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Working Memory and Mathematics Performance

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Abstract: This study investigated the relationship between working memory and mathematics performance. It is a correlational study utilising experimental tasks to investigate the relationship, using backwards digit span task to test working memory and a simple maths quiz for maths performance. Thirty (30) participants from psychology undergraduates were involved. The result showed a positive relationship between working memory and maths performance based on total correct recall, whilst a negative relationship was found between working memory and maths performance based on total time taken. This indicates the existence of a significant relationship between verbal working memory and maths. Working memory is related to the mathematical aspects of manipulation of numerical value and the procedures involved in solving maths problems, thus more correct answers and lesser time taken with the increase of working memory level. Further study is recommended to explore the role of attention in working memory in retrieval speed of information as it is implied from the non-normal distribution of the data.

Keywords: Verbal working memory, maths, attention, retrieval, time taken, correct recall

1. Introduction

Mathematics (maths) is an essential element in life. We practise the skills every day (Ojose, 2011). We use it in calculating our daily budgets, when purchasing essentials, measuring ingredients in cooking, and, for academics, to analyse data. Therefore, it is imperative that it is studied to contribute for the betterment of the skills involved. The performance in mathematics varies from person to person. The factors leading to the performance level are various with one of it being working memory. This led to much research being done with regards to working memory and its relationship with maths performance and maths anxiety (Allen et al., 2019). Research done on the matter also seeks to enhance the outcome in mathematics performance (ultimately academic achievement), especially the role of working memory and many have sought the training in working memory in the hopes that it may improve maths performance. Only by knowing the true nature and the role played by the working memory on maths performance can it really add to the betterment of maths performance (Cragg et. al., 2017).

Maths is especially emphasised in Malaysia. It is taught from kindergarten until Sijil Pelajaran Malaysia (SPM) level (fifth form in secondary school). Many universities or tertiary level education institutions require that maths achievement is credit (at least C) to enrol. For instance, psychology students of Universiti Malaysia Sarawak (UNIMAS) are required to pass maths in SPM level (E grade), but from foundation level, at least a C in maths or additional maths (like Teaching English as Second Language [TESL] course in UiTM). Recently, Sarawak emphasised on the improvement of education. With this, comes the emphasis on science, technology, engineering, and mathematics (STEM) education. The Minister of Education, Innovation, and Talent Development, Dato Sri Roland Sagah was reported to have said on the importance of STEM education to prepare the younger generation for future prospects (Petingi, 2023). This shows the importance of mathematics in the development of youth, and indirectly, the development of our country.

In practice, maths involves the numbers being manipulated and then the retention of numbers and the operations in memory to arrive at a solution. Working memory is a temporary store of information where it can be manipulated. This means that a relationship between working memory and maths is expected. The study of working memory is of interest for some time with many models developed to explain it. One famous model is the Baddeley & Hitch (1974) model, it has subsystems which are phonological loop and visuospatial sketchpad. Studies found that maths involved verbal and visual aspects of working memory (Allen et al., 2019; Cragg et al. 2017; Miller & Bichsel, 2004). Ideally, maths, being a universal language, is studied in every culture, or across cultures. Furthermore, different demographics may produce variations in both working memory performance and maths performance. However, based

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on previous studies, only a few studies specify their target groups. Many focus on school children and adults in general, whilst a few specifically mention their target group, like science students and humanities students, such as studying maths anxiety and working memory, i.e. Dowker & Sheridan (2022) and a good grasp on adult samples with varying educational backgrounds (studying working memory and maths performance and math anxiety). A study was conducted which included psychology undergraduates but only comparing the age and strategy, e.g. from primary school to adult (Cragg et al., 2017).

In addition, the study between maths and working memory in Malaysia is limited. This is significant considering that mathematics is taught in Malaysia in mainly two languages, i.e. English and Malay. This may contribute to differences in performance in working memory, number recall and maths performance in general as found by Peng et al. (2020) and Kirjavainen et al. (2020). It was found that different aspects in a language may impact different skills in maths. It may involve phonological processing in numerical representation and vocabulary and comprehension in understanding concepts and problem solving.

In the domains of verbal (phonological) working memory, some studies used words recall in measuring working memory. For instance, Cragg et al. (2017) used animal names, or using sentences (recalling certain words at the end of a sentence); i.e. Miller & Bichsel (2004) and listening span task (working memory capacity, L-span task) in Ashcraft & Kirk (2001). This may have a negative impact on different demographics (culture and education level). On the other hand, some studies used digit span tasks i.e. Van Bueren et al. (2022) and Dowker & Sheridan (2022). The use of digit span tasks is more appropriate considering it is a study on maths and also to reduce the effect of the usage of second language in maths. Therefore, this study included or specified the target demographics, which were psychology students in UNIMAS, representing the Malaysian context and also university students. The hypotheses of the study are: 1) There is a relationship between working memory and maths performance based on total correct recall; and 2) There is a relationship between working memory and maths performance based on total time taken.

