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The role of mathematical anxiety and working memory on the performance of different types of arithmetic tasks

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ABSTRACT

Goal of the current study was to compare the respective roles of domain general cognitive skills with domain specific quantitative understanding, as well as the effect of math anxiety, on the performance of different types of arithmetic tasks. Fifty-eight adults performed a battery of tests.

We found dissociations between domain general abilities that supported verbally or spatially mediated arithmetic tasks. The verbally mediated tasks were supported by the verbal central executive component of working memory, while the spatially mediated task, number line knowledge, was supported by the spatial central executive component of working memory.

Different tasks had differential relationships with math anxiety: math anxiety effected school-like math tasks more than verbally mediated tasks and number line task. Math anxiety was negatively influenced by the spatial central executive component of working memory, indicating that spatial working memory can be a source of vulnerability to math anxiety.

1. Introduction

Converging evidence from infants, preschool children, adults as well as non-human primates, has consistently shown that there is an inherent and neurologically based ability to process approximate quantities [15,16,29,30,8]. The representation of approximate quantities, known as the approximate number system (ANS), is a preverbal ability to intuitively understand and approximate discrete quantity as well as the relationship between quantities. However, math ability relates to both the ANS [28–30] as well as several general cognitive skills [55,56]. This is seen in previous research, which has found that different types of math tasks require different combinations of cognitive skills [37], similar to Dehaene's triple code model, which postulates that different skills are recruited based on the task demands [19,20]. The verbal code is activated during well-rehearsed tasks such as retrieval of arithmetic facts, while the semantic code is activated during tasks that require representations of numbers on the mental number line [19,20,37].

Hence, math ability involves a hybrid of cognitive skills and innate quantitative understanding leaving the source of vulnerability up for debate. In line with this view, multiple cognitive skills were found to have significance for both typical and atypical math development. For example, Szűcs et al. [56] found that for typically developing children, verbal and phonological processing, visuospatial working memory (WM), spatial abilities, and executive functions all play a significant role in explaining individual differences in arithmetic abilities. Similarly, Szucs et al. [55] proposed that abnormalities in executive functions, specifically inhibition, and visuospatial WM, are at the heart of pure arithmetic learning disability.

WM is one of the most studied domain general processes examined in math research [12,26,54]. The multicomponent view of WM makes a distinction between WM, which is responsible for the short-term storage of verbal (phonological loop) or visuospatial information (visuospatial sketchpad), and central executive (CE) WM, which is responsible for the manipulation of information and high-level monitoring and control(A. [9]; A. [10]). The CE includes specialized subsystems for verbal and visuospatial information [2].

Previous research has examined the relationship between the components of WM and math performance. The visuospatial sketchpad is involved in the solution of multi-digit operations [26,31] while the phonological loop maintains intermediate arithmetic results [25,57]. The CE is needed for sequencing complex arithmetic procedures that involve intermediate steps such as carrying and borrowing [34]. In accordance with the multicomponent view of WM, the verbal code relies on verbal WM and CE, while the semantic code requires spatial-numerical representations based on visuospatial WM and CE [22,44]. Specifically, Prado et al. [44] discovered that stronger verbal WM capacity predicted recruitment of the verbal region in the brain (left

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temporal cortex) during the solution of multiplication facts (based on the verbal code). In contrast, stronger spatial WM capacity predicted recruitment of the spatial region (right parietal cortex) during the solution of a subtraction task.

Beyond cognition, other emotional and environmental factors can affect math performance. Math anxiety is a feeling of tension and anxiety that interferes with the manipulation of numbers and solution of mathematical problems in a wide variety of everyday life and academic situations [52]. The direction of the relationship between mathematics anxiety and mathematics performance are not clear: poor performances can increase mathematics anxiety or mathematics anxiety can result in avoidance from math practice [17,32]. Ashcraft and Faust [3] found that math anxiety had little effect on the performance of simple arithmetic: participants with high math anxiety had similar performance as participants with low math anxiety in simple operations. However, for the solution of complex arithmetic problems that place higher demands on WM, participants with high math anxiety had poorer and slower performance compared to participants with low math anxiety.

Following this logic, a dominant theory links math anxiety and WM [4]. Accordingly, participants with high math anxiety have reduced WM resources during the solution of math problems due to math anxiety-induced verbal ruminations, which lead to poorer performance on numerical and mathematical tasks that require verbal WM resources. In line with this view, Mammarella, Hill, Devine, Caviola, and Szucs [40] found reduced verbal WM in a group of participants with high math anxiety.

