2
First classification								
Keep Track	37.16	1.91,394.36[a]	<.01	.15	26.95	1,207	<.01	.12
Odd One Out	19.21	2,414	<.01	.09	11.71	1,207	<.01	.05
Digit Span Backward	43.20	2,414	<.01	.17	10.56	1,207	<.01	.05
Second classification								
Keep Track	26.64	1.92,395.63[a]	<.01	.12	20.85	2,206	<.01	.17
Odd One Out	12.26	2,412	<.01	.06	12.79	2,206	<.01	.11
Digit Span Backward	30.28	2,412	<.01	.13	3.79	2,206	<.02	.04

[a] On these analyses a Greenhouse-Geisser correction was conducted.

shifting and inhibition tasks scores were recoded, so correlations are always positive in the expected direction. Two different statistical analyses were carried out. All analyses were conducted using an alpha of .05. First, the development of the three executive functions and group differences in this development were investigated. For each task two ANOVAs for repeated measures were carried out to examine whether the means on the tasks indeed differed between the measurements. In eight ANOVAs the two groups of the first classification were added as the independent variable, and in the other eight ANOVAs the three groups of the second classification were added as the independent variable. Mauchly's test of sphericity was used to test the assumption of sphericity. For the Animal Stroop and Keep Track this assumption was violated. Therefore, a Greenhouse–Geisser correction was conducted on four of the analyses. Post hoc analyses with a Bonferroni adjustment were carried out correcting for an experiment-wise error rate. The results of the repeated measures ANOVAs are described separately for each executive function.

Shifting

In each of the two classifications no main effect of group was found. Only the analyses on Animal Shifting showed a main effect of time. There was a significant development in the expected direction between all the measurements for both the first classification, $F(2, 414) = 25.38$, $p < .01$, $\eta^2 = .11$, and the second classification, $F(2, 412) = 22.78$, $p < .01$, $\eta^2 = .10$. In none of the analyses was a significant interaction effect between time and group found.

Inhibition

In each of the two classifications no main effect of time or group was found for Local Global or the Simon Task. Animal Stroop scores increased significantly between the first and the second measurement but not between the second and the third measurement. This main effect of time was found for both the first classification, $F(1.94, 400.81) = 65.75$, $p < .01$, $\eta^2 = .24$, and the second classification, $F(1.94, 398.87) = 44.56$, $p < .01$, $\eta^2 = .18$. Furthermore, these analyses showed a main effect of group. Group differences were found between the two groups in the first classification, $F(1, 207) = 5.65$, $p = .02$, $\eta^2 = .03$, and all three groups in the second classification, $F(2, 206) = 4.16$, $p = .02$, $\eta^2 = .04$. The group differences were consistent with the expectations: Children with low mathematical ability obtained lower scores than typically developing children. In none of the analyses was a significant interaction effect between time and group found.

Working Memory

The analyses showed a main effect of time in the expected direction on each task on both classifications (see Table 3). The significant development for Odd One Out was found only between the first and the second measurement in both classifications. The same result was found for Digit Span Backward for the second classification. Furthermore, a main effect of group, consistent to the expectations, was found on each task within both classifications (see Table 3). Children with low mathematical ability obtained lower scores than typically developing children. Odd One Out and Keep Track post hoc analyses revealed that in the second classification no difference was found between the PVL and PBA groups. A significant interaction effect was found for Keep Track on the second classification, $F(3.84, 397.90) = 3.02$, $p = .02$, $\eta^2 = .03$. The PVL group developed faster than the PBA group between the first and the second measurements.