Therefore, the purpose of this study is to investigate the relationship between working memory and maths performance. In doing so, answering two research questions:

1) Is there a relationship between verbal working memory and mathematics performance based on total correct recall?
2) Is there a relationship between verbal working memory and mathematics performance based on total time taken?

2. Literature Review

Working memory model used is by Baddeley & Hitch (1974) which consists of two core aspects: the central executive and the slave systems: 1) phonological loop and 2) visuospatial sketchpad. Baddeley (1992) stated that phonological loop or verbal working memory maintains speech-based information which include spoken, written, and printed words and digits. Another important model is one by Adams et al. (2018) and Cowan (1998) which went away with the slave systems but suggest the systems are embedded in one and that information from the environment activates the long-term memory. Barrouillet (2004) expanded Cowan's model suggesting the impact of attention which in turn affect the retrieval speed of information from the long-term.

Mathematics (maths) is basically a science that works with logics of shape, quantity, and order (Hom & Gordon, 2021), and it is essential that everyone has maths literacy which is the capacity to know and apply basic mathematics (Ojose, 2011). Ashcraft & Krause (2007) cited that there is a positive relationship between arithmetic and working memory. It involves the manipulation of numerical values and also the total number of steps in problem solving. As the size of the problem increases, so do the demands on working memory. Mixed digits and mixed operations may add to the demand of working memory (Raghubar et al. 2010). Furthermore, working memory functions more when the solution requires strategy and operation or procedure, which means manually calculating the values, rather than direct memory retrieval. Cragg et al. (2017) found that when working memory load was imposed on the subjects, there is impairment in the accuracy and time taken in performing maths.

However, considering Cowan's (2014) model, even the retrieval strategy is working memory as it involves an attentional filter activating long-term memory. According to Cragg et al. (2017), the central executive component is responsible for the retrieval. Retrieval strategy in maths refers to the method of directly retrieving long-term memory to solve a problem. For example, in the problem 2 + 2= 4, we retrieve the answer from long-term memory, without going through the counting or procedural strategy which is manually counting the values. Cragg et al. (2017) cited a study that found that counting taxed the working memory and not retrieval. However, evidence suggested that even retrieval has demands on working memory, such as by Cragg et al. (2017) that regardless of strategies used, disruptions in working memory equals impairment in maths performance.

In their review, Raghubar et al. (2010) found that there is more evidence in the role of phonological loop in arithmetic performance than the role of visuospatial sketchpad. According to Peng et al. (2020), working memory accounts for 8% ~ 16% in variance between language and maths, which proves the existence of the phonological loop in connection to maths. In learning maths, language skills are necessary, such as comprehension and vocabulary, and also phonological processing (Peng et al., 2020; Kirjavainen et al., 2019). According to the research by Van Bueren et al. (2022), they tested verbal working memory with backward digit span task. In this task, participants were presented with a number sequence verbally and had to recall it in reverse order. They found that higher performance in working memory was related to better mathematical abilities.

A recent review by Allen et al. (2019) suggests that there is a positive relationship between visuospatial working memory and mathematics performance. They found that children develop their maths skills as they grow, changing their strategy to a more verbal approach. Li & Geary (2017) studied the performance of school children in maths, from kindergarten to ninth grade. They found that children with larger gains in visuospatial working memory, have better mathematical achievement. They found that visuospatial working memory was specific to maths achievement and not achievement in general, unlike verbal working memory is a predictor of both reading achievement (Li & Geary, 2017) and maths performance (Ashcraft & Krause, 2007).

One factor that plays a role in affecting working memory and maths performance is maths anxiety. Individuals exhibiting high levels of maths anxiety were found to have lower working memory capacity (Ashcraft & Kirk, 2001). When an individual is anxious, performance in maths worsen (Finell et al., 2022). Worrying thoughts limit the processing capacity required in maths performance by spending working memory resources on irrelevant stimuli.

According to Miller & Bichsel (2003), maths performance is influenced by both visual and verbal working memory with maths anxiety affecting visual working memory. Their findings on maths anxiety affecting visual working memory contradicted others where they hinted on the effect of anxiety in verbal working memory as they utilised and tested verbal aspects of the working memory, such as by Ashcraft & Kirk (2001). However, research by Živković et al. (2022) concurred with Miller & Bichsel (2003), where anxiety affects the visuospatial working memory rather than verbal working memory. These studies indicated that indirectly there is a huge role played by visuospatial working memory in maths performance albeit the previous studies and the bulk of the studies indicating the major role of verbal working memory.

