Research Article https://doi.org/10.12973/ejper.7.2.83

European Journal of Psychology and Educational Research

Volume 7, Issue 2, 83 - 92.

ISSN: 2589-949X

http://www.ejper.com

The Effect of Problem Size on Children's Arithmetic Performance: Interference Control in Working Memory

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Received: February 11, 2024 ▪ Revised: April 25, 2024 ▪ Accepted: May 26, 2024

Abstract: This study investigates school-age children's arithmetic operations performance while solving larger-size problems which produces interferences in memory. Complex problems can trigger competing responses in working memory, which are irrelevant to a task goal and increase the likelihood of interference from previously learned problems (De Visscher et al., 2018). Interference control in working memory is required to be able to manage and suppress irrelevant information while performing cognitive tasks such as arithmetic problem-solving (Unsworth, 2010). The present study explores potential cognitive processes while performing arithmetic tasks and emphasizes the important role of interference control for better performance in such tasks. This study applied a mixed-effect model experimental design. Forty-four primary school children were involved in the study. The results showed that children's performance in terms of correct responses was similar for both small-size and large-size problems. However, their response speed was significantly lower in larger-size problems, which created more interference in working memory.

Keywords: *Arithmetic operations, problem-size effect, working memory, interference control.*

To cite this article: Boz, S. (2024). The effect of problem size on children's arithmetic performance: Interference control in working memory. *European Journal of Psychology and Educational Research*, *7*(2), 83-92. https://doi.org/10.12973/ejper.7.2.83

Introduction

Proficiency in basic arithmetic operations is a fundamental cornerstone of mathematics (math) learning; hence, four-operation problems are part of the math curriculum for most at the primary school level (Boz & Erden, 2021; Ministry of National Education (2018). According to Berg (2008), difficulty in this area contributes to a negative impact on children's educational development. Therefore, understanding the reasons why they struggle in arithmetic operations can be considered a significant aspect when planning to focus on how to improve their math skills. From this perspective, possible cognitive processes of arithmetic performance in children at the primary school level were included in this study to provide a broad view of exploration in math learning.

All processes of understanding numbers and counting involve cognitive mechanisms (Hubber et al., 2014) where children store, monitor and manipulate information in their memory and those processes are related to working memory (WM) (De Stefano & LeFevre, 2004; Raghubar et al., 2010). An interference framework of WM (Cowan, 1999; Oberauer, 2001) has been examined to discover the role of WM in arithmetic operation tasks since interference control allows children to suppress distractions or irrelevant information and maintain their attention on relevant information for a task goal, which is crucial for solving complex arithmetic problems (Campbell & Oliphant, 1992). Specifically, this framework (Cowan, 1999; Oberauer, 2001) provides a distinctive structure to understand individual differences in WM performance. For instance, individuals who have a better ability to resist interference, as defined by interference control models, may exhibit better WM performance and potentially better mathematical skills (Kane & Engle, 2000).

Previous research demonstrates that arithmetic problems are more associated with interference control in WM during information processing in problem-solving tasks (e.g. De Visscher & Noël, 2016). Therefore, involving the interference framework of WM in this study presents a highly promising approach (Marton et al., 2014) to understand how cognitive abilities and math performance are correlated with each other. From this perspective, the main purpose of this study is to investigate how school-age children perform when they are exposed to interferences during arithmetic

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tasks. Within the exploration of the role of interference control in arithmetic skills, this study can provide valuable insights into educational strategies to support children's development in math.

Literature Review

Arithmetic Skills

The most important goal of math education is to enable students to become problem solvers. Due to this goal, problem-solving is a main activity in teaching math (Schoenfeld, 1989; Silver, 1985). Since arithmetic operations are the most important prerequisite for problem-solving, it has been the core skill of math curricula for primary school learners. Difficulties in this skill pose considerable problems for children's development in math. For instance, if students are not able to solve simple addition problems, they cannot perform more complex addition problems (Geary & Brown, 1991), and if they do not succeed in addition problems, they cannot develop their multiplication skills (Cooney et al., 1988).