However, other studies have found that participants with high math anxiety have lower performance compared to participants with low math anxiety even in tasks with low verbal WM demands such as basic serial counting or numerical comparison (E A. [38]; E. A. [39,51]). Hence, the relationship between math anxiety and verbal WM resources is still unclear.

The first goal of the study was to explore the respective roles of domain general cognitive skills, in particular the subsystems of WM, and domain specific math abilities (ANS) on the performance of different types of arithmetic and numerical tasks. In line with previous research [18], we proposed that domain specific skills, namely the ANS, would have some contribution to adults' performance on arithmetic tasks, whereas domain general skills, especially specialized subsystems of WM, would be more significant. We proposed a differential relationship between the WM subsystems and performance on the arithmetic tasks. Verbal WM and CE was expected to play a critical role in the retrieval of arithmetic facts and in procedural knowledge, while visuospatial WM and CE was expected to associate with performance in tasks related to the representation of numbers on the mental number line [44].

The secondary goal of the present study was to test the role of math anxiety on different types of arithmetic and numerical tasks. Due to math anxiety induced verbal ruminations and, subsequent reduced verbal WM resources, we expected to find that participants with higher math anxiety would have poorer performance in tasks that were heavily based on verbal WM and CE, such as retrieval of arithmetic facts and procedural knowledge and school-like arithmetic; in contrast, their performance on visuospatial WM and CE tasks, such as the representations of number on the mental number line, should be less affected by math anxiety.

2. Material and methods

2.1. Participants

The study included 58 college students (28 male and 30 females) (mean age 23.46, S.D. 3.06) who came to the Student Support and Diagnostic Center for Learning Disabilities and ADHD at the Hebrew University in order to receive testing accommodations and other benefits. All of the participants performed the entire diagnostic battery of the *MATAL*, a computerized, normed diagnostic tool that is used for learning disability assessments for college students in Israel. All of the participants performed the entire diagnostic battery of tasks. Participation in the current study was offered to every student who came to the center. The additional tasks for the current study were given before or after diagnosis. All the participants had correct or corrected vision and no clinical pathology, some of the participants had difficulties in reading, math or attention and 78% of the participants had a prior clinical diagnosis of ADHD, dyslexia, or dyscalculia. All participants had finished 12 years of study in the Israeli educational system and passed matriculation tests. See Table 1 for the full demographic data and the results of the current diagnostic process.

Table 1
Demographic table.

	Male 28	Females 31
Average age	**23.51 (4.184)**	**23.13 (3.19)**
Self-report of math difficulties	**6**	**18**
Diagnosis of dyscalculia (by the MATAL)	**2**	**3**
Diagnosis of dyslxia (by the MATAL)	**9**	**6**
Diagnosis of ADHD (by the MATAL)	**9**	**11**

2.2. Stimuli, apparatus, and procedure

The *MATAL* (The Hebrew acronym *MATAL* means: Learning Functioning System) is a computerized assessment tool used to diagnose learning disabilities in Israeli university students. It was developed by Israel's National Institute for Testing and Evaluation.

The *MATAL* assesses math, reading, writing, ADHD, and English (as a second language). Except for the English tasks, all *MATAL* tasks are conducted in Hebrew. The diagnostic battery includes 2 questionnaires and 20 tasks (the tasks relevant for the current study are described below). Students complete the entire battery in two sessions that last approximately 3 h each with an examiner present, followed by an intake session with a psychologist. The scores of the individual tasks in the *MATAL* are standardized and reaction time (RT) measures are converted so that positive higher scores in both accuracy and RT measures are indicative of superior performance. It is important to note that the scores do not distribute normally, rather they have a negative skew resulting in more extreme negative standard scores than is found in normal distributions.

All participants underwent the entire diagnostic battery for learning disabilities including testing for math, reading and writing disabilities, and ADHD. The participants also performed WM tasks, an ANS task, and completed a math anxiety questionnaire for the current study.

2.2.1. Arithmetic tests

All arithmetic tests, except for the Brief Mathematics Assessment-1(BMA), are part of the *MATAL*. The tasks fall into three categories: 1. Solution of simple arithmetic operations. 2. Procedural knowledge. 3. Representations of number on the number line. All tasks were computerized except for the BMA.

2.2.1.1. Procedural knowledge. The task was designed to measure procedural knowledge. It consisted of 96 equations that were presented sequentially on the computer screen, and participants needed to determine by keypress whether the equation was correct or incorrect. The equations included numbers that ranged from 1 to 4 digits (e.g. $45+25=70$ or $1850\text{-}350=1550$). All equations required logarithmic, simple calculations. The equations were equally divided into addition, subtraction, multiplication and division, and evenly into correct and incorrect solutions within each category (i.e., 12 addition problems with correct solution). In the practice trials, an equation