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Planning and Self-Control, but not Working Memory, Directly Predict Multiplication Performance in Adults

Parvin Nemati*[a], Johanna Schmid[ab], Mojtaba Soltanlou[ac], Julian-Till Krimly[a], Hans-Christoph Nuerk[abd], Caterina Gawrilow[ab]

[a] Department of Psychology, University of Tuebingen, Tuebingen, Germany. **[b]** LEAD Graduate School & Research Network, University of Tuebingen, Tuebingen, Germany. **[c]** Graduate Training Centre of Neuroscience/ IMPRS for Cognitive and Systems Neuroscience, Tuebingen, Germany. **[d]** Leibniz-Institut für Wissensmedien, Tuebingen, Germany.

Abstract

Empirical evidence suggests that working memory (WM) is closely related to arithmetic performance. WM, which is the ability to monitor and update recent information, underlies various cognitive processes and behaviors including planning, self-regulation, and self-control. However, only a few studies have examined whether WM uniquely explains variance in arithmetic performance when other WM-related domain-general factors are taken into account. In this study, we examined whether WM explains unique variance in arithmetic performance when planning, self-regulation, and self-control are considered as well. We used the Tower of London task as a measure of planning, self-rated reports as a measure of self-regulation and self-control, and WM measures, to test which of these domain-general functions predicts complex multiplication performance. Results showed that planning predicted multiplication accuracy and self-control predicted response time, while WM and self-regulation did not predict complex multiplication performance. Although WM was not a direct predictor of multiplication performance, it possibly exerted its influence as part of planning ability. We suggest that complex multiplication is not predicted by WM per se, but rather by WM-related general cognitive and behavioral factors, namely self-control and the planning component of executive functions.

Keywords: arithmetic performance, multiplication, executive functions, planning, working memory, self-regulation, self-control

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*Corresponding author at: University of Tübingen, Schleichstr. 4, 72076 Tübingen, Germany. E-mail: parvin.nemati@uni-tuebingen.de

People use numerical skills in their everyday life in various situations such as shopping or paying bills at restaurants. About 20% of adults do not achieve basic levels of mathematic competence required for these life skills (Williams, 2003). This mathematical incompetence leads to lower income and less financial security in life (Butterworth, Varma, & Laurillard, 2011; Parsons & Bynner, 2005). Therefore, it is worthwhile to examine the factors that can lead to this incompetence. Two groups of factors that influence mathematical skills have been described in the literature. One group consists of domain-specific factors, such as the approximate number system (e.g., Libertus, Feigenson, & Halberda, 2011; for review see Dietrich, Huber, & Nuerk, 2015) or spatial-numerical associations (e.g., Siegler & Opfer, 2003; but see Cipora et al., 2016). The second group consists of domain-general factors such as social (e.g., Byrnes & Wasik, 2009), behavioral (e.g., McClelland et al., 2007), and cognitive factors (e.g., Bull, Espy, & Wiebe, 2008; Bull & Scerif, 2001).

Various domain-general cognitive abilities have been reported to influence complex arithmetic performance. One category of such abilities is executive functions (EF), which include three core cognitive processes: inhibition, shifting, and working memory (WM; Miyake et al., 2000). There is strong evidence for the contribution of EF to mathematical performance (e.g., Agostino, Johnson, & Pascual-Leone, 2010; Blair & Razza, 2007; Clark, Pritchard, & Woodward, 2010; Cragg & Gilmore, 2014; Gathercole, Pickering, Knight, & Stegmann, 2004; Lee, Ng, & Ng, 2009). The component of EF most frequently associated with complex mathematics is WM, which is a system of storage and manipulation of recent visuospatial and verbal information (Baddeley, 2012; Baddeley & Hitch, 1974). Previous studies have repeatedly shown that WM is strongly related to different mathematical skills (e.g., Cragg & Gilmore, 2014; De Smedt et al., 2009; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013; Han, Yang, Lin, & Yen, 2016; Raghubar, Barnes, & Hecht, 2010; Swanson, Jerman, & Zheng, 2008; Szücs, Devine, Soltesz, Nobes, & Gabriel, 2013; Van der Ven, Kroesbergen, Boom, & Leseman, 2012).

WM contributes to basic arithmetic skills (i.e., addition, subtraction, multiplication, division) because these computations require concurrent storage and processing of digits (e.g., Peng, Namkung, Barnes, & Sun, 2016; Raghubar et al., 2010; Swanson & Jerman, 2006). However, WM is differentially related to performance on different types of arithmetic tasks. For example, it has been shown that WM capacity affects both addition and subtraction problem solving through its influence on the ability to retrieve answers from long-term memory (Barrouillet & Lépine, 2005; Barrouillet, Mignon, & Thevenot, 2008; but see Fayol & Thevenot, 2012, for alternative accounts of addition problem solving). However, in multiplication problem solving, it has been suggested that WM is involved in retrieval strategies as well as computation processing (Mabbott & Bisanz, 2003; Seitz & Schumann-Hengsteler, 2000) with an increasing load of WM for complex problems solved via non-retrieval strategies (Tronsky, 2005). Moreover, research indicates that specific domains of WM (e.g., verbal WM and visuospatial WM) may be differentially associated with different types of arithmetic skills (Lee & Kang, 2002). For instance, neuroimaging findings revealed that addition and subtraction problem solving are more associated with visuospatial WM than simple multiplication problem solving, whereas multiplication relies more on retrieval strategies than manipulation of visual Arabic digits (e.g., Zhou et al., 2007). Further studies, however, did not replicate this finding, pointing out limitations and methodological problems with the previous studies (Cavdaroglu & Knops, 2016; Imbo & LeFevre, 2010). As for instance, Cavdaroglu and Knops (2016) suggested that multiplication and subtraction depend on both verbal and visuospatial domains of WM when the difficulty of WM measures and calculation tasks are controlled within and across participants.

Further research suggests that the contribution of different domains of WM to arithmetic skills is influenced not only by the type of problems or domains of WM but also by an individual's age (Menon, 2016). For example, there is some evidence that the contributions of different domains of WM to mathematical performance change dynamically during development, and that visuospatial WM plays an increasing role in improving mathematical skills (e.g., Menon, 2016; Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Soltanlou, Pixner, & Nuerk, 2015). In sum, each domain of WM seems to affect distinct arithmetic operations differently at various developmental stages.

However, most of these studies investigated WM as the only domain-general factor predicting arithmetic performance and may, therefore, be misleading because WM is also associated with other EFs such as inhibition and planning (e.g., Hasher, Zacks, & May, 1999; Oberauer, 2001; see also a computational model of frontal lobe dysfunction for relation between WM and planning; Goela, Pullara, & Grafman, 2001). Planning is described as the ability which contributes to problem solving (Newell & Simon, 1972; Simon, 1978). It has been shown that planning is associated with better math problem solving in children (e.g., Clark et al., 2010; Kirby & Ashman, 1984). Poor planning skills are related to failure to organize mathematical problem solving in children, that is, difficulty in analyzing the demands of the problem and using the best procedures to solve it (Naglieri & Johnson, 2000). In addition, improving planning skills has been found to play a beneficial role in interventions for children with poor arithmetic skills (e.g., Naglieri & Johnson, 2000). Hence, it has been suggested that planning is crucial for successful mathematical performance and is linked to cognitive strategies used in mathematical computations (Das, Naglieri, & Kirby, 1994). In spite of the important role of planning in arithmetic computations in the few available studies, studies on the relationship between planning skills and arithmetic computations especially in adults are scarce.

Solving complex multiplication tasks that requires different sequences of computations and cognitive processes likely involves planning skills, for instance, organizing the best strategies step by step to solve the problem. Accordingly, we focused on planning ability as well as WM, because it has been suggested that planning is one of the essential skills for mathematical computations (e.g., Kirby & Ashman, 1984; Sikora, Haley, Edwards, & Butler, 2002). Planning also relies on WM (e.g., Albert & Steinberg, 2011; Goela et al., 2001; Köstering, Stahl, Leonhart, Weiller, & Kaller, 2014; Zelazo, Carter, Reznick, & Frye, 1997) to maintain and revise sequences of plans (Gilhooly, 2005). Therefore, we aimed at examining the impact of WM and planning on solving complex multiplication tasks. In the current study, we used the Tower of London (TOL) task to operationalize planning. The TOL is a common instrument for measuring planning skills in cognitive and clinical studies (Kaller, Rahm, Köstering, & Unterrainer, 2011) and similar to WM, it is known to critically rely on the activity of the prefrontal cortex (for a review see Unterrainer & Owen, 2006). Furthermore, aside from cognitive domain-general factors, few studies have indicated a plausible contribution of *behavioral* domain-general factors to arithmetic performance (see also Cragg & Gilmore, 2014).

Therefore, in addition to cognitive components, we assessed self-reported self-regulation and self-control as two behavioral factors closely related to cognitive EF factors (Hofmann, Schmeichel, & Baddeley, 2012) that may influence arithmetic performance. Self-regulation can be defined as the ability to control emotions, thoughts, and behaviors (Best & Miller, 2010). An important aspect of self-regulation is goal-directed behavior (Hofmann et al., 2012), as for instance, making an appropriate decision to achieve a previously self-determined goal, by considering different opportunities and acting according to their consequences (McClelland, Geldhof, Cameron, & Wanless, 2015). Self-control as a subset of self-regulation serves more as an active attempt to resist temptations, and is related to overriding unwanted, impulsive responses (Baumeister, 2002; Diamond, 2013). For instance, self-control may be required to resist eating a high-calorie desert while on a diet or to suppress unwanted, distracting thoughts while solving math problems. Another aspect of self-control is to have the discipline to not give up a task despite tempting action opportunities (Diamond, 2013; Duckworth, Peterson, Matthews, & Kelly, 2007). This perseverance is important because achieving difficult long-term goals, such a future educational success, requires maintaining effort and interest over time (Duckworth et al., 2007). Completing a difficult time-consuming task such as a complex math task may also depend on discipline and perseverance to some extent.