Calculation abilities form a basis for advanced mathematical skills (Ashcraft, 1992) because proficiency and fluency in arithmetic operations when making calculations and gaining knowledge about strategies, build strong foundations in basic math skills before advancing to complex math problems (Geary, 2003). Fuchs et al. (2008) proved that there were conceptual relationships between problem solving and arithmetic skills. In this perspective, arithmetic skills and fluency are assumed to be prerequisites of math skills. A variety of cognitive processes and strategies are required to accomplish these objectives. For instance, an answer of simple addition is retrieved from memory, and procedural strategies, such as counting or decomposition, are used while doing complex addition (Hubber et al., 2014). The activities, such as the ability to store, monitor, and manipulate information, which are required for arithmetic operations, are related to WM (De Stefano & LeFevre, 2004; Raghubar et al., 2010).

Recent research (Ji & Guo, 2023) has also demonstrated that children who have strong WM skills can perform better in math, underlying the relationship between arithmetic skills and cognitive processes. WM skills are required to manage multiple steps in complex calculations and solve problems effectively and more accurately. These findings assure that supporting WM development can enhance school-age children's math proficiency (Sala & Gobet, 2017; Shipstead et al., 2012).

Interference Framework of WM and Math

WM is the system used for short-term storage and where cognitive task-related information, such as reasoning, thinking, and problem-solving, is manipulated throughout performing the task (Baddeley, 1992). The capacity of WM is limited, and this characteristic of WM can lead to poor performance in cognitive tasks. It is possibly caused by inadequate control of irrelevant information (Hasher & Zacks, 1988). When the incoming information exceeds the available capacity, individuals may experience limitations in holding information in memory and updating the items during the processing of new information. This may result in difficulties in differentiating old information from new information. This phenomenon is called proactive interference (Jonides & Nee, 2006) when previous information or traces in memory can interfere with the processing of new information during task performance. For example, when an individual must deal with this kind of distraction in memory while performing a task, such as counting or reading, representations of the distractor are encoded into WM and create interference (Engle et al., 1999; Oberauer et al., 2012; Oberauer & Lewandowsky, 2008).

The information must be suppressed when it distracts current or new information. Otherwise, representations of relevant information will interfere with the irrelevant information, which will then be recalled instead of the target items (Palladino, 2006). Since relevant and irrelevant information compete to have access to WM during the processing, interference control is required to resist the irrelevant information to prevent it from taking first place or to remove it once it enters the memory (Hasher et al., 2007; Unsworth & Engle, 2007). Learners who are able to control this mechanism can perform better in cognitive tasks.

Regarding the context of math, learning difficulties in complex topics derive from previously learned knowledge and procedures (Lee & Lee, 2019). For example, a person with misconceptions is more prone to choosing an improper strategy to solve a math problem in which well-entrenched heuristics or strategies substitute new information that seems to share a similar structure (McNeil & Alibali, 2005). Therefore, the efficiency of memory representations of arithmetic problems relies on problems which were learned previously (Nairne, 1990). For instance, a problem that is mostly similar to a previously learned problem is a strong element for the occurrence of interference during the storage stage and thus will reduce the possibility of retrieval of relevant items from the memory (De Visscher & Noël, 2014). This phenomenon can impact the efficiency and accuracy of problem-solving, probably resulting in decreased performance and more errors (Dotan & Zviran-Ginat, 2022). This notion is also supported by Oberauer and Kliegl (2006), in such that when two similar items with overlapping features need to be stored in memory, the features of representatives are more prone to interacting with each other, leading to interference. As an example, since multiplication is a repeated addition of equal quantities, it shares common cognitive skills with addition. The simultaneous processing for both addition and multiplication contributes to interference, potential retrieval errors and/or slow processing.

There is a common consensus that arithmetic facts are constructed in interrelating structures in long-term memory (e.g. Campbell, 1995) and that when one encounters an arithmetic problem, pertinent incorrect answers might be activated. As a result, the cluster of related but incorrect answers creates competition with correct answers which interfere with the process of retrieving correct answers (Campbell & Tarling, 1996). This interference results in failures and slow processing of information (Noël & De Visscher, 2018).