Second, eight discriminant analyses (four for each classification) were carried out to investigate the overall accuracy of the predicted classifications in the groups based on the executive functioning scores and the score for preparatory mathematical abilities. The sensitivity of the predictors was described: the percentages of children in the observed groups that were predicted correctly. Four discriminant analyses were conducted to examine how well executive functions, in addition to preparatory mathematical abilities, could predict group membership in the first classification. The results of these analyses are displayed in Table 4. In the

Table 4. Results of Discriminant Analyses: Percentages of Children Classified Correctly

	First Classification		Second Classification			
Predictor	G2L	G2T	PVL	PVL as PBA	PBA	TA
Mean EF	65.4	61.8	71.4	23.8	40.0	58.3
WM	63.5	62.4	57.1	28.6	28.9	50.3
ENT	76.9	63.5	57.1	33.3	26.7	67.1
ENT and WM	75.0	65.6	66.7	28.6	40.0	59.4

Note: G2L = Grade 2 low; G2T = Grade 2 typical; PVL = persistently very low; PBA = persistently below average; TA = typically achieving; EF = executive functions; WM = working memory; ENT = Early Numeracy Test.

Table 5. Results of Discriminant Analyses on the Mean of the Eight Executive Function Tasks: Standardized Canonical Discriminant Function Coefficients

		First Classification	Second Classification
Function	Task	Standardized Canonical Discriminant Function Coefficient	Standardized Canonical Discriminant Function Coefficient
Shifting	Sorting Task	−.19	−.28
	Animal Shifting	−.12	−.04
Inhibition	Animal Stroop	−.46	−.42
	Simon Task	.33	.33
	Local Global	−.08	−.30
Working memory	Keep Track	.72	.68
	Odd One Out	.46	.44
	Digit Span Backward	.51	.32

first analysis, the executive function tasks were used to investigate which executive function task predicted group membership best. Because the number of predicted variables should be smaller than 1:20 (Stevens, 1986), the mean of the three measurements was taken as a score on the executive function tasks. The overall Wilks's Lambda was significant, $\Lambda = .88$, $\chi^2(8) = 24.95$, $p < .01$, indicating that the eight executive function tasks could distinguish the low and the typical achievers in Grade 2 (G2L and G2T). Of the children, 62.7% were classified correctly into their group (see Table 4). The standardized canonical discriminant function coefficients were the highest for the three WM tasks (see Table 5), which means that the three WM tasks demonstrated the strongest relationship with the general mathematical achievement. Therefore, three other discriminant analyses were conducted to investigate the predictive value of the WM tasks only and the predictive value of WM over the ENT. First, the predictive value of only WM and only the ENT score was examined. The overall Wilks's Lambda was significant for both WM, $\Lambda = .92$, $\chi^2(3) = 17.89$, $p < .01$, 62.7% classified correctly, and the ENT, $\Lambda = .86$, $\chi^2(1) = 30.43$, $p < .01$, 67% classified correctly (see Table 5). Second, the predictive value of the ENT score together with the scores on the three WM tasks on the first measurement was examined. The overall Wilks's Lambda was significant, $\Lambda = .84$, $\chi^2(4) = 36.63$, $p < .01$. Of the children, 67.9% were classified correctly. The predictive value of the individual ENT score was lower than the predictive value of the WM tasks only, concerning the 25% lowest performing children. The WM tasks did not have an additional value besides just the ENT task.

A similar procedure as described above was carried out for the second classification: the groups with persistent very low, below average, or typical mathematical performance during first and second grade (from 6 to 8 years). Again, the mean of the three measurements was taken as score on the executive function tasks in the first analysis to investigate which executive function task predicted group membership best. The overall Wilks's Lambda was significant, $\Lambda = -.16$, $\chi^2(9) = 36.46$, $p < .01$, indicating that the eight executive function tasks differentiated between the three groups. Of the children, 55.7% were classified correctly (see Table 4). From Table 5 it can be seen that in general the three WM tasks demonstrated the strongest relationship with the mathematical achievement.