Previous studies have indicated that both self-regulation and self-control can predict mathematical performance in children (e.g., Blair & Razza, 2007; Gawrilow, Gollwitzer, & Oettingen, 2011). However, studies on the relationship between self-regulation, self-control, and arithmetic performance are rather scarce. The few existing studies indicate that self-regulation and self-control may contribute to mathematical performance by blocking out distracting information (e.g., Gawrilow et al., 2011; Passolunghi & Siegel, 2001) and through their relations to various components of EF such as inhibition or WM (e.g., Best & Miller, 2010; Hofmann, Friese, Schmeichel, & Baddeley, 2011; McClelland & Cameron, 2012; McClelland et al., 2007). Previous studies have shown that WM is related to self-regulation and self-control (Hofmann et al., 2011), as for instance, self-regulation involves WM in representing goals and updating goal-related information (Kane, Bleckley, Conway, & Engle, 2001; Miller & Cohen, 2001). In support of the influence of WM on self-control, previous research has shown that individuals with higher WM capacity are more able to resist visual distractors in various visual tasks than individuals with less WM capacity (e.g., Kane et al., 2001; Unsworth, Schrock, & Engle, 2004). Therefore, an assumption underlying the use of these behavioral ratings (i.e., self-regulation and self-control) is that they are measuring behaviors that are related to both arithmetic performance and WM. Accordingly, we aimed to test whether WM explains unique variance when these WM-related behavioral components (i.e., self-regulation and self-control) are considered.

In the present study, we assessed complex multiplication because it requires a variety of cognitive skills (Han et al., 2016). For instance, WM is necessary for maintaining and updating information and step-by-step planning, and self-regulation and self-control are needed for ignoring distractions such as intrusive thoughts. In addition, previous studies that examined domain-general factors contributing to simple multiplication performance identified WM as the most relevant cognitive process (e.g., Han et al., 2016; Soltanlou et al., 2015), but little is known about the role of other domain-general cognitive demands in complex multiplication problem solving. Therefore, we aimed to investigate whether any of these domain-general factors can predict complex multiplication performance better than WM.

Furthermore, we investigated the operand-relatedness effect, which has been mostly implicated in simple multiplication. Operand-relatedness within multiplication refers to the solution belonging to another problem, mainly the neighbors of the correct solution in the multiplication table (e.g., $3 \times 7 = 24$). Studies have shown that this effect leads to slower response times and more errors in simple multiplication (e.g., Campbell & Graham, 1985; Cooney, Swanson, & Ladd, 1988; Stazyk, Ashcraft, & Hamann, 1982). Theoretical models of multiplication processing such as network retrieval (Ashcraft, 1982), distribution of association (Siegler, 1988), and network interference (Campbell, 1987) interpreted this effect within the framework of a network of nodes comprising the solutions of problems belonging to the multiplication table, which are related to each other. Therefore, we aimed to extend the operand-relatedness effect that previously has been shown in simple multiplication to complex multiplication in the current study.

In sum, in the present study, we investigated the relation of the aforementioned domain-general factors to complex multiplication problem solving to determine which one is the best predictor of complex multiplication performance in adults, and to test whether any of these domain-general factors can predict complex multiplication performance better than WM. Regarding the operand-relatedness effect, we hypothesized that although we usually do not learn complex multiplication from a table, due to step-by-step computations (i.e., first multiplying unit to unit, following to multiplication table, then unit to decade), the operand-relatedness effect may exist in complex multiplication.

To examine our hypotheses, we employed computerized tasks to measure cognitive factors (i.e., WM and planning) and online questionnaires to assess behavioral factors (i.e., self-regulation and self-control). Furthermore, participants performed computerized complex multiplication task in our laboratory.

Method

Participants

Forty undergraduate students (33 females, age: *M* = 20.95 years, *SD* = 1.08) of a German University participated in this study. All participants received detailed information about the study and then gave written informed consent to participate in the study. They received either course credits or eight Euro per hour. Detailed sample characteristics are provided in Appendix A. All data were collected pseudonymised (i.e., not labeled by name) using personal codes.

Measures

Working Memory (WM)

To assess WM, we used visuospatial WM tasks (i.e., N-Back and Corsi block-tapping) because they have been shown to have strong relations with multiplication performance (e.g., Han et al., 2016; Soltanlou et al., 2015).

N-Back — The N-Back task had a spatial 2-Back design, where in each trial one of the following capital letters: B, F, K, H, M, Q, R, X, (Kane, Conway, Miura, & Colflesh, 2007) plus L and S was presented in the left or right field of a two-split grid frame on the screen. Participants were instructed to press a green button (i.e., *L* on a German keyboard) if the presented letter and its position in the two-grid frame matched the one presented two trials before (2-Back), and to press the red button (i.e., *A* on a German keyboard) if it did not match. The response keys were counterbalanced across participants. Each two-split grid with a letter was presented for 1000 ms and then disappeared from the screen. Response duration was 3000 ms from the time that two-split grid was presented. The inter-stimulus interval was 1000 ms. The task began with 10 practice trials, followed by 320 test trials. The target condition (the condition in which the presented letter and its position match the condition presented two trials before) constituted 30% of all trials.

Corsi Block-Tapping — The computerized version of the Corsi block-tapping task was used (Corsi, 1973), chosen from the Psychology Experiment Building Language test battery (PEBL; Mueller, 2013). The test consisted of nine black 1/4-inch cubes distributed over a gray screen. On any given trial, some of the cubes lit up in a particular sequence, starting with three lighted-cubes sequence. There were two trials for each sequence. The sequence was increased by one when at least one of two trials of the same sequence was recalled correctly. Otherwise, the test was stopped and the maximum length of sequences with at least one correct recall was calculated as the score. In the forward recall, participants were asked to use the cursor to tap the cubes in the same order as they had lit, while in the backward recall, the procedure was the same in reversed order. A maximum of 18 test trials was presented.

Planning

Tower of London (TOL) — The computerized version (Kaller et al., 2011) of the TOL task (Shallice, 1982) was used in the present study to assess planning. Participants were instructed to solve a set of TOL problems

(Kaller et al., 2011) which consisted of 28 trials of three-, four-, five-, and six-move problems (eight trials each except four trials for the three-move problem) presented in fixed order. The test contained two boards (reference and test). Each board had three pegs and three balls with three different colors: blue, yellow and red. Participants were asked to move the balls on the test board in order to make the arrangement of the balls identical to the patterns on the reference board shown on top of the screen. Participants were instructed to plan how to move the balls before starting to move them and to use the minimum number of moves to solve the problems. The accuracy score was calculated as the number of problems solved correctly in the minimum number of moves within the time limit divided by the total number of problems.

Complex Multiplication

In total, 48 complex multiplication problems (Appendix B) along with their solutions were presented in a computerized verification task. The computerized complex multiplication task was created with PsychoPy software (Peirce, 2009). The multiplication problems consisted of a one-digit operand (range: 2-9) times a two-digit operand (range: 13-19), with two-digit solutions (range: 48-98). Presented solutions consisted of correct (50%) and incorrect (50%) solutions. Half of the incorrect solutions were operand-related solutions and the other half were operand-unrelated solutions. Operand-related solutions differed from the correct solution by ±1 to one of the operands. Therefore, they were neighbors of the correct solution in the multiplication table. Operand-unrelated solutions were not from the multiplication table. The operand-related solutions were matched by distance difference to the correct solutions and parity with operand-unrelated solutions. The experiment started with 8 practice trials. Multiplication problems along with solutions were presented at the same time in the center of the screen in the form of x × xx = xx in half of the trials, and in the form of xx × x = xx in the other half. The order of small and large operand within the trials was counterbalanced. Trials were presented to participants in a fixed order. Each trial started with a fixation point of 500 ms, followed by a blank screen for 500 ms. Then a multiplication problem along with a solution (e.g., 4 x 19 = 76) was presented until a response was made or a limited time of 6000 ms passed. Participants were asked to respond by pressing a green key (*L* in German keyboard) when the solution was correct and a red key (*A* in German keyboard) when the solution was incorrect. The response keys were counterbalanced across participants. After response or no response in given time (6000 ms), the presented problem disappeared and 1000 ms later next trial began. No feedback was provided.

Self-Regulation and Self-Control

German short versions of the Conners' adult attention-deficit/hyperactivity disorder (ADHD) Rating Scale (sample item: "I am easily bored"; CAARS; Conners, Erhardt, & Sparrow, 1999), and of the Brief Self-control Scale (sample item: "I wish I had more self-discipline"; Bertrams & Dickhäuser, 2009; Tangney, Baumeister, & Boone, 2004) were used to assess self-regulation and self-control, respectively. We used ADHD rating scales for measuring self-regulation, because a deficit in self-regulation is one of the major behavioral problems in ADHD (Barkley, 1997). In addition, attention plays a significant role in self-regulation (e.g., Norman and Shallice's Supervisory Attention System; Norman & Shallice, 1986). The online questionnaire was created with SoSci Survey (Leiner, 2014) for both of our behavioral ratings (i.e., Brief Self-control Scale and CAARS).