Tasks with increased complexity typically involve multiple steps and are therefore more susceptible to interference. This highlights the significance of monitoring the progression of a task, understanding which steps have been completed, and providing accurate calculations at each step. Therefore, monitoring skills can be an indicator of solving multi-step mathematical problems. However, monitoring is highly demanding on WM because information is maintained and manipulated while its quality is evaluated simultaneously (Morris & Jones, 1990). As an example, when an individual is performing arithmetic operations, retaining the intermediate result is required. During this process, recalling and employing arithmetic procedures could potentially be disrupted by proactive interference. Additionally, larger problems are more susceptible to generating incorrect answers due to the problem size effect. The typical explanation for this problem size effect is that smaller problems (e.g., simple additions, single-digit multiplication) are more commonly solved through the retrieval strategy compared to larger problems (e.g., complex subtraction, multi-digit problems) (Thevenot et al., 2010; Zbrodoff & Logan, 2005). As procedural strategies which require previously learned information are employed to solve larger problems, the weight of proactive interference increases. In addition to this, the complexity and the large quantity of information contribute to the increase in binding numerical values to their corresponding operation types (Oberauer et al., 2012). Dynamic binding is needed for the mechanism where the new information is constructed and maintained in WM by integrating it with its representations. Bindings must be quickly built and dissolved again when the representations are updated or discarded (Oberauer & Lange, 2009). All these cognitive processes can be executed efficiently with strong management of interference control which is considered as a factor influencing children's arithmetic skills.

Although various research has delved into the cognitive processes involved in arithmetic skills (De Visscher & Noël, 2014; Lee & Lee, 2019), there is little consensus about the specific effect of interference caused by problem size. Recent research suggested that larger or more complex problems are apt to create higher cognitive load and interference (Thevenot et al., 2010; Zbrodoff & Logan, 2005). Larger problems are more prone to trigger proactive interference because procedural strategies that require recalling previously learned problems are used to solve larger problems (Zbrodoff & Logan, 2005). From this view, the present study was constructed from the inference-based phenomenon to highlight the important role of interference control in school-aged children's problem-solving skills in math. It was anticipated that the pattern of performance in arithmetic operations would be different for the two conditions of multiplication and division and that participants would perform better in small-size problems than larger-size ones. This study demonstrated a clear understanding of how interferences affected participants' performance in arithmetic operations when the complexity of problems increased.

Methodology

Research Design

A mixed-effect model experimental research design was used in this study to generalize linear models with observations to predict discrete outcome variables.

Sample and Data Collection

Participants included 44 (19 female and 25 male) typically developing children in primary school between the ages of 9 and 11 years. The mean age of the participants was 10.5 (SD = 0.9). All participants fulfilled the following criteria: 1) no learning disability, no emotional or neurological disorder, or no communication impairment, 2) a Mathematics score between 70 and 100 out of 100, 3) a score within the average of the Test of Nonverbal Intelligence (Brown et al., 2010). The mean score of the intelligence test was 111.14 (SD = 10.86) ranging from 91 to 134. Participants were students who had been studying in different schools in the same region in Istanbul. All children in this study were Turkish and spoke Turkish as their first and primary language. According to the results of the questionnaire which was used to collect demographic information and socio-economic status data, children's parents' education level ranged from high school to college degree.

All participants completed the arithmetic tests to understand the effect of interference within subjects and to compare their performance in different operation tasks. All tasks were administered online using E-Prime Go which was obtained from E-Prime 3.0 software (Psychology Software Tools, 2020) to present stimuli and record responses remotely. Response time was not limited, and participants were allowed to use paper and pencil. Accuracy and reaction time data were collected from each task through E-Prime Go result sheets. Accuracy and reaction time data were used separately as dependent variables to compare within-subject performance at arithmetic tests.

Instruments

Baseline and interference conditions of arithmetic operations were administered to test children's WM capacity in terms of interference control while solving arithmetic problems. Participants completed the tasks in a quiet place at their house in a Zoom meeting. A link was sent to download the test from E-Prime Go. They were presented with questions online on the computer screen. They could use pencils and paper to solve the problems. The stimuli were shown until they answered the question. All instructions for the tasks were displayed on the computer screen. This test constituted four subtasks: Addition, Subtraction, Multiplication, and Division, and each task included 10 questions within two different conditions. During the tasks, participants had to press a key on the keyboard (A, B, C or D), that were associated with answer options. The baseline condition contained simple operations with small sizes (e.g., 3-digit numbers) of operands for each operation, whereas the interference condition involved large-size operands. Each subtask contained 10 questions. For addition, subtraction, multiplication, and division, the baseline condition included seven, five, five, and four questions, respectively. The rest of the 10 questions for each subtask belonged to the interference-based condition. The difficulty of the arithmetic operations was adjusted to the children's grade level and the Turkish math curriculum was considered to decide the digit size of the numbers for each math test. They performed a singular iteration for each task within the developed baseline and interference conditions.