From the literatures, it was found that the working memory tasks utilised were usually language-specific, with emphasis on the English language and also only on the native speaking population where maths is studied and tested only in their native tongue. For example, Cragg et al. (2017) used animal names aurally presented to test working memory. Ashcraft & Kirk (2001) utilised two tasks, listening span (L-span) and computation span (C-span) tasks. The former required the participants to listen to a sentence and answer a question relating to the sentence before proceeding to the next sentence and at the end of the sentence the participant must recall the last word of the sentence. The second task was similar but replaced the sentences with arithmetic problems, again requiring the recall of the last number of the problem. Their study indicated the use of English language especially with the first task. Van Bueren et al. (2022) and Finell et al. (2022) both reported the use of digit span task. However, the presentation and the recall were done verbally, indicating the use of a specific language. This current study seeks to be neutral in language use as maths is studied bilingually in Malaysia, suggesting the universality of mathematics.

3. Methodology

Thirty psychology undergraduates from UNIMAS participated in the study. They were briefed about the experiment and provided with informed consent forms prior to the experiment. They are individually tested. The study is a correlational study utilising experimental method to investigate the relationship between working memory and mathematics performance. The independent variable is working memory whilst the dependent variable is maths performance based on total correct recall and total time taken. The instrument used to measure working memory is the digit span task. A series of numbers are presented to the participant verbally or via a computer using tests available online, like from memorylosstest.com. The participants were tasked to recall the number in correct order. It can be done in forward order (Finell et al., 2021) or backwards (Van Bueren et al., 2022; Raghubar et al., 2010) as it is suggested to be a purer measure of working memory (Dowker & Sheridan, 2022). Therefore, the study was done using backwards digit span task.

The basic principle of the test is that a participant will memorise and recall a string of digits, and the test will stop when the participant failed twice on a certain level (Woods et al., 2010), such as inaccurately recalling at 7 digits span. Three trials were given to the participants. When the participants failed two out of three, then the test was stopped, and the highest span reached without failure was recorded. For example, in backward digit span task, in the first level, a three-digit span sequence will be presented. A sequence of 234 is presented to a participant. He will have to recall 432 to succeed. After successfully completing three trials of the three-digit span sequence, the participants moved on to the next span (four-digit span), and on until two errors out of three trials were found.

To measure maths performance, only the four foundations of maths, or four basic arithmetic were tested, i.e. addition, multiplication, subtraction, and division. As such, a simple quiz website, https://www.thatquiz.org/tq-1/math/arithmetic/, was used. In this website, there will be two types of operations that are available but only one was used which was the single operation (9 + 9 = ?). The level was also set at 20 (the numbers shall be up to 20). Level 20 means that the highest number in an operation is 20 for addition, subtraction, and multiplication, whilst in division level 20 means 20 is the highest number for the answers to the operation. In addition, subtraction, and multiplication, they are usually written as a + b = c, a – b = c, and a * b = c. Level 20 in this means that for ‘a’ and ‘b’ in the equation, the highest possible number is 20. For example, 17 + 14 = 34 for addition, 19 – 17 = 2 for subtraction, and 16 * 4 = 64 for multiplication. However, in division, where a/b = c, only ‘c’ is capped at 20, e.g. 288/18 = 16.

Firstly, the participants were given a consent form to be filled. Then, they were to include the demographics information, which include age, CGPA, year of study in a form. After filling the form, the participant performed the digit span task from 3.3 above. They were given three trials, and when two trials resulted in failures, the highest span reached was recorded, as in 3.3 above. Then, the participants answered 20 questions for the maths quiz. The total time taken, and total correct answers were recorded. The data received was then analysed using SPSS software. Normality test was run to ascertain the distribution of the data. Following the non-normal distribution of the data, Spearman correlation was used to determine the relationship between working memory and maths performance based on total correct recall and total time taken.

4. Results

In total, there were thirty (30) participants. Table 1 exhibits the demographics information of the participants. Female students were the majority of the participants numbering to 22 whilst there were only 8 male students participating. 22-year-old students made up the majority of the participants with 19 participants, with ages 21, 23, 24, and 26 numbering 2, 7, 1, and 1 participant respectively. Third year (year 3) students constitute most of the participants 26 people whilst there were 4 second year students. The cumulative grade point average (CGPA) of the students reported has mean of 3.73 (M = 3.73).