Procedure

This study was part of a larger project which aimed to investigate the effect of self-regulatory training on mathematical performance. First, an online questionnaire consisting of items for assessing demographic information, self-regulation, and self-control, was sent via email to each participant. After responding to the online questionnaire, participants were invited to our laboratory to perform computerized tasks in individual sessions. Subsequently, WM, planning, and multiplication performance were assessed using computerized tasks in the lab. Each task lasted approximately 10-15 min. Half of the participants completed the domain-general cognitive tasks first, and the other half completed the multiplication task first. Written detailed instructions emphasizing both speed and accuracy were presented before each task.

Analysis

Response times (RTs) of participants in complex multiplication task were measured by key-press, and defined by the time interval between the presentation of the problems and the response. Only RTs for correct responses were included in the analyses. Furthermore, RTs shorter than 200 ms were not considered. In a second step, RTs outside of the interval of ±3 SD around the individual mean were excluded repetitively until no more outliers remained (for the same procedure see Nuerk, Weger, & Willmes, 2001, and follow-up articles). Therefore, about 0.11% of the responses were not considered for further analyses. Moreover, four trials (with the same components but different correct and incorrect solutions) were excluded because they were presented with wrong solutions in the task.

In order to find the relation between domain-general factors and multiplication performance, a bivariate correlation was calculated. Moreover, to uncover which domain-general factors predict multiplication performance in adults, two separated stepwise regression analyses were conducted on mean RTs and error rates. It should be noted that prior to regression analysis, the WM variables were aggregated by adding z-scores of Corsi block-tapping task and z-scores of N-back task accuracy to guarantee adequate statistical power of the model by reducing the number of predictors. The same procedure was conducted with WM non-aggregated measures to provide full insight into the non-aggregated WM measures. Furthermore, there was a statistically significant correlation between WM tasks (see Table 1), as they all assessed visuospatial WM. Full information on separate contributions of the single WM tasks to multiplication performance can be found in Table 3. Due to the strong correlation between TOL task and WM measures, an additional mediation analysis was conducted to test whether the variance explained by WM in multiplication errors was included in the TOL task. Finally, the operand-relatedness effect was calculated by using paired *t*-test between operand-related and operand-unrelated conditions.

Results

Relation Between Multiplication Performance and Domain-General Factors

Descriptive Statistics and Correlation Analysis

Descriptive statistics for all study variables are provided in Table 1 along with the correlation matrix. Furthermore, the analysis of ceiling and floor effect for all variables revealed a ceiling effect in the N-Back task (Appendix C). Multiplication error rate was significantly negatively correlated with TOL accuracy (r = -.43, p = .003), and there was a significant negative correlation between multiplication RT and self-control (r = -.34, p = .015; see Table 1). Moreover, several significant correlations were observed within domain-general factors. TOL accuracy showed a significant correlation with self-control (r = -.45, p = .002) and WM aggregated measures (r

= .50, p = .001). There was a significant correlation between self-regulation and N-Back accuracy (r = .28, p = .042). Moreover, significant correlations were found between three WM tasks and between planning accuracy and WM tasks (Table 1).

Table 1

Descriptive Statistics and Correlations Between Domain-General Factors and Multiplication Performance

Variable	*M*	*SD*	1	2	3	4	5	6	7	8
1. Multiplication Error (%)	0.18	0.11	-							
2. Multiplication RT (ms)	3.10	0.56	.27*	-						
3. Self-Regulation	13.62	5.57	-.17	-.00	-					
4. Self-Control	41.42	8.74	.04	-.34*	-.17	-				
5. N-Back Accuracy	0.87	0.09	-.30*	-.16	.28*	.04	-			
6. Corsi-Block Forward	5.50	0.65	-.27*	-.05	.22	-.18	.35*	-		
7. Corsi-Block Backward	6.05	0.81	-.18	.15	.22	-.20	.31*	.47**	-	
8. TOL Accuracy	0.73	0.13	-.43**	.13	.23	-.45**	.53**	.36*	.25	-
9. WM[a]	0.00	5.27	-.33*	-.03	.31	-.15				.50**

Note. N = 40.

[a]WM = aggregated WM tasks including Corsi Block-Tapping Forward, Corsi Block-Tapping Backward, and N-Back Accuracy. Ranged between -5.65 and 5.11.

*p < .05. **p < .01, one-tailed.

Regression Analysis

Stepwise multiple regression analysis was conducted to test whether self-regulation, self-control, WM, and TOL accuracy significantly predict participants' performance in the multiplication task. Two series of stepwise regression analyses were separately conducted for multiplication error rate and RT as dependent variables. The stepwise model of total error rate, R^2 = 0.18, adjusted R^2 = 0.16, $F(1, 38)$ = 8.59, p = .006, showed only TOL accuracy as a significant predictor (p = .006), while the other predictors failed to explain significant amounts of additional variance (Table 2). The stepwise model of total RT, R^2 = 0.12, adjusted R^2 = 0.09, $F(1, 38)$ = 5.11, p = .029, identified only self-control ratings as a significant predictor (p = .029), while the other predictors failed to explain significant amounts of additional variance (Table 2). Furthermore, the results of multiple regression analyses with non-aggregated WM tasks as predictors were largely consistent with aggregated WM tasks and are presented in Table 3.

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Table 2

Stepwise Multiple Regression Analysis Predicting Complex Multiplication Performance From TOL Accuracy, Self-Regulation, Self-Control, and WM

Dependent variable	Predictor	Excluded variable	*B*	*t*	*p*	Standardized *B*
Total errors (%)	TOL Accuracy		-0.35	-2.93	.01*	-0.43
		Self-Regulation	-0.08	-0.52	.60	
		Self-Control	-0.19	-1.15	.26	
		WM[a]	-0.15	-0.90	.37	
RT (ms)	Self-Control		-0.02	-2.26	.03*	-0.34
		Self-Regulation	-0.06	-0.41	.69	
		WM	-0.08	-0.52	.61	
		TOL Accuracy	-0.03	-0.20	.84	

Note. *N* = 40.

[a]WM = aggregated WM tasks including Corsi block-tapping forward, Corsi block-tapping backward and N-Back accuracy.

**p* < .05.

Table 3

Stepwise Multiple Regression Analysis Predicting Complex Multiplication Performance From TOL Accuracy, Self-Regulation, Self-Control, and Non-Aggregated WM Tasks

Dependent variable	Predictor	Excluded variable	*B*	*t*	*p*	Standardized *B*
Total errors (%)	TOL Accuracy		-0.35	-2.93	.01*	-0.43
		Self-Regulation	-0.08	-0.52	.60	
		Self-Control	-0.19	-1.15	.26	
		Corsi Block Forward	-0.13	-0.83	.41	
		Corsi Block Backward	-0.08	-0.52	.60	
		N-Back Accuracy	-0.10	-0.60	.55	
RT (ms)	Self-Control		-0.02	-2.26	.03*	-0.34
		Self-Regulation	-0.06	-0.41	.69	
		Corsi Block Forward	-0.11	-0.73	.47	
		Corsi Block Backward	-0.08	0.51	.61	
		N-Back Accuracy	-0.15	-0.96	.34	
		TOL Accuracy	-0.03	-0.20	.84	

Note. *N* = 40.

**p* < .05.

Mediation Analysis

Mediation analyses were conducted following the guidelines by Baron and Kenny (1986) to test whether planning accuracy (measured by TOL) is a mediator in the relationship between WM and multiplication performance. Thus, TOL accuracy might predict multiplication errors, and WM may predict multiplication errors indirectly through TOL accuracy because WM measures and TOL accuracy were strongly correlated (Table 1). If WM predicts TOL accuracy, which in turn predicts multiplication errors, regression analyses may not be the appropriate model to use. The direct influence of WM on multiplication errors would not explain variance, because this variance would already be accounted for by the planning variable (influenced itself by WM). We tested this assumption with both the aggregated (Figure 1) and the non-aggregated WM measures (Figure 2). The effect of aggregated WM on multiplication errors without controlling for TOL accuracy was significantly negative, (b = -0.02, p = .039; Path c, see Figure 1 and Appendix D). However, when TOL accuracy was entered into the model the direct effect of WM on multiplication errors was reduced and no longer significant (*b* = -0.01, *p* = .357; Path *c´*, see Figure 1). Instead, WM influenced TOL accuracy significantly (*b* = 0.03, *p* = .001; Path a, see Figure 1), which in turn influenced multiplication errors significantly (*b* = -0.29, *p* = .032; Path *b,* see Figure 1 and Appendix D). The one-tailed Sobel test confirmed that there is a significant indirect effect of WM on multiplication error through TOL accuracy (*b* = -0.01, *p* = .030). Therefore, the mediation model supported the assumption that TOL accuracy mediates the effect of aggregated WM measures on multiplication errors (Figure 1).