For testing validity and reliability, the pilot study was conducted with a smaller sample of children who have similar characteristics as the participants of the present study. The expert review confirmed the content validity of the arithmetic operations test. It was ensured that the arithmetic problems aligned with the educational curriculum and standards for the age group of the study. The pre- and post-test results were compared to confirm construct validity and it was found that the test measures the task goal accurately. Reliability was assessed by using Cronbach's alpha, which provided a satisfactory value ($\alpha = 0.82$).

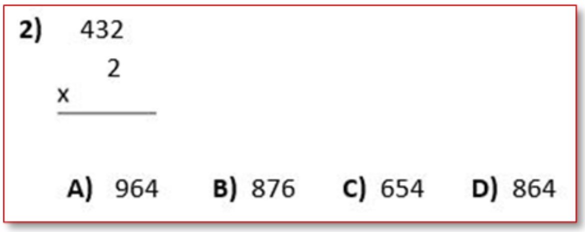

Figure 1. Example of the baseline condition

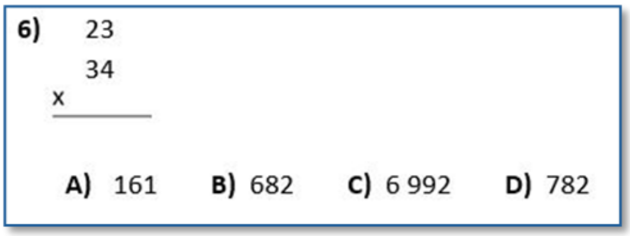

Figure 2. Example of the interference condition

Analyzing of Data

This study conducted mixed-effects regression analyses to investigate the within-subject effect on hierarchical data. Subsequent analyses were used to determine if there was a significant difference in terms of accuracy and reaction time performance patterns in the different conditions and operation types of the arithmetic operations task. Each set of analyses was examined to understand whether there was a main effect of conditions or item types in terms of accuracy and reaction time performance patterns across the different conditions and the different operation types of the arithmetic operations test.

Correct and incorrect answers in accuracy data were collected as binary data and a mixed-effects logistic regression model was conducted in condition of family binomial and link logit. Unaggregated reaction time data normally distributed was transformed for each participant after removing the outliers. This mixed-effects linear regression model was conducted with maximum likelihood estimation.

The responses and level-1 variables for each task were nested within each participant. To do this, the dependent variable was identified, its distributions were checked, and the model was initially run without any predictors. Level-1 predictors were incrementally added in subsequent analyses. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) statistics were compared to evaluate whether the model was the best fit. The model chosen for this study had the lowest AIC/BIC values. R studio version 4.2.1 (R Core Team, 2022) was used for both data processing and analysis.

Findings / Results

A set of analyses was conducted to address the purpose of this study, which was built to interpret participants' performance in the arithmetic operation tasks. The accuracy and reaction time data of the tasks were analyzed across the baseline and the interference conditions, and the operation item types (addition, subtraction and division).

The main effect of the condition was not significant for accuracy, but it was significant for reaction time. Participants showed higher reaction time performance in the interference condition compared to the baseline condition whereas they performed with similar accuracy across the condition.

Table 1. Arithmetic operations accuracy and reaction time predicted by condition

Accuracy			
Variable	**Estimate (SE)**	**z**	***p***
Fixed effects			
Intercept	2.990 (0.558)	5.354	**< .001**
Interference	0.556 (0.499)	1.114	0.265
Random effects	**Variance**	***sd***	
Intercept	0.768	0.877	
Reaction time			
Variable	**Estimate (SE)**	***t***	***p***
Fixed effects			
Intercept	20201.9 (1015.9)	19.886	**< .001**
Interference	4488.1 (556.9)	8.06	**< .001**
Random effects	**Variance**	***SD***	
Intercept	34318402	5858	
Residual	188381619	13725	

Note: Sample n = 44. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

In the baseline condition, the main effect of operation type was not significant for accuracy, but it was significant for reaction time. Participants' accuracy performance was similar across operation types, however, participants had higher reaction times on multiplication and division than on addition and subtraction (see Figure 3).