Therefore, three other discriminant analyses were conducted to investigate the predictive value of the WM tasks only and the predictive value of WM over the ENT. First, the predictive value of only WM and only the ENT score was examined. The overall Wilks's Lambda was significant for both WM, $\Lambda = -.10$, $\chi^2(4) = 21.63$, $p < .01$, 46.4% classified correctly, and the ENT, $\Lambda = .81$, $\chi^2(2) = 41.88$, $p < .01$, 57.4% classified correctly (see Table 5). Moreover, Table 4 also shows the percentage of the PVL group that was classified correctly (WM = 57.1%, ENT = 57.1%) and the percentage of the PBA group that was classified correctly (WM = 28.6%, ENT = 33.3%). Together, 85.7% of the children in the PVL group were classified into one of the risk groups (PVL or PBA group) based on the WM scores. Of the children from the PVL group a total of 90.4% were classified into one of the risk groups (PVL or PBA) based on the ENT score. Second, the predictive value of the ENT score together with the scores on the three WM tasks at the first measurement was examined. The overall Wilks's Lambda was significant, $\Lambda = -.21$, $\chi^2(5) = 50.02$, $p < .01$. Of the children, 56.0% were classified correctly. Of the PVL group, a total of 95.3% were classified into one of the at-risk groups (PVL or PBA). The predictive value of the individual ENT score was comparable to the predictive value of the WM tasks only, concerning the (very) low-performing children at risk for developing mathematical difficulties. The ENT score in combination with the WM scores gave the best prediction of which children were at risk for mathematical difficulties (PVL or PBA; 95.3%).

Conclusion and Discussion

The aim of this study was to investigate whether executive functions are a good early predictor of later mathematical difficulties, both persistent and based on one single test score, compared to the predictive value of preparatory mathematical abilities. Therefore, two classifications were made. First, children were grouped into two groups based on their low or typical math performance at the end of second grade (G2L and G2T). Second, the same children were grouped into three groups based on their mathematical performance throughout first and second grade: PVL, PBA performers, and normal, high, or fluctuating performers (TA). The PVL and PBA children are those children that need special attention because they are at risk for developing mathematical difficulties (PBA) or already show disabilities in their mathematical performance (PVL). The advantage of the first classification was to investigate the prediction of future achievements, whereas the second classification targeted only children with persistent low scores in their mathematical performance.

The development of executive functions in these groups was investigated to examine whether there were differences between the groups and between the three measurements of executive functions measurements. In contrast to the expectations that children with poor mathematical ability perform worse on all three executive functions, in the present study only on the WM tasks differences in development and between groups were found. The low-performing children in Grade 2 (G2L) and the PVL or PBA performing children in Grades 1 and 2 obtained significant lower scores on WM than typically performing children. Furthermore, the results of the discriminant analyses show WM ability as the executive function that predicts mathematical difficulties best. These findings for the WM tasks correspond with previous studies in which a relationship was found between WM, or the related concept of updating, and mathematical difficulties (e.g., Bull et al., 2008; Kroesbergen et al., 2009; Mabbott & Bisanz, 2008; Passolunghi et al., 2007; Schuchardt et al., 2008; Vukovic & Siegel, 2010). WM ability is believed to be necessary because information from long-term memory must be stored and manipulated during mathematical problem solving. Children with lower WM skills are expected to experience difficulties in storing and manipulating information during mathematical problem solving (Andersson, 2008).

No unequivocal results were found for the shifting and inhibition tasks, concerning the development and group differences on the five tasks. In some studies a relation between shifting ability and mathematical achievement was found (e.g., Bull et al., 2008). However, this relationship was not confirmed by others (Espy et al., 2004; Van der Sluis et al., 2004). Except for the Animal Stroop task, the groups did not differ in their development of shifting and inhibition in the present study, which seems to indicate that these two executive functions do not play a crucial role in mathematical abilities. The results of the discriminant analyses revealed a similar pattern. In comparison to WM ability, shifting and inhibition did not contribute to the correct classification of children at risk for mathematical difficulties. According to several studies (Andersson, 2008; Van der Sluis et al., 2007), shifting ability is believed to be involved in mathematical performance by supporting alternation between strategies and subsolutions in multistep mathematics problems, and inhibition ability is believed to be necessary for active suppression of immature strategies and task-irrelevant information during mathematical problem solving (Bull et al., 2008; St Clair-Thompson & Gathercole, 2006). However, the complexity of mathematical tasks in first and second grade is relatively simple, as not all tasks require multistep solutions or contain irrelevant information. This could mean that the role of shifting and inhibition in mathematical tasks increases when the complexity of the tasks and the required knowledge increase. Further research is necessary to investigate the role of these two executive functions in older children.