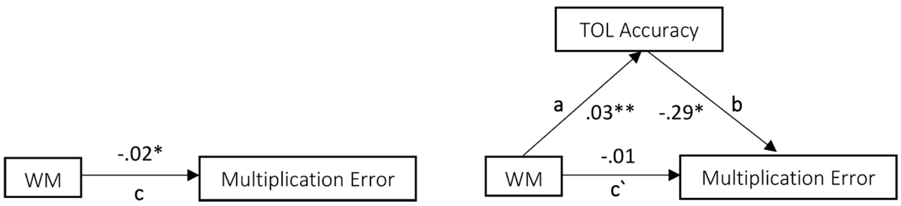

Figure 1. Mediation model being tested on the basis of Baron and Kenny (1986). Path *c* tested the relationship (left diagram) between the independent variable and the dependent variable without controlling for TOL Accuracy, path *a* tested the relationship (right diagram) between the mediator and the independent variable and path *c´* tested the direct relationship between the independent variable and the dependent variable when controlling for TOL Accuracy. Multiplication Error = dependent variable, WM = independent variable (aggregated WM measures), TOL Accuracy = mediator (planning accuracy).

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

The effects of non-aggregated WM measures on multiplication errors without controlling for TOL accuracy were not significant (Path *c, d, e*; see Figure 2 and Appendix D). When TOL accuracy was entered into the model, the already insignificant direct effects of non-aggregated WM measures on multiplication errors were further reduced (Path *c´´*, *d´´, e´´;* see Figure 2). However, TOL accuracy influenced multiplication errors significantly (*b* = -0.28, *p* = .032; Path *b,* see Figure 2 and Appendix D). The effects of Corsi-Block forward (*b* = -0.02, Path *d´´*) and Corsi-Block backward (*b* = -0.00, Path *e´´*) on multiplication error with controlling for TOL accuracy were not significant. However, the results of a one-tailed Sobel test confirmed a significant indirect effect of N-Back accuracy on multiplication error through TOL accuracy (*b* = -0.18, *p* = .041). In sum, the mediation analysis with non-aggregated WM measures suggests that TOL accuracy partially mediates the effect of non-aggregated WM measures on multiplication errors (Figure 2) and N-Back accuracy explains most variance in the indirect path between WM measures and multiplication errors.

Furthermore, additional mediation analyses were conducted to test the extent to which the relationship between TOL accuracy and multiplication error is mediated by WM measures and to explore the common and specific multiplication accuracy variance predicted by TOL and WM measures (Appendix E). The results showed that WM (both aggregated and non-aggregated) partially mediated the effect of TOL accuracy on multiplication errors (Appendix E). However, the results of the Sobel test indicated a non-significant indirect effect of TOL accuracy on multiplication error through aggregated WM measures (*b* = -0.06, *p* = .401) and non-aggregated WM measures (N-Back Accuracy, *b* = -.03, *p* = .695; Corsi-Block Forward, *b* = -0.03, *p* = .590; Corsi-Block Backward, *b* = -0.00, *p* = .918).

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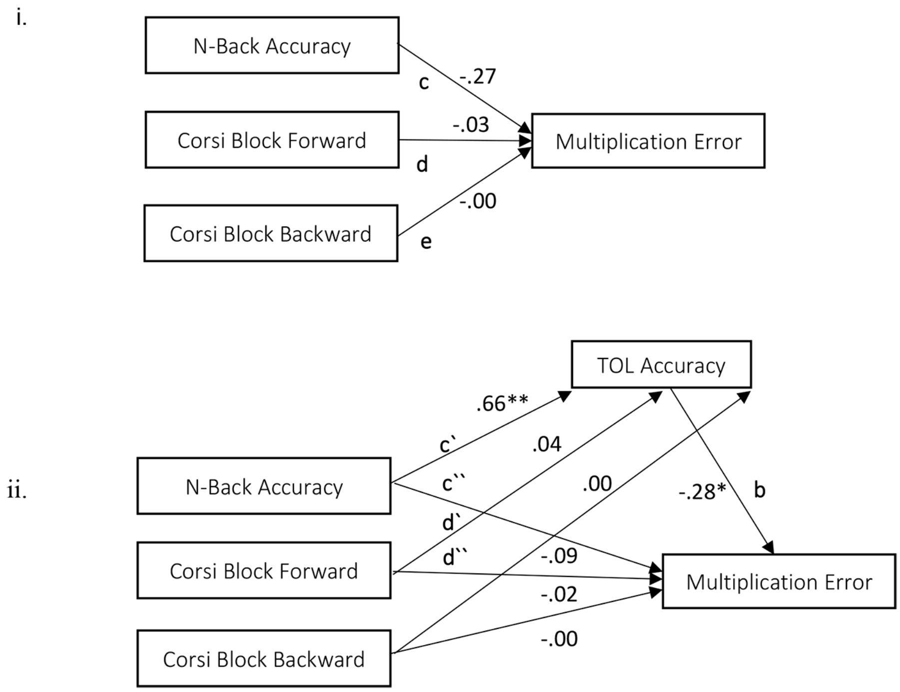

Figure 2. Path analysis model tested the mediator role of TOL accuracy in the direct (i) and indirect (ii) relationships between the independent variables (non-aggregated WM measures) and the dependent variable (multiplication errors). Multiplication Error = dependent variable; N-Back = independent variable; Corsi-Block Forward = independent variable; Corsi-Block Backward = independent variable; TOL Accuracy = mediator (planning accuracy).

$^{*}p < .05$. $^{**}p < .01$.

Comparison of Operand-Related and Operand-Unrelated

The operand-relatedness effect in multiplication was replicated in this study by using paired *t*-tests between operand-related and operand-unrelated conditions. Participants made significantly fewer errors in the operand-unrelated condition ($M = .12$; $SD = .12$) than the operand-related condition ($M = .20$; $SD = .10$), $t(39) = 3.96$, $p < .001$. Furthermore, participants were significantly faster in the operand-unrelated condition ($M = 2.88$; $SD = .64$) than the operand-related condition ($M = 3.14$; $SD = .60$), $t(39) = 4.25$, $p < .001$. However, no domain-general cognitive factor significantly predicted variance for the operand-relatedness effect.

Discussion

The present study investigated the role of domain-general factors including WM, planning, self-regulation, and self-control abilities in complex multiplication performance in adults. Consistent with previous studies in children (e.g., Bull et al., 2008; Bull & Lee, 2014; Clark et al., 2010; Von Aster & Shalev, 2007), our overall findings indicate that domain-general factors support mathematical performance in adults.

The Role of WM and Planning as Cognitive Factors in Multiplication Performance

Although most previous studies emphasized the major role of WM in multiplication performance (e.g., Soltanlou et al., 2015), interestingly we found a dominant influence of domain-general planning on complex multiplication problem-solving in adults. Moreover, the results of regression analysis with non-aggregated WM measures were largely consistent with aggregated WM measures. Therefore, WM in both aggregated and non-aggregated analyses failed to directly account for complex multiplication performance, probably because WM exerted its influence indirectly via TOL performance, as TOL is strongly associated with the WM measures (Table 1). Indeed, the results of mediation analyses showed that this was the case (Figure 1). Both the aggregated WM measures (Figure 1) as well as the N-Back measure in the non-aggregated analysis (Figure 2) predicted planning performance, which in turn predicted multiplication performance. The non-significant effect of WM on multiplication performance can thus not be interpreted such that WM is not important for multiplication performance. Instead, it seems that WM continues to influence multiplication performance, but indirectly as part of planning. However, in a longitudinal study by Bull and colleagues (2008) on arithmetic performance in pre-school and primary school children, WM measures predicted the variance in arithmetic performance despite the effect of the TOL task. The finding of our study is partially in line with this longitudinal study, which reported a predictive role of planning, memory, and inhibition in mathematical problem solving (Bull et al., 2008). The authors reported visuospatial short-term memory and verbal WM as the best predictors, and then planning as a better predictor than inhibition. Therefore, in accordance with our study, planning predicts arithmetic variance, but in contrast to our results, WM also predicts unique variance in Bull and colleagues (2008). One reason might be the effect of age; we tested adults, while Bull and colleagues (2008) tested children. Age effects on cognitive components predicting multiplication performance have already been shown in previous studies, even with small age changes such as one school year (e.g., Soltanlou et al., 2015). Therefore, the predictors of arithmetic performance in children and adults may differ.

The other reason for the differences between the study by Bull and colleagues (2008) and our study might be the type of problems. Bull and colleagues (2008) used simple math tasks for pre-school children, but we used complex multiplication task in the current study to measure complex arithmetic computations. Multi-digit multiplication requires sequential planning and processing (mostly unit × unit, then unit × decade, and then in the case of carrying, adding the decade of first calculation to the second). This complexity might result in stronger associations with complex tasks - in this case, complex multiplication - that require different cognitive processes simultaneously. Therefore, this study shows that planning, as a more complex cognitive factor, is a better predictor of complex arithmetic performances in adults. This account is also consistent with the theoretical idea that planning has a multi-componential nature in adults including different skills, particularly visuospatial WM (e.g., Albert & Steinberg, 2011; Köstering et al., 2014). It is also in line with a recent study by Han and colleagues (2016), which found that even within updating WM tasks, the more complex task was a better predictor of complex multiplication performance in adults. In sum, on the basis of this new literature, the important influence of planning on complex multiplication and the disappearance of unique WM variance when planning is considered can be reconciled with the more recent studies and theories on the topic.

Finally, there might be a methodological reason for the differences between the study by Bull and colleagues (2008) and our study. Although the N-Back task was the only significant predictor in our mediation analysis, the performance of our participants indicated a ceiling effect, as they made few errors (Appendix C). It is conceivable that when a more difficult version of the N-Back task is used in future studies, there may be more variance, leading not only to an indirect contribution of WM via planning, but also to a direct contribution.