Table 2. Arithmetic operations accuracy and reaction time predicted by operation type of baseline condition

Accuracy			
Variable	**Estimate (SE)**	**z**	***p***
Fixed effects			
Intercept	57.46 (319.5)	0.180	0.857
Subtraction	-17.53 (320.8)	-0.055	0.956
Multiplication	-18.37 (277.2)	-0.066	0.947
Division	-18.18 (278.2)	-0.065	0.948
Random effects	**Variance**	***SD***	
Intercept	0	0	
Reaction time			
Variable	**Estimate (SE)**	***t***	***p***
Fixed effects			
Intercept	16046.5 (724.1)	22.16	**< .001**
Subtraction	3171.9 (711.6)	4.457	**< .01**
Multiplication	693.1 (548.7)	1.263	0.208
Division	1308.6 (580.3)	2.255	**< .05**
Random effects	**Variance**	***sd***	
Intercept	13070892	3615	
Residual	39107925	6254	

Note: Sample n = 44. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

In the interference condition, again, the main effect of operation type was not significant for accuracy, but it was significant for reaction time. Participants performed with similar accuracy across operation types, while their reaction time performance was higher in multiplication than in addition, subtraction, and division (see Figure 3). Specifically, participants showed higher reaction time performance in interference condition than in baseline condition (see Figure 3).

Table 3. Arithmetic operations accuracy and reaction time predicted by operation type of interference condition

Accuracy			
Variable	**Estimate (SE)**	**z**	***p***
Fixed effects			
Intercept	0.137 (1.489)	0.092	0.927
Subtraction	1.104 (0.838)	1.318	0.187
Multiplication	1.171 (1.245)	0.941	0.347
Division	0.423 (0.818)	0.517	0.605
Random effects	**Variance**	***sd***	
Intercept	1.525	1.235	
Reaction time			
Variable	**Estimate (SE)**	***t***	***p***
Fixed effects			
Intercept	17020.2 (947.8)	17.96	**< .001**
Subtraction	2230.1 (614.9)	3.626	**< .001**
Multiplication	-641.6 (581.5)	-1.103	0.271
Division	1366.7 (619.8)	2.205	**< .001**
Random effects	**Variance**	***sd***	
Intercept	30286992	5503	
Residual	45521185	6747	