For the practical relevance of the present study, a comparison was made between the predictive value of WM ability and the predictive value of preparatory mathematical abilities. The present study confirms the predictive value of preparatory mathematical abilities in identifying children at risk for developing mathematical difficulties (Jordan, Kaplan, Locuniak, & Ramineni, 2007; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Locuniak & Jordan, 2008; Morgan et al., 2009; Stock et al., 2010) because the ENT identified 76.9% of the G2L group in the first classification and 57.1% of the PVL and PBA group in first and second grade. With the results of the present study, the importance of WM ability is added to this knowledge, especially for persistent mathematical difficulties in first and second grade. The three WM tasks at the beginning of first grade predicted the same percentage (57.1%) of children with mathematical difficulties through first and second grade as preparatory mathematical ability did. This confirms findings from a previous study (Welsh et al., 2010). Together, the ENT and the WM tasks predicted the children with mathematical ability even better (66.7%). Furthermore, almost all children (95.3%) with persistent mathematical difficulties were identified as at risk for developing problems in mathematical performance on the basis of these two factors.

On a practical level, this implies that many children at risk for developing mathematical difficulties can be identified at the beginning of first grade through a test battery with WM tasks, such as the *Automated Working Memory Assessment* (AWMA; Alloway, 2007), as a supplement to a diagnostic instrument that measures the preparatory mathematical abilities of these children. Clinicians are encouraged to take WM ability into account when assessing math learning disabilities. Apart from facilitating the identification of at-risk children, this will also give useful insight into possible gaps in the skills of these children.

However, in the first classification the WM tasks had no additional predictive value. Because of the distinction that was made between difficulties based on one test score (first classification) and persistent mathematical difficulties based on four test scores (second classification), this seems to indicate that the role of WM ability increases when it concerns persistent mathematical difficulties instead of difficulties based on one single measurement. Besides, the children were older at this last measurement, so this could indicate that the role of WM in mathematics decreases when children become older or that the predictive value of WM is less strong when the prediction is carried out 1.5 years before the measurement of mathematical abilities. Further research is necessary to confirm this statement and to investigate the specific possibilities for using WM ability for identifying children at risk for mathematical learning disabilities.

In the past decade more attention has been paid to stimulating preparatory mathematical abilities in children performing below average (Kaufmann, Delazer, Pohl, Semenza, & Dowker, 2005; Van de Rijt & Van Luit, 1998; Van Luit & Schopman, 2000). This study confirms the practical importance of studying the possibility of stimulating preparatory mathematical abilities. Moreover, this study emphasizes the importance of also stimulating other skills such as WM ability to prepare preschool children for formal mathematic instruction in first and second grade. Research has shown the possibility of stimulating WM in older children (Holmes, Gathercole, & Dunning, 2009), but limited studies have been carried out focusing on training WM in kindergarten and first grade. Therefore, research on stimulating different components of WM in young children should be carried out.

To summarize, this study confirms the practical importance of using the concept of WM in screening children at risk for math learning disabilities and assist these children by prevention programs with a focus on preparatory mathematical abilities and WM. However, the results of the current study should be interpreted in light of several limitations. First, in previous studies separate tasks were combined into a common score on basis of factor analysis (Fournier-Vicente, Larigauderie, & Gaonach, 2008; Huizinga et al., 2006; Miyake et al., 2000; St Clair-Thompson & Gathercole, 2006; Van der Sluis et al., 2007). In this study, the interpretation of the observed differences was possible only at the task level. Therefore, despite the use of control tasks, the task impurity problem (e.g., Miyake et al., 2000) raises the question of if the tasks are true representations of the underlying executive functions. A second limitation is the use of the same tasks at three measurements. An executive function can be measured best when a task is new to the child, regarding the content as well as the form, because the tasks tend to suffer from relatively low test–retest reliability (Rabbitt, 1997). Efforts were made to minimize this problem by keeping the measurements 6 months apart. Despite the limitations, this study indicates that it may be promising to use WM ability in early identification of children at risk for mathematical learning difficulties.

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