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RESEARCH ARTICLE

Enhancing Secondary Students' Problem-Solving Achievement and Behaviour in Linear Algebra: The Impact of the Thinking Aloud Pair Problem-Solving Strategy

Nurfirzanah Fadzil[1], Sharifah Osman*[1], Jamilah Ahmad[1], Agustan Syamsuddin[2], Idawati Fadollah[2], Maharida Manindar[2]

[1]School of Education, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia
[2]Department of Mathematics, Universitas Muhammadiyah Makassar, Indonesia

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***Corresponding Author**

sharifah.o@utm.my

ABSTRACT

Mathematical problem-solving is a fundamental skill in education, especially in areas like linear algebra, where students often face considerable challenges. This study examines the impact of the Thinking Aloud Pair Problem-Solving (TAPPS) strategy in enhancing students' problem-solving behaviour and academic performance. Adopting a quasi-experimental design, the study involved 30 secondary school students from Johor, Malaysia. Quantitative data were gathered through pre- and post-tests, including a problem-solving behaviour questionnaire and an achievement test. Results revealed significant improvements in both problem-solving behaviour and academic achievement after implementing the TAPPS strategy. Additionally, a moderate positive correlation was identified between problem-solving behaviour and achievement. These findings emphasise the potential of the TAPPS strategy to strengthen students' mathematical reasoning, reflection, and accuracy when solving linear algebra problems. The implications are significant for educators seeking innovative methods to improve mathematical problem-solving skills in secondary education.

INTRODUCTION

Mathematical problem-solving is widely recognised as a vital skill in modern education, serving as a basis for logical reasoning, cognitive growth, and the application of abstract concepts to real-world situations. These competencies are not only crucial for success in mathematics but also play a significant role in developing analytical skills that can be transferred across various fields (Gurat, 2018). In recent decades, educational systems worldwide have increasingly emphasised problem-solving as an integral component of mathematics curricula, as evidenced by international assessments such as Trends in International Mathematics and Science Study (TIMSS) and the Programme for International Student Assessment (PISA). These assessments evaluate students' ability to apply mathematical knowledge to complex problems and establish benchmarks for educational outcomes globally (Mandasari, 2021).

Despite this emphasis, many students continue to struggle to master mathematical problem-solving skills. In Malaysia, for instance, student performance in international assessments such as TIMSS and PISA has consistently fallen short, revealing persistent gaps in problem-solving abilities compared with their peers in other countries (Fern & Matore, 2020; Palraj et al., 2017). This disparity has raised significant concerns among educators, policymakers, and researchers, leading to a renewed focus on enhancing problem-solving skills in the classroom, particularly in subjects such as linear algebra.

Linear algebra, which deals with vector spaces and linear equations, presents unique challenges to students. Many find it difficult to transition from grasping mathematical theories to applying them to practical contexts. Previous research indicates that students often struggle with tasks such as translating word problems into algebraic expressions, solving complex equations, and meaningfully interpreting results (Ibrahim et al., 2019; Wati et al., 2018). In Malaysia, this issue is particularly pronounced as students frequently rely on rote learning and procedural knowledge instead of fostering deep conceptual understanding and flexible problem-solving strategies (Ling & Mahmud, 2023). Conventional teacher-centred instructional methods further exacerbate these challenges, limiting student engagement and hindering the development of critical thinking skills (Bature, 2020).

The Polya model of problem-solving, introduced by George Polya in the mid-20th century, offers a structured approach to tackling these challenges. The model comprises four essential stages: (1) understanding the problem, (2) devising a plan, (3) executing the plan, and (4) reflecting on the solution (Hafizah et al., 2015). Although the Polya model has been widely adopted in mathematics education, its implementation in Malaysian classrooms has yielded mixed results. Many students still find it challenging to apply the model effectively, especially when confronted with nonroutine or real-world problems (Hubbard et al., 2017). This highlights the need for instructional strategies that not only introduce the Polya model but also actively engage students in problem-solving processes.

The Thinking Aloud Pair Problem-Solving (TAPPS) strategy, developed by Whimbey and Lochhead (1987), offers a promising solution to these challenges. The TAPPS is a collaborative instructional technique that encourages students to verbalize their thought processes while solving problems. In this approach, one student articulates their reasoning aloud, while the other listens, provides feedback, and helps refine the problem-solving strategy. This method fosters metacognitive awareness, enabling students to reflect on their strategies, identify errors, and make real-time adjustments (Kumar Shah, 2019). Grounded in constructivist and social constructivist theories, TAPPS emphasizes active learning and social interaction in knowledge construction (Olusegun, 2015). Through verbal dialogue and collaborative reflection, students can build new knowledge based on their prior understanding, thereby enhancing their problem-solving skills and mathematical achievement.