Note: Sample n = 44. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

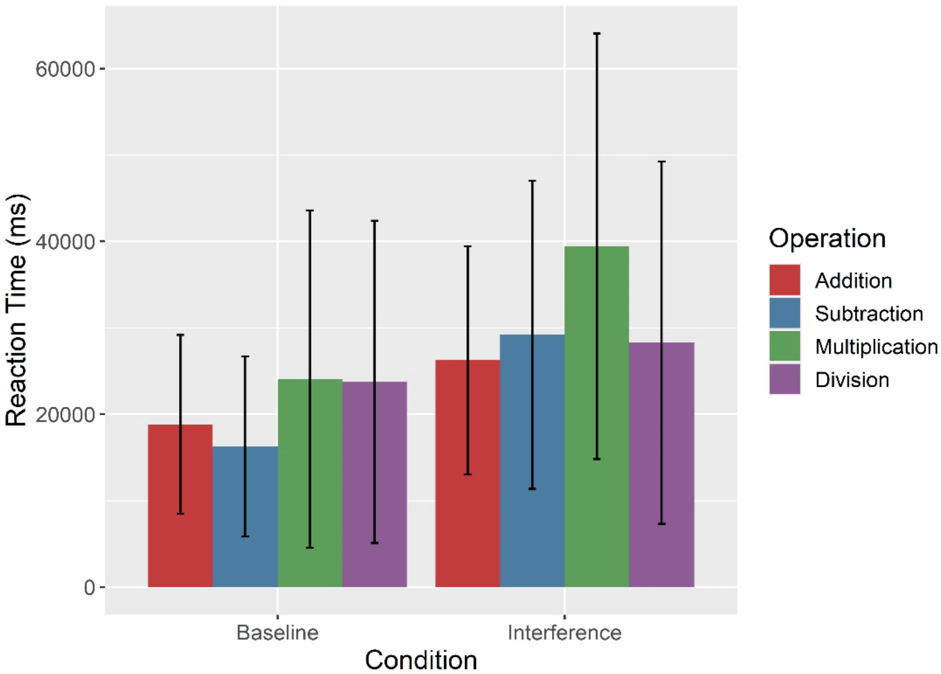

Figure 3. Arithmetic operations accuracy means by condition and operation type

Discussion

In this study's context, arithmetic tasks consisting of all four types of operations were used to test mathematical skills under the baseline and interference conditions. The purpose of using those tests was to verify whether participants perform differently while solving large-size problems which create interference in memory. The assumption based on the impact of problem size in the performance of arithmetic operations was the notion that larger-size problems would trigger more interference since the nature of the task required participants to recall procedures that were previously learned (Zbrodoff & Logan, 2005). According to the results of the analysis, participants showed similar accuracy performance in both baseline and interference conditions, whereas their reaction time performance was higher in the interference condition than in the baseline condition. Since the interference condition contains the larger-size problems, these findings align with the assumption. Furthermore, participants exhibited higher reaction time performance in multiplication and division in the baseline condition, whereas their reaction time performance was considerably higher in multiplication in the interference condition. Participants spent a longer time when they solved the multiplication and the division problems due to the higher complexity of those tasks. Since multiplication and division require more complex calculations and step-by-step processes, reaction time can increase to decrease the likelihood of errors (LeFevre et al., 1996). Heitz's (2014) speed-accuracy trade-off theory can explain this, which proposes that decisions made fast might be less accurate, whereas decisions made more accurately can contribute to longer time.

Additionally, while operating large-size numbers, participants need to control which steps are taken, which ones are left out, and whether the calculations at each step are correct. Being able to manage those steps is possible with good monitoring skills. However, monitoring may create high demand in WM since evaluating the quality of information is required besides maintaining and manipulating the information (Morris & Jones, 1990). For example, when individuals are engaged in carrying and borrowing numbers in arithmetic operations, intermediate steps need to be monitored in the process where recalling and applying arithmetic procedures can be potentially disrupted by proactive interference, resulting in slow processing in WM. In larger-size problems, the increased binding in previous information can interfere with the bindings of the current information (Oberauer et al., 2012). On the other hand, updating was used while solving larger-size problems; in other words, more complex tasks require the execution of various operations simultaneously, such as progressing problem steps, accessing new information, applying calculations, and improving the understanding of the problem (Ecker et al., 2010). This continuous updating may lead to proactive interference if a similarity occurs between old and new information in complex forms.

Overall, although extensive research provides resources on the connection between arithmetic skills and WM, the impact of interference has not been fully understood. This study contributes to a nuanced understanding of cognitive processes underlying arithmetic problem-solving in educational psychology, thereby offering practical implications in education settings. By considering cognitive load in terms of problem size and complexity, which create interferences, more effective teaching methods can be developed to enhance children's mathematical proficiency (Geary, 2011).

Conclusion

The present study explored the relationship between cognitive and mathematical skills for school-age learners. The results support that the interference model of WM provides an effective framework to understand the reasons for different skill levels in math in terms of WM. These findings also highlight the necessity for early intervention in children with low WM capacity or poor interference control. The arithmetic operation tasks designed based on a theoretical basis of cognitive settings and including manipulations of the task goal can determine the impact of interferences and cognitive load. Since these cognitive skills are essential for success in math, interventions designed to enhance these abilities can yield long-term efficacy not only in math but also in other academic disciplines. All in all, this study suggests that considering the cognitive skills of school-age children in math proficiency can encourage the continuation of this research line to support the interdisciplinary approach by involving cognitive processes in mathematical practices for learners.

Recommendations

The outcomes of this study when applied in educational settings can have practical implications. This study provides an interdisciplinary approach where mathematical implications are incorporated with cognitive manipulations, enabling researchers to continue this research path. Future researchers should investigate a longitudinal study where they can include WM training to analyze its effect on cognitive and math skills and the findings can be used in early intervention for children with low WM capacity or poor interference control.

Cognitive skills are essential not only in math but also in other subject areas. Therefore, different interventions can be designed to enhance cognitive skills and yield long-term efficacy in other academic disciplines.

Limitations

The present study has notable limitations that need to be acknowledged. Most prominently, the study lacks an appropriate sample size. It was possible to conduct research with such a sample size, but this could potentially impact the statistical power of the findings and generalizability. Despite the limited number of participants, this study may help and be the initial catalyst for further research to understand to what extent interference control in working memory impacts mathematical skills.

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