Table 1. Demographics information

Demographic variable	Categories	Frequency (n)	Percentage	M
Gender	Male	8	26.7	-
	Female	22	73.3	-
Age	21	2	6.7	-
	22	19	63.3	-
	23	7	23.3	-
	24	1	3.3	-
	26	1	3.3	-
Year of Study	2	4	13.3	-
	3	26	86.7	-
CGPA	-	30	-	3.73

Table 2 showed the result of the study. The mean for working memory is 5.40 (M = 5.40) showing that on average the participants scored at level 5 of digit span task for working memory. Maths performance based on total correct recall had a mean of 16.23 (M = 16.23), siding on the higher score, an overall good performance. Maths performance based on total time taken recorded a mean of 3.05 (M = 3.05), indicating that, on average, participants took 3.05 minutes to solve the math quiz. The results indicated that maths based on total correct recall was better than the time taken, scoring on a higher side rather than the longer time taken. This suggests the overall good performance in maths.

Table 2. Descriptive data for working memory and maths performance (total correct recall and total time taken)

	n	M	SD	Min.	Max.
Working Memory	30	5.40	1.329	3	8
Maths (total correct recall)	30	16.33	2.758	7	20
Maths (total time taken)	30	3.05	1.403	1.28	7.12

Table 3 shows the test of normality. A test of normality was run to ascertain the distribution of the data. Due to the small number of samples, Shapiro-Wilk's value was used. Significance value, *p* value, for Shapiro-Wilk should be more than .05 to be considered normal. Hence, working memory, maths (total correct recall), and maths (total time taken) are not normally distributed with *p* value of .019, .004, and .012 respectively. Therefore, Spearman correlation coefficient is used instead of Pearson's.

Table 3. Test of normality

	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Working Memory	.218	30	<.001	.915	30	.019
Maths (total correct recall)	.185	30	.010	.886	30	.004
Maths (total time taken)	.150	30	.083	.906	30	.012

Table 4 illustrates the result of Spearman's correlation coefficient between working memory and maths performance based on total correct recall. The *p* value was smaller than the 0.05 level of significance ($p = .024$), thus the first hypothesis had not enough evidence to be rejected. The correlation coefficient between working memory and maths performance based on total correct recall was r_s (28) = .412. Therefore, it can be concluded that there is a significant positive relationship between working memory and maths performance based on total correct recall.

Table 4. Correlation between working memory and maths (total correct recall)

			Working memory	Maths (total correct recall)
Spearman's rho	Working memory	Correlation Coefficient	1.000	.412
		Sig. (2-tailed)	.	.024
		N	30	30
	Maths (total correct recall)	Correlation Coefficient	.412	1.000
		Sig. (2-tailed)	.024	.
		N	30	30

Table 5 indicated the result of Spearman's correlation coefficient between working memory and maths performance based on total time taken. The *p* value is significant, having $p < 0.05$ level of significance ($p = .036$), thus the second hypothesis failed to be rejected. However, the correlation coefficient between working memory and maths performance based on total time taken is negative, r_s (28) = -.385. It is concluded that there is a significant negative relationship between working memory and maths performance based on total time taken.

Table 5. Correlation between working memory and maths (total time taken)

			Working memory	Maths (total time taken)
Spearman's rho	Working memory	Correlation Coefficient	1.000	-.385
		Sig. (2-tailed)	.	.036
		N	30	30
	Maths (total time taken)	Correlation Coefficient	-.385	1.000
		Sig. (2-tailed)	.036	.
		N	30	30

5. Discussion

Based on the data from Table 4, it was reported that there is a significant positive relationship between working memory and maths performance based on total correct recall. The correlation is considered moderate with the r_s value being more than .4 (r_s = .412). Participants were tasked to perform a backwards digit span working memory task and a maths quiz consisting of 20 questions. Participants with higher working memory performed better in maths, thus contributing to the positive relationship. The maths aspects tested consists of the four basic arithmetic: addition and multiplication, and subtraction and division. Higher working memory levels give an individual more resources to solve maths problems. This can be found in the relationship between maths and working memory. Ashcraft and Krause (2007) explained that there are two aspects of the relationship between working memory and maths performance: 1) manipulation of numerical values, and 2) procedures (total number of steps) in problem solving. Furthermore, working memory is more taxed when the operands in maths problems grow larger, similar to what was suggested by Cragg et al. (2017) with regards to problem size. Ashcraft & Krause (2007) stated that use of procedural strategies is more taxing than retrieval, comparing this with Cragg et al. (2017) where there is not much difference between the strategies including retrieval.