Previous studies have demonstrated that the TAPPS can significantly improve students' cognitive and metacognitive skills. For instance, Björn et al. (2019) found that the TAPPS enhanced students' abilities to solve mathematical word problems by encouraging critical thinking about the problem-solving process. Similarly, Lasak (2017) showed that students utilizing the TAPPS were better equipped to reflect on their mathematical reasoning and develop effective strategies for tackling complex problems. Despite these insights, research on the effectiveness of TAPPS in the context of linear algebra, particularly in Malaysia, remains limited. Additionally, there is a scarcity of studies exploring the relationship between students' problem-solving behaviour and mathematical achievement, highlighting a critical area for further investigation.

This study aimed to address these gaps by examining the impact of the TAPPS strategy on students' mathematical problem-solving behaviour and achievement in linear algebra. Specifically, this study focused on the following research questions (RQ):

RQ1: Is there a significant difference in students' mathematical problem-solving behaviour before and after learning linear algebra using the TAPPS strategy?

RQ2: Is there a significant difference in students' mathematical problem-solving achievements in linear algebra before and after using the TAPPS strategy?

RQ3: Is there a significant positive correlation between students' mathematical problem-solving behaviour and their achievement in linear algebra?

By addressing these questions, this study aims to contribute to the existing body of knowledge on effective instructional strategies for mathematics education. Furthermore, the findings may inform educational practices and policies, particularly in Malaysia, where enhancing problem-solving skills is a national priority. This study's dual focus on behaviour and achievement provides a comprehensive perspective on the learning process, offering practical insights for educators seeking to implement innovative teaching strategies in their classrooms.

2.0 MATERIALS AND METHODS

2.1 Research Design

This study employed a quasi-experimental design with a one-group pre-test and post-test design to evaluate the impact of the Thinking Aloud Pair Problem-Solving (TAPPS) strategy on students' mathematical problem-solving behaviour and achievement in linear algebra. This design was chosen because it allows for the assessment of changes within the same group of participants over time, thus minimizing variability due to individual differences (Maciejewski, 2020). Although randomization was not feasible, efforts were made to ensure the homogeneity of the sample to control for extraneous variables.

2.2 Participants

The study was conducted in a secondary school in Johor, Malaysia and involved a sample of 30 students aged 13. The participants were selected based on their enrolment in a mathematics course that covered linear algebra topics. Informed consent was obtained from the students and their guardians, and ethical approval was granted by the school's administration. All participants had prior exposure to linear algebra and the Polya problem-solving model but had not been introduced to the TAPPS strategy before the study. The participants were selected and randomly grouped into pairs for the TAPPS sessions. The teacher actively assisted students during the experiment, providing guidance as needed throughout the sessions.

2.3 Instruments

Two main instruments were used to collect quantitative data:

Mathematical Problem-Solving Achievement Test: A customized test consisting of six linear algebra problems was designed to measure students' problem-solving performance. The test items were adapted from standardized curriculum materials to suit the context of this study. The test was administered before and after the intervention to assess the changes in student achievement.

Mathematical Problem-Solving Behaviour Questionnaire: Adapted from Desoete (2007) and modified by Mustapha et al. (2017), this 22-item questionnaire measured students' problem-solving behaviour based on the four stages of the Polya model: understanding the problem, devising a plan, carrying out the plan, and reflecting. Each item was rated on a 5-point Likert scale (1 = never, 5 = always), with a total score ranging from 25 to 125. The questionnaire was administered before and after the intervention.

2.4 Procedure

Before the intervention, the participants completed the pre-test and mathematical problem-solving behaviour questionnaire. They were then introduced to the TAPPS strategy through instructional sessions conducted by the researcher, who also served as a teacher for the study. The TAPPS sessions focused on fostering collaborative problem-solving by having students work in pairs, with one student verbalizing their thought process while the other student listened and provided feedback. The Polya model was used as a framework for guiding the problem-solving process, and the students were encouraged to reflect on their strategies and solutions throughout the sessions.

Following the TAPPS intervention, which spanned for four weeks, students were administered the post-test and post-intervention behavioural questionnaire. All assessments and activities were conducted in a classroom setting, and the same set of linear algebra problems was used in both pre-and post-tests to ensure consistency.

Data Analysis

The data collected from the pre-and post-tests were analysed using both descriptive and inferential statistics. The following statistical tests were conducted:

Wilcoxon Signed Rank Test: This non-parametric test was used to analyse changes in students' problem-solving behaviour before and after the intervention, as the data were ordinal in nature. The test assessed whether the differences in the median scores were statistically significant.

Paired t-test: Since the achievement test scores were normally distributed, a paired t-test was used to compare pre- and post-test scores to determine whether the TAPPS strategy significantly impacted students' mathematical problem-solving achievement.

Spearman's Rank Correlation Coefficient: To examine the relationship between students' mathematical problem-solving behaviour and achievement, Spearman's correlation was used because of the non-parametric nature of the behavioural data. The correlation coefficient (r) was calculated to assess the strength and direction of this relationship.

All statistical analyses were conducted using SPSS version 25.0, with a significance level set at $p < .05$ for all tests.