In summary, on the basis of the current data, we can be confident that planning plays a major role in predicting complex multiplication performance, and that WM exerts influence on complex multiplication performance indirectly via planning. However, what requires further investigation is whether WM explains the unique variance of complex multiplication performance in addition to the indirect influences exerted via planning. In our data, this is not the case, but it remains possible for other WM tasks.

The Role of Self-Regulation and Self-Control as Behavioral Factors in Multiplication Performance

Regarding multiplication RT, self-control was the only significant predictor: more self-control was associated with faster responses. One reason could be that procedural arithmetic computations (i.e., step-by-step computation during arithmetic problem solving) require concentrating and ignoring irrelevant information, which in turn rely on self-control (e.g., Gawrilow et al., 2011; Passolunghi & Siegel, 2001). Therefore, participants with more self-control were better able to suppress unwanted thoughts and to ignore distracting information, which is associated with faster computations and more rapid responses. This finding is in line with previous studies suggesting an association between self-control ability and better performance in various tasks (e.g., Gawrilow et al., 2011; Passolunghi & Siegel, 2001). Furthermore, it is consistent with previous studies suggesting that people with self-control deficits, such as patients with frontal lobe dysfunctions, exhibit slower RTs with high variability across wide range of tasks (e.g., Dimoska, Johnstone, Barry, & Clarke, 2003; Kofler et al., 2013; Senderecka, Grabowska, Szewczyk, Gerc, & Chmylak, 2012).

However, unexpectedly, self-regulation did not show any relation to complex multiplication performance in the present study. One possible reason could be the insufficiency of our measurement instrument (i.e., ADHD symptoms self-report) that was used for assessing self-regulation in healthy adults in this study. Although a strong association between ADHD symptoms and self-regulation deficits exists in individuals with ADHD (Barkley, 1997; Nigg, 2006), this association might not be as valid in healthy adults with limited variance in self-regulation.

Operand-Related and Operand-Unrelated

Interestingly, in the present study, the operand-relatedness effect was found in complex multiplication, which suggests an extension of this effect beyond the multiplication table. Although several studies in adults (e.g. Campbell, 1997; Domahs, Delazer, & Nuerk, 2006) and children (e.g., Butterworth, Marchesini, & Girelli, 2003; Koshmider & Ashcraft, 1991; Lemaire & Siegler, 1995) reported operand-relatedness effect in one-digit multiplication problems, the current study is – to the best of our knowledge – the first study that reports this effect in two-digit multiplication. In accordance with our hypothesis, because of step-by-step computations, we found that the operand-relatedness effect exists even in complex multiplication, which mostly stems from multiplying units.

Limitations of the Current Study

An important limitation of the current study is that participants were all university students and not representative of the general population. An additional limitation was the lack of latent variable approach regarding EFs as we did not assess different indicators for EF core components (i.e., inhibition, shifting, updating WM; Miyake et al., 2000) that contributed differentially to performance in the complex EF tasks. Future studies should have a similar componential approach and explore differential roles of EF components in all basic arithmetic operations in other populations and age groups as well. That might contribute to better understanding of multiplication incompetence in people with arithmetic problems.

Furthermore, in the current study, we used a visuospatial N-Back task which included letters as stimuli in the two-split grid frames. Participants were asked to remember the letters as well as their location to answer correctly. Hence, performance in our N-Back task might also recruit verbal WM capacity to some extent. It could not predict complex multiplication performance when other domain-general factors such as planning and self-control were considered. However, verbal and visuospatial WM were not disentangled in our study, which is a limitation, because some previous studies suggested a stronger involvement for verbal WM than visuospatial WM in multiplication performance (e.g., Dehaene & Cohen, 1997; Lee & Kang, 2002). Moreover, other studies indicated that both verbal and visuospatial domains of WM have an important role in multiplication performance when the difficulty of the tasks are balanced within and between participants (e.g., Cavdaroglu & Knops, 2016). Therefore, our suggestion for future studies is to control the difficulty of the tasks within and between participants as well as to properly disentangle the predictive role of verbal WM and visuospatial WM with a latent variable approach: both verbal and visuospatial WM tasks should be considered in one single study to clarify their possible incremental (direct) contributions to complex multiplication performance in adults, in addition to planning and the N-Back task. Our data suggest that visuospatial WM may not predict unique variance in addition to planning; however, that does not preclude that other domains of WM may do so.

In addition, consistent with previous research indicating that people with self-regulation deficits such as people with ADHD may have difficulties in visuospatial WM (e.g., Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Rommelse et al., 2008; Westerberg, Hirvikoski, Forssberg, & Klingberg, 2004), our data showed an association between less severe ADHD symptoms and better performance in the N-Back task in healthy adults. However, it has been shown by the other studies that ADHD patients comorbid with dyslexia seem to have deficits in verbal WM (e.g., Bental & Tirosh, 2007; Willcutt et al., 2001). Therefore, our suggestion for the future studies is to include verbal WM as well as visuospatial WM in the same study in ADHD patients with and without different comorbidities to elucidate their contributions to complex multiplication performance as well as to test whether self-regulation deficits can affect multiplication performance through verbal WM or visuospatial WM difficulties.

Another point is that since both complex multiplication and planning were the most complex tasks, a stronger correlation between the two is not surprising. This assumption needs to be tested in future studies that investigate the correlation between simple arithmetic and planning or consider additional complex tasks to examine the uniqueness of the relationship between planning and complex multiplication. Finally, as outlined above, there was a ceiling effect in our N-Back task (Appendix C). Participants made few mistakes in this task. Nevertheless, the N-Back task was the strongest predictor of planning in the mediation model (Figure 2). With a more difficult version of the task and more variance between participants, the influence on planning could be even more pronounced, and a direct influence on multiplication might be revealed, in addition to the indirect influence already shown here.

Summary and Conclusions

The findings of the present study show that planning is a better predictor for multiplication accuracy than other domain-general factors (i.e., WM, self-control, and self-regulation). This might be traced back to procedural processes that are required for both planning and complex multiplication problem solving, and may also be due to the multi-componential nature of planning which involves other domain-general factors such as WM. For both dependent variables, the hallmark construct of domain-general factors, WM, no longer explained any unique variance when other cognitive and behavioral domain-general factors were considered. However, due to the strong association between WM and planning and the results of mediation analyses, we cannot conclude that WM has no influence on multiplication performance, but rather that it influences complex multiplication performance through planning performance. The mediation analyses seem to suggest that WM is part of the planning component of EF, which may be most relevant for more complex arithmetic computations. We conclude that more domain-general factors engaged in arithmetic processing need to be taken into account when the total influence of one factor like WM is examined. However, as we argued in our limitation section, our findings are restricted to well-educated adults, namely university students, and to complex multi-digit multiplications as well as particular assessment tasks and the complexity of the version used. Whether these results generalize to other age groups, less skilled individuals, and less complex problems and other ways to assess WM and planning as well as other control measures remains an important question for follow-up studies. Nevertheless, we argue that our results strongly suggest that not only WM, but other domain-general factors need to be considered to better understand the foundations of arithmetic performance.

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Competing Interests

The authors have declared that no competing interests exist.

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References

Agostino, A., Johnson, J., & Pascual-Leone, J. (2010). Executive functions underlying multiplicative reasoning: Problem type matters. *Journal of Experimental Child Psychology, 105*(4), 286-305. doi:10.1016/j.jecp.2009.09.006

Albert, D., & Steinberg, L. (2011). Age differences in strategic planning as indexed by the Tower of London. *Child Development, 82*(5), 1501-1517. doi:10.1111/j.1467-8624.2011.01613.x

Ashcraft, M. H. (1982). The development of mental arithmetic: A chronometric approach. *Developmental Review, 2*(3), 213-236. doi:10.1016/0273-2297(82)90012-0

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology, 63*, 1-29. doi:10.1146/annurev-psych-120710-100422

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Baddeley, A. D., & Hitch, G. (1974). Working memory. *Psychology of Learning and Motivation, 8*, 47-89. doi:10.1016/S0079-7421(08)60452-1

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*(1), 65-94. doi:10.1037/0033-2909.121.1.65

Baron, R. M., & Kenny, D. A. (1986). The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of Personality and Social Psychology, 51*, 1173-1182. doi:10.1037/0022-3514.51.6.1173

Barrouillet, P., & Lépine, R. (2005). Working memory and children's use of retrieval to solve addition problems. *Journal of Experimental Child Psychology, 91*(3), 183-204. doi:10.1016/j.jecp.2005.03.002

Barrouillet, P., Mignon, M., & Thevenot, C. (2008). Strategies in subtraction problem solving in children. *Journal of Experimental Child Psychology, 99*(4), 233-251. doi:10.1016/j.jecp.2007.12.001

Baumeister, R. F. (2002). Ego depletion and self-control failure: An energy model of the self's executive function. *Self and Identity, 1*(2), 129-136. doi:10.1080/152988602317319302

Bertrams, A., & Dickhäuser, O. (2009). Messung dispositioneller Selbstkontroll-Kapazität: Eine deutsche Adaptation der Kurzform der Self-Control Scale (SCS-KD). *Diagnostica, 55*(1), 2-10. doi:10.1026/0012-1924.55.1.2

Bental, B., & Tirosh, E. (2007). The relationship between attention, executive functions and reading domain abilities in attention deficit hyperactivity disorder and reading disorder: A comparative study. *Journal of Child Psychology and Psychiatry, and Allied Disciplines, 48*(5), 455-463. doi:10.1111/j.1469-7610.2006.01710.x

Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child Development, 81*(6), 1641-1660. doi:10.1111/j.1467-8624.2010.01499.x

Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development, 78*(2), 647-663. doi:10.1111/j.1467-8624.2007.01019.x

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology, 33*(3), 205-228. doi:10.1080/87565640801982312

Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives, 8*(1), 36-41. doi:10.1111/cdep.12059

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology, 19*(3), 273-293. doi:10.1207/S15326942DN1903_3

Butterworth, B., Marchesini, N., & Girelli, L. (2003). Basic multiplication combinations: Passive storage or dynamic reorganization? In A. J. Baroody & A. Dowker (Eds.), *The development of arithmetic concepts and skills: Constructive adaptive expertise* (pp. 187-201). Mahwah, NJ, USA: Lawrence Erlbaum Associates.