To explain problem size, in maths there are four basic arithmetic skills: addition, multiplication, subtraction, and division. Basically, in addition, if the sum or multiply of two values is more than ten (10), it will involve a carry operation where the additional tens will be carried over to the next place (Courant et al., 1996). Inversely, in subtraction, a ten value may be borrowed and brought to the ones place to make it possible to subtract with a larger number. These showed the extra procedure and extra need to retain the value in the working memory. It is even more complex in multiplication and division where an individual may need to remember the multiples of a number so further multiplication involving more digits or division can be performed.

A positive relationship was also reported in a study by Miller & Bichsel (2004). They found that in intercorrelation between measures, both visual and verbal working memory were significantly and positively related to basic and applied maths performance. Their study was on maths anxiety, and they found that working memory is secondary to maths anxiety in predicting maths performance. One explanation afforded by them was, amongst individuals with high maths anxiety, those with high working memory have more resources in performing maths than those with lower working memory.

Another study by Cragg et al. (2017) also reported a positive relationship between working memory and maths performance. They found that previous studies suggest that strategies used in solving maths problems were where the working memory is most evident. Their study stated that regardless of strategies, working memory interfered with all three strategies (retrieval, decomposition, counting) to a similar extent. However, they suggest that working memory's role in maths performance is influenced by the problem size when using strategies, excluding memory retrieval to arrive at a solution. Dowker & Sheridan (2022) studied the attitude on maths and maths performance, and the influence of various factors including working memory. They found that oral maths was predicted by working memory. In other words, mental arithmetic has a positive relationship with working memory as is evident in the current study. Dowker & Sheridan (2022) stated that science students having longer digit span than humanities students, reported better maths performance, implying the relationship between working memory and maths performance.

From the two elements; problem size and strategies; it was observed that most people that have errors in their maths quiz erred in either division or multiplication or both. This further proves the relationship between working memory and maths performance based on total correct recall in conjunction with the aspects of maths mentioned above and the two elements aforementioned. Combining the two elements or aspects of problem size and strategies, we can expect an increase in time needed to perform more complex maths problems. With bigger problem size, more time will be needed and working memory is exerted more. This was shown in table 5, there is a significant negative relationship between working memory and maths performance based on total time taken. This means that as the level of working memory of an individual increases, the less time is needed for that individual to solve maths problems. However, the correlation is weak, with $rs = -.385$, with $rs < .4$ being considered weak.

One explanation that may be given is the varying maths skill and knowledge an individual possesses. Cragg et al. (2017) suggested that further studies need to be done with regards to the differences between science students and humanities students. This was evident in their study that science students reported a longer digit span than humanities students. Owing to this fact, the background of the participants of the current study, undergraduates of psychology programme from UNIMAS, is diverse prior to undergraduates with some from the science stream, others studied business, literature, linguistics, or having a diploma in administration. This variety of background means that there are different levels of maths skills and knowledge. Cragg et al. (2017) found that retrieval strategies, finding solution through retrieval from memory, involves working memory. Barrouillet & Lépine (2005) found that children with higher working memory can retrieve faster in simple arithmetic problems. They take into account Cowan's model of working memory activating the long-term memory in retrieval and also the model by Barrouillet et al. (2004), time-based resource-sharing model that takes into account the attention required in working memory tasks and also the number of memory retrievals. These can account to the retrieval of the multiples in solving multiplication and division in maths as mentioned earlier.

6. Conclusion

In conclusion, Firstly, the number of participants is small. It may not be statistically strong enough to create powered research. This brought about the lack of diversity in the participants, focusing only on the psychology undergraduates, thus the results may not be generalised. However, the study is still valid with only 30 participants as it is considered the minimum value for most research, 10 to 20 participants for a simple experiment may be possible. The psychology undergraduates came from various backgrounds prior to enrolling in bachelor's studies. That may account for a little bit of diversity. Secondly, there is an issue of attitude towards maths amongst the participants. A negative attitude towards maths may result in poor performance in maths in spite of working memory level. This combined with small number of participants may have cause the data being not normally distributed. However, the study only tested simple arithmetic, which the participants have basic knowledge of, thus the attitude towards maths may be negligible. Furthermore, the study did not cover many aspects of maths, only touching the four foundational arithmetic: addition, multiplication, subtraction, and division. It also only included whole numbers and single operations. Thus, it only correlates with some parts based on the elements by PISA, i.e. quantity and relationship. Nevertheless, as the study sought to test the basics, the four arithmetic and whole number are still adequate. The working memory test may be limited in terms of the aspect it tested. The backward digit span task focused only on verbal working and digit processing. There are other tests to test verbal working memory.

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Conflict of Interest

The authors declare no conflicts of interest.

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