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From brain to education. *Science, 332*(6033), 1049-1053. doi:10.1126/science.1201536

Byrnes, J. P., & Wasik, B. A. (2009). Factors predictive of mathematics achievement in kindergarten, first and third grades: An opportunity–propensity analysis. *Contemporary Educational Psychology, 34*(2), 167-183. doi:10.1016/j.cedpsych.2009.01.002

Campbell, J. I. D. (1987). Network interference and mental multiplication. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13*(1), 109-123. doi:10.1037/0278-7393.13.1.109

Campbell, J. I. D. (1997). On the relation between skilled performance of simple division and multiplication. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23*(5), 1140-1159. doi:10.1037/0278-7393.23.5.1140

Campbell, J. I. D., & Graham, D. J. (1985). Mental multiplication skill: Structure, process, and acquisition. *Canadian Journal of Psychology/Revue canadienne de psychologie, 39*(2), 338-366. doi:10.1037/h0080065

Cavdaroglu, S., & Knops, A. (2016). Mental subtraction and multiplication recruit both phonological and visuospatial resources: Evidence from a symmetric dual-task design. *Psychological Research, 80*(4), 608-624. doi:10.1007/s00426-015-0667-8

Cipora, K., Hohol, M., Nuerk, H.-C., Willmes, K., Brożek, B., Kucharzyk, B., & Nęcka, E. (2016). Professional mathematicians differ from controls in their spatial-numerical associations. *Psychological Research, 80*, 710-726. doi:10.1007/s00426-015-0677-6

Clark, C. A., Pritchard, V. E., & Woodward, L. J. (2010). Preschool executive functioning abilities predict early mathematics achievement. *Developmental Psychology, 46*(5), 1176-1191. doi:10.1037/a0019672

Conners, C. K., Erhardt, D., & Sparrow, E. P. (1999). Conners' adult ADHD rating scales (CAARS). North Tonawanda, NY, USA: Multi Health System Inc.

Cooney, J. B., Swanson, H. L., & Ladd, S. F. (1988). Acquisition of mental multiplication skill: Evidence for the transition between counting and retrieval strategies. *Cognition and Instruction, 5*(4), 323-345. doi:10.1207/s1532690xci0504_5

Corsi, P. M. (1973). Human memory and the medial temporal region of the brain. *Dissertation Abstracts International: Section B. The Sciences and Engineering, 34*, 891.

Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in Neuroscience and Education, 3*(2), 63-68. doi:10.1016/j.tine.2013.12.001

Dehaene, S., & Cohen, L. (1997). Cerebral pathways for calculation: Double dissociation between rote verbal and quantitative knowledge of arithmetic. *Cortex, 33*(2), 219-250. doi:10.1016/S0010-9452(08)70002-9

Das, J. P., Naglieri, J. A., & Kirby, J. R. (1994). *Assessment of cognitive processes: The PASS theory of intelligence*. Needham Heights, MA, USA: Allyn & Bacon.

De Smedt, B., Janssen, R., Bouwens, K., Verschaffel, L., Boets, B., & Ghesquière, P. (2009). Working memory and individual differences in mathematics achievement: A longitudinal study from first grade to second grade. *Journal of Experimental Child Psychology, 103*(2), 186-201. doi:10.1016/j.jecp.2009.01.004

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135-168. doi:10.1146/annurev-psych-113011-143750

Dietrich, J. F., Huber, S., & Nuerk, H. C. (2015). Methodological aspects to be considered when measuring the approximate number system (ANS)–A research review. *Frontiers in Psychology, 6*, Article 295. doi:10.3389/fpsyg.2015.00295

Dimoska, A., Johnstone, S. J., Barry, R. J., & Clarke, A. R. (2003). Inhibitory motor control in children with attention-deficit/ hyperactivity disorder: Event-related potentials in the stop-signal paradigm. *Biological Psychiatry, 54*(12), 1345-1354. doi:10.1016/S0006-3223(03)00703-0

Domahs, F., Delazer, M., & Nuerk, H.-C. (2006). What makes multiplication facts difficult: Problem size or neighborhood consistency? *Experimental Psychology, 53*(4), 275-282. doi:10.1027/1618-3169.53.4.275

Duckworth, A. L., Peterson, C., Matthews, M. D., & Kelly, D. R. (2007). Grit: Perseverance and passion for long-term goals. *Journal of Personality and Social Psychology, 92*(6), 1087-1101. doi:10.1037/0022-3514.92.6.1087

Fayol, M., & Thevenot, C. (2012). The use of procedural knowledge in simple addition and subtraction problems. *Cognition, 123*(3), 392-403. doi:10.1016/j.cognition.2012.02.008

Friso-van den Bos, I., van der Ven, S. H., Kroesbergen, E. H., & van Luit, J. E. (2013). Working memory and mathematics in primary school children: A meta-analysis. *Educational Research Review, 10*, 29-44. doi:10.1016/j.edurev.2013.05.003

Gathercole, S. E., Pickering, S. J., Knight, C., & Stegmann, Z. (2004). Working memory skills and educational attainment: Evidence from national curriculum assessments at 7 and 14 years of age. *Applied Cognitive Psychology, 18*(1), 1-16. doi:10.1002/acp.934

Gawrilow, C., Gollwitzer, P. M., & Oettingen, G. (2011). If-then plans benefit executive functions in children with ADHD. *Journal of Social and Clinical Psychology, 30*(6), 616-646. doi:10.1521/jscp.2011.30.6.616

Gilhooly, K. J. (2005). Working memory and planning. In R. Morris & G. Ward (Eds.), *The cognitive psychology of planning* (pp. 71-88). New York, NY, USA: Psychology Press.

Goela, V., Pullara, S. D., & Grafman, J. (2001). A computational model of frontal lobe dysfunction: Working memory and the Tower of Hanoi task. *Cognitive Science, 25*(2), 287-313. doi:10.1207/s15516709cog2502_4

Han, C.-C., Yang, T.-H., Lin, C.-Y., & Yen, N.-S. (2016). Memory updating and mental arithmetic. *Frontiers in Psychology, 7*, Article 72. doi:10.3389/fpsyg.2016.00072

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application* (pp. 653-675). Cambridge, MA, USA: The MIT Press.

Hofmann, W., Friese, M., Schmeichel, B. J., & Baddeley, A. D. (2011). Working memory and self-regulation. In K. D. Vohs & R. F. Baumeister (Eds.), *Handbook of self-regulation: Research, theory, and applications* (2nd ed., pp. 204-225). New York, NY, USA: The Guilford Press.

Hofmann, W., Schmeichel, B. J., & Baddeley, A. D. (2012). Executive functions and self-regulation. *Trends in Cognitive Sciences, 16*(3), 174-180. doi:10.1016/j.tics.2012.01.006

Imbo, I., & LeFevre, J. A. (2010). The role of phonological and visual working memory in complex arithmetic for Chinese- and Canadian-educated adults. *Memory & Cognition, 38*(2), 176-185. doi:10.3758/MC.38.2.176

Kaller, C. P., Rahm, B., Köstering, L., & Unterrainer, J. M. (2011). Reviewing the impact of problem structure on planning: A software tool for analyzing tower tasks. *Behavioural Brain Research, 216*(1), 1-8. doi:10.1016/j.bbr.2010.07.029

Kane, M. J., Bleckley, M. K., Conway, A. R., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General, 130*(2), 169-183. doi:10.1037/0096-3445.130.2.169

Kane, M. J., Conway, A. R., Miura, T. K., & Colflesh, G. J. (2007). Working memory, attention control, and the N-back task: A question of construct validity. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(3), 615-622. doi:10.1037/0278-7393.33.3.615

Kirby, J. R., & Ashman, A. F. (1984). Planning skills and mathematics achievement: Implications regarding learning disability. *Journal of Psychoeducational Assessment, 2*(1), 9-22. doi:10.1177/073428298400200102

Kofler, M. J., Rapport, M. D., Sarver, D. E., Raiker, J. S., Orban, S. A., Friedman, L. M., & Kolomeyer, E. G. (2013). Reaction time variability in ADHD: A meta-analytic review of 319 studies. *Clinical Psychology Review, 33*(6), 795-811. doi:10.1016/j.cpr.2013.06.001

Koshmider, J. W., & Ashcraft, M. H. (1991). The development of children's mental multiplication skills. *Journal of Experimental Child Psychology, 51*(1), 53-89. doi:10.1016/0022-0965(91)90077-6

Köstering, L., Stahl, C., Leonhart, R., Weiller, C., & Kaller, C. P. (2014). Development of planning abilities in normal aging: Differential effects of specific cognitive demands. *Developmental Psychology, 50*(1), 293-303. doi:10.1037/a0032467

Lee, K. M., & Kang, S. Y. (2002). Arithmetic operation and working memory: Differential suppression in dual tasks. *Cognition, 83*(3), B63-B68. doi:10.1016/S0010-0277(02)00010-0

Lee, K., Ng, E. L., & Ng, S. F. (2009). The contributions of working memory and executive functioning to problem representation and solution generation in algebraic word problems. *Journal of Educational Psychology, 101*(2), 373-387. doi:10.1037/a0013843

Leiner, D. J. (2014). SoSci Survey (Version 2.5.00-i) [Computer software]. Available from http://www.soscisurvey.com

Lemaire, P., & Siegler, R. S. (1995). Four aspects of strategic change: Contributions to children's learning of multiplication. *Journal of Experimental Psychology: General, 124*(1), 83-97. doi:10.1037/0096-3445.124.1.83

Libertus, M. E., Feigenson, L., & Halberda, J. (2011). Preschool acuity of the approximate number system correlates with school math ability. *Developmental Science, 14*(6), 1292-1300. doi:10.1111/j.1467-7687.2011.01080.x

Mabbott, D. J., & Bisanz, J. (2003). Developmental change and individual differences in children's multiplication. *Child Development, 74*(4), 1091-1107. doi:10.1111/1467-8624.00594

Martinussen, R., Hayden, J., Hogg-Johnson, S., & Tannock, R. (2005). A meta-analysis of working memory impairments in children with attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child and Adolescent Psychiatry, 44*(4), 377-384. doi:10.1097/01.chi.0000153228.72591.73

Menon, V. (2016). Working memory in children's math learning and its disruption in dyscalculia. *Current Opinion in Behavioral Sciences, 10*, 125-132. doi:10.1016/j.cobeha.2016.05.014

McClelland, M. M., & Cameron, C. E. (2012). Self-regulation in early childhood: Improving conceptual clarity and developing ecologically valid measures. *Child Development Perspectives, 6*(2), 136-142. doi:10.1111/j.1750-8606.2011.00191.x

McClelland, M. M., Cameron, C. E., Connor, C. M., Farris, C. L., Jewkes, A. M., & Morrison, F. J. (2007). Links between behavioral regulation and preschoolers' literacy, vocabulary, and math skills. *Developmental Psychology, 43*(4), 947-959. doi:10.1037/0012-1649.43.4.947

McClelland, M. M., Geldhof, G. J., Cameron, C. E., & Wanless, S. B. (2015). Development and self-regulation. In W. F. Overton & P. C. M. Molenaar (Eds.), *Theory and method: Handbook of child psychology and developmental science* (7th ed., Vol. 1., pp. 523-565). Hoboken, NJ, USA: Wiley.

Meyer, M. L., Salimpoor, V. N., Wu, S. S., Geary, D. C., & Menon, V. (2010). Differential contribution of specific working memory components to mathematics achievement in 2nd and 3rd graders. *Learning and Individual Differences, 20*(2), 101-109. doi:10.1016/j.lindif.2009.08.004

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*(1), 167-202. doi:10.1146/annurev.neuro.24.1.167

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*(1), 49-100. doi:10.1006/cogp.1999.0734

Mueller, S. T. (2013). The Psychology Experiment Building Language (Version 0.13) [Computer software]. Available from http://pebl.sourceforge.net

Naglieri, J. A., & Johnson, D. (2000). Effectiveness of a cognitive strategy intervention in improving arithmetic computation based on the PASS theory. *Journal of Learning Disabilities, 33*(6), 591-597. doi:10.1177/002221940003300607

Newell, A., & Simon, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ, USA: Prentice-Hall.

Nigg, J. T. (2006). *What causes ADHD? Understanding what goes wrong and why*. New York, NY, USA: The Guilford Press.

Norman, D. A., & Shallice, T. (1986). *Attention to action: Willed and automatic control of behavior*. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation* (pp. 1-18). Boston, MA, USA: Springer.

Nuerk, H.-C., Weger, U., & Willmes, K. (2001). Decade breaks in the mental number line? Putting the tens and units back in different bins. *Cognition, 82*(1), B25-B33. doi:10.1016/S0010-0277(01)00142-1

Oberauer, K. (2001). Removing irrelevant information from working memory: A cognitive aging study with the modified Sternberg task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*(4), 948-957. doi:10.1037/0278-7393.27.4.948

Parsons, S., & Bynner, J. (2005). *Does numeracy matter more?* London, United Kingdom: Institute of Education.

Passolunghi, M. C., & Siegel, L. S. (2001). Short-term memory, working memory, and inhibitory control in children with difficulties in arithmetic problem solving. *Journal of Experimental Child Psychology, 80*(1), 44-57. doi:10.1006/jecp.2000.2626

Peirce, J. W. (2009). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics, 2*, Article 10.

Peng, P., Namkung, J., Barnes, M., & Sun, C. (2016). A meta-analysis of mathematics and working memory: Moderating effects of working memory domain, type of mathematics skill, and sample characteristics. *Journal of Educational Psychology, 108*, 455-473. doi:10.1037/edu0000079

Raghubar, K. P., Barnes, M. A., & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learning and Individual Differences, 20*(2), 110-122. doi:10.1016/j.lindif.2009.10.005

Rommelse, N. N. J., Van der Stigchel, S., Witlox, J., Geldof, C., Deijen, J. B., Theeuwes, J., . . . Sergeant, J. A. (2008). Deficits in visuo-spatial working memory, inhibition and oculomotor control in boys with ADHD and their non-affected brothers. *Journal of Neural Transmission, 115*(2), 249-260. doi:10.1007/s00702-007-0865-7

Seitz, K., & Schumann-Hengsteler, R. (2000). Mental multiplication and working memory. *The European Journal of Cognitive Psychology, 12*(4), 552-570. doi:10.1080/095414400750050231

Senderecka, M., Grabowska, A., Szewczyk, J., Gerc, K., & Chmylak, R. (2012). Response inhibition of children with ADHD in the stop-signal task: An event-related potential study. *International Journal of Psychophysiology, 85*(1), 93-105. doi:10.1016/j.ijpsycho.2011.05.007

Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal Society of London: Series B. Biological Sciences, 298*(1089), 199-209. doi:10.1098/rstb.1982.0082

Siegler, R. S. (1988). Strategy choice procedures and the development of multiplication skill. *Journal of Experimental Psychology: General, 117*(3), 258-275. doi:10.1037/0096-3445.117.3.258

Siegler, R. S., & Opfer, J. E. (2003). The development of numerical estimation: Evidence for multiple representations of numerical quantity. *Psychological Science, 14*(3), 237-243. doi:10.1111/1467-9280.02438

Sikora, D. M., Haley, P., Edwards, J., & Butler, R. W. (2002). Tower of London test performance in children with poor arithmetic skills. *Developmental Neuropsychology, 21*(3), 243-254. doi:10.1207/S15326942DN2103_2

Simon, H. A. (1978). Information-processing theory of human problem solving. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes* (pp. 271-295). Hillsdale, NJ, USA: Erlbaum.

Soltanlou, M., Pixner, S., & Nuerk, H.-C. (2015). Contribution of working memory in multiplication fact network in children may shift from verbal to visuo-spatial: A longitudinal investigation. *Frontiers in Psychology, 6*, Article 1062. doi:10.3389/fpsyg.2015.01062

Stazyk, E. H., Ashcraft, M. H., & Hamann, M. S. (1982). A network approach to mental multiplication. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8*(4), 320-335. doi:10.1037/0278-7393.8.4.320

Swanson, H. L., Jerman, O., & Zheng, X. (2008). Growth in working memory and mathematical problem solving in children at risk and not at risk for serious math difficulties. *Journal of Educational Psychology, 100*(2), 343-379. doi:10.1037/0022-0663.100.2.343

Swanson, H. L., & Jerman, O. (2006). Math disabilities: A selective meta-analysis of the literature. *Review of Educational Research, 76*, 249-274. doi:10.3102/00346543076002249

Szücs, D., Devine, A., Soltesz, F., Nobes, A., & Gabriel, F. (2013). Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment. *Cortex, 49*(10), 2674-2688. doi:10.1016/j.cortex.2013.06.007

Tangney, J. P., Baumeister, R. F., & Boone, A. L. (2004). High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *Journal of Personality, 72*(2), 271-324. doi:10.1111/j.0022-3506.2004.00263.x

Tronsky, L. N. (2005). Strategy use, the development of automaticity, and working memory involvement in complex multiplication. *Memory & Cognition, 33*(5), 927-940. doi:10.3758/BF03193086

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working memory capacity and the antisaccade task: Individual differences in voluntary saccade control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*(6), 1302-1321. doi:10.1037/0278-7393.30.6.1302

Unterrainer, J. M., & Owen, A. M. (2006). Planning and problem solving: From neuropsychology to functional neuroimaging. *Journal of Physiology – Paris, 99*(4-6), 308-317. doi:10.1016/j.jphysparis.2006.03.014

Van der Ven, S. H. G., Kroesbergen, E. H., Boom, J., & Leseman, P. P. M. (2012). The development of executive functions and early mathematics: A dynamic relationship. *The British Journal of Educational Psychology, 82*(1), 100-119. doi:10.1111/j.2044-8279.2011.02035.x

Von Aster, M. G., & Shalev, R. S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology, 49*(11), 868-873. doi:10.1111/j.1469-8749.2007.00868.x

Westerberg, H., Hirvikoski, T., Forssberg, H., & Klingberg, T. (2004). Visuo-spatial working memory span: A sensitive measure of cognitive deficits in children with ADHD. *Child Neuropsychology, 10*(3), 155-161. doi:10.1080/09297040409609806

Willcutt, E. G., Pennington, B. F., Boada, R., Ogline, J. S., Tunick, R. A., Chhabildas, N. A., & Olson, R. K. (2001). A comparison of the cognitive deficits in reading disability and attention-deficit/hyperactivity disorder. *Journal of Abnormal Psychology, 110*(1), 157-172. doi:10.1037/0021-843X.110.1.157

Williams, J. (2003). *The Skills for Life survey: A national needs and impact survey of literacy, numeracy and ICT skills*. London, United Kingdom: The Stationery Office, Department of Education and Skills.

Zelazo, P. D., Carter, A., Reznick, J. S., & Frye, D. (1997). Early development of executive function: A problem-solving framework. *Review of General Psychology, 1*(2), 198-226. doi:10.1037/1089-2680.1.2.198

Zhou, X., Chen, C., Zang, Y., Dong, Q., Chen, C., Qiao, S., & Gong, Q. (2007). Dissociated brain organization for single-digit addition and multiplication. *NeuroImage, 35*(2), 871-880. doi:10.1016/j.neuroimage.2006.12.017

Appendices

Appendix A: Sample Background Characteristic

Table A.1

Sample Background Characteristic

Variables[a]	Entire Sample (*N* = 40)
***M* Age in years (*SD*)**	20.95 (1.98)
Gender	
Female	33
Handedness	
Right	39
Field of study (%)	
Psychology	40
Cognitive Science	37
Medicine	8
Media	2
Educational Science	8
Environment Science	5
Participation payment	
Course credit	16
Money	24
Math score in University entrance exam	
below 8	7
8 to 11	12
12 to 15	21

[a]Information obtained from background online questionnaire.

Appendix B: Complex Multiplication Stimuli

Table B.1

Complex Multiplication Stimuli

			Incorrect Solutions	
First operand	Second operand	Correct Solutions	Operand-related[a] Errors	Operand-unrelated Errors
4	19	76	72	90
13	7	91	84	86
14	6	84	98	80
17	5	85	90	82
18	3	54	57	59
3	19	57	76	64
5	13	65	70	68
16	3	48	51	34
7	14	98	84	79
15	6	90	75	94
18	4	72	68	91
5	19	95	90	88

[a]operand-related errors are matched by Mean, Mean distance difference from correct solutions and parity to operand-unrelated errors.

Appendix C: Ceiling/Floor Effect in Cognitive and Behavioral Measures

Table C.1

Ceiling/Floor Effect in Cognitive and Behavioral Measures

Variable	*M* (*SD*)	*K-S*[a]	*Skewness*	*Kurtosis*
Multiplication Error (%)	0.18 (0.11)	.03	1.02	1.18
Multiplication RT (ms)	3100 (560)	.20	0.27	0.19
Self-Regulation	13.62 (5.57)	.13	0.82	1.15
Self-Control	41.42 (8.74)	.20	0.18	-0.36
N-Back Accuracy	0.87 (0.09)	.01	-1.79	3.98
Corsi Forward	5.50 (0.65)	.13	0.22	-0.68
Corsi Backward	6.05 (0.81)	.00	0.95	1.39
Planning Accuracy	0.73 (0.13)	.00	-0.80	0.02

Note. $N = 40$.

[a]Kolmogorov-Smirnov p-values.

Appendix D: Path Model Statistics for TOL Accuracy as Mediator of Aggregated and Non-Aggregated WM Measures and Multiplication Errors (%)

Table D.1

Path Model Statistics for TOL Accuracy as Mediator of Aggregated WM Measures and Multiplication Errors (%)

	Dependent Variable: Multiplication Errors (%)				
Variable	**Path Identifier**	***B***	**Standardized *B***	***SE***	***p***
TOL[a] Accuracy					
	b	-.29	-.35	.13	.03
WM[b]					
	a	.03	.50	.01	.00
	c	-.01	-.33	.01	.04
	c´	-.01	-.15	.01	.36

Note. N = 40.
[a]TOL = Tower of London. [b]Aggregated WM measures.

Table D.2

Path Model Statistics for TOL Accuracy as Mediator of Non-Aggregated WM Measures and Multiplication Errors (%)

	Dependent Variable: Multiplication Errors (%)				
Variable	**Path Identifier**	***B***	**Standardized *B***	***SE***	***p***
TOL[a] Accuracy					
	b	-.28	-.35	.14	.05
N-Back Accuracy					
	c	-.27	-.24	.17	.12
	c´	.66	.48	.19	.00
	c´´	-.09	-.08	.20	.66
Corsi-Block Forward					
	d	-.03	-.18	.03	.24
	d´	.04	.20	.03	.14
	d´´	-.02	-.11	.03	.54
Corsi-Block Backward					
	e	-.00	-.03	.02	.87
	e´	.00	.01	.02	.93
	e´´	-.00	-.02	.02	.90

Note. N = 40.
[a]TOL = Tower of London

Appendix E: Path Model Statistics for Aggregated and Non-Aggregated WM Measures as Mediator of TOL Accuracy and Multiplication Errors (%)

i.

ii.

iii.

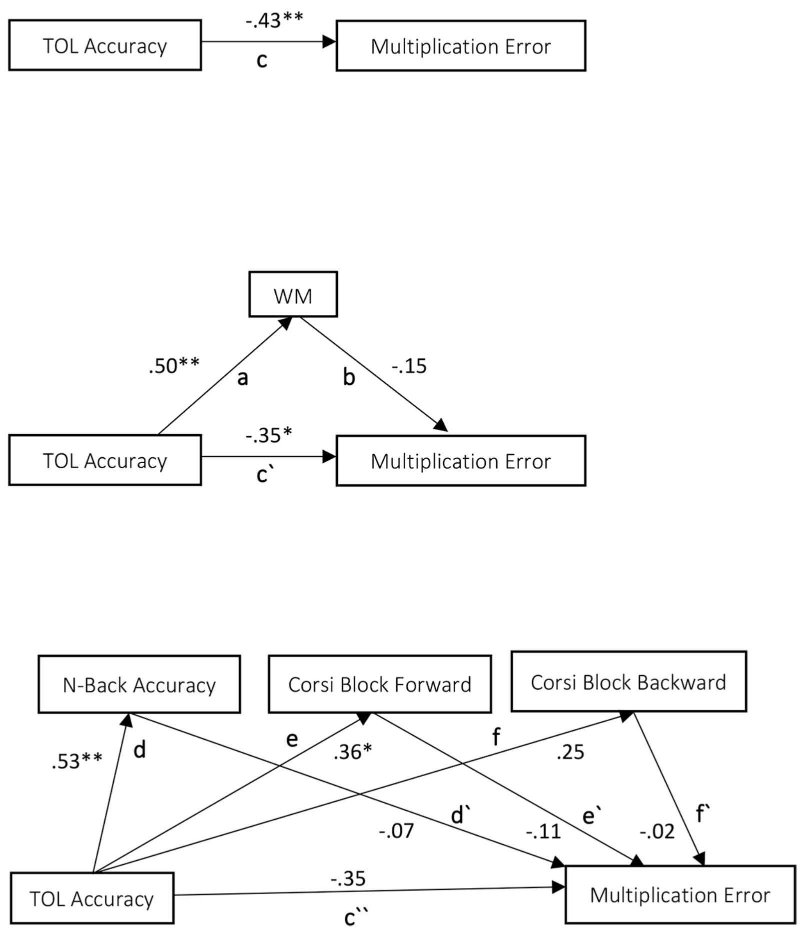

Figure E1. Path analysis model tested the mediator role of aggregated and non-aggregated WM measures in the relationship between the independent variables (TOL Accuracy) and the dependent variable (multiplication errors). (i) Path *c* tested the relationship between the independent variable and the dependent variable without controlling for aggregated and non-aggregated WM measures. (ii) Path *a* tested the relationship between the aggregated WM measures as a mediator and the independent variable and path *c´* tested the relationship between the independent variable and the dependent variable with controlling for aggregated WM measures. (iii) Paths *d, e* and *f* tested the relationships between the non-aggregated WM measures as mediators and the independent variable and path c´´ tested the relationship between the independent variable and the dependent variable with controlling for non-aggregated WM measures. Numbers represent the standardized regression coefficients. Multiplication Error = dependent variable, TOL Accuracy= independent variable (planning accuracy), N-Back = mediator, Corsi-Block Forward = mediator, Corsi-Block Backward = mediator.

**p* < .05. ***p* < .01.

Table E1

Path Model Statistics for Aggregated and Non-Aggregated WM Measures as Mediators of Planning and Multiplication Errors (%)

	Dependent Variable: Multiplication Errors (%)				
Variable	**Path Identifier**	***B***	**Standardized *B***	***SE***	***p***
TOL[a] Accuracy					
	a	8.51	.50	2.38	.00
	c	-.35	-.43	.12	.00
	c´	-.29	-.35	.13	.03
	c´´	-.28	-.35	.14	.05
WM[b]					
	b	-.01	-.15	.01	.36
N-Back Accuracy					
	d	.37	.53	.09	.00
	d´	-.09	-.07	.20	.67
Corsi-Block Forward					
	e	1.76	.36	.72	.01
	e´	-.02	-.11	.03	.53
Corsi-Block Backward					
	f	1.50	.25	.94	.11
	f´	.00	-.02	.02	.90

Note. *N* = 40.

[a]TOL = Tower of London. [b]Aggregated WM measures.

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