3.0 RESULTS

3.1 Impact of TAPPS on Mathematical Problem-Solving Behaviour

The pre-and post- questionnaire data were analyzed using descriptive and inferential statistics. The first research question sought to determine whether there was a significant difference in students' mathematical problem-solving behaviour before and after the implementation of the TAPPS strategy. The Wilcoxon signed-rank test revealed a statistically significant improvement in problem-solving behaviour after the intervention ($Z = -4.484$, $p < .000$). Table 1 summarizes the results, showing that 27 students demonstrated improved problem-solving behaviour, while only three students exhibited no change or decline in behaviour.

Table 1: Wilcoxon Signed Rank Test Results for Problem-Solving Behaviour

	N	Mean Rank	Sum of Ranks	Z	Asymp. Sig (2-tailed)
Negative Rank	$3a$	4.83	14.50	-4.484^{b}	.000
Positive Rank	27^{b}	16.69	450.50		
Ties	$0c$				
Total	30				

3.2 Mathematical Problem-Solving Achievement

The second research question investigated whether the TAPPS strategy has a significant effect on students' mathematical problem-solving achievement in linear algebra. A paired t-test was used to compare the pre- and post-test scores. The results shown in Table 2 indicate a significant improvement in student achievement after the intervention ($t(29) = -7.533$, $p < .000$). The mean score increased from 51.67 (pre-test) to 70.47 (post-test), reflecting a substantial gain in mathematical problem-solving proficiency.

Table 2: Paired t-test Results for Mathematical Problem-Solving Achievement

Test	Mean	Standard Deviation	t	df	Sig (2-tailed)
Pre	51.67	9.20	-7.533	29	.000
Post	70.47	6.82			

This study elaborates on students' achievement in mathematical problem-solving by comparing student grades before and after TAPPS, as depicted in Figure 1.

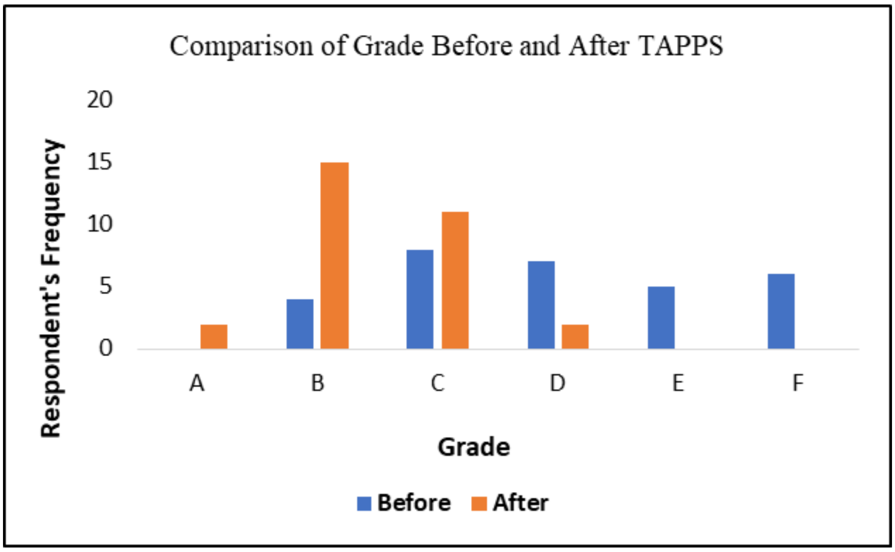

Figure 1: Comparison of Students' Grades Before and After TAPPS

Overall, there was a noticeable improvement in the students' mathematical problem-solving achievements following the implementation of the TAPPS. Most students achieved a grade of B after using the strategy, and no students received failing grades (E or F) post-intervention. Additionally, the number of students who earned an A grade increased by two, while the number of students with a D grade decreased. In conclusion, the TAPPS proved to be an effective tool for enhancing students' ability to solve mathematical problems.

3.3 Correlation Between Problem-Solving Behaviour and Achievement

The third research question explored the correlation between students' problem-solving behaviour and mathematical achievement. Spearman's Rank Correlation Coefficient analysis, as shown in Table 3, revealed a moderate positive correlation between the two variables ($r = .519$, $p < .002$). This result suggests that students who demonstrated improved problem-solving behaviour were more likely to achieve higher scores on mathematical problem-solving tests.

Table 3: Spearman's Rank Correlation Coefficient for Problem- Solving Behaviour and Achievement

Variable	**Correlation Coefficient (r)**	**Sig. (2-tailed)**	**NN**
Problem-Solving Behaviour	0.519	.002	330
Mathematical Problem-Solving Achievement	0.519	.002	330

These results highlight the moderate positive correlation between problem-solving behaviour and achievement, highlighting the importance of fostering reflective strategic thinking in students as a means of improving their overall performance in mathematics.

4.0 DISCUSSION

The results of this study emphasise the valuable role of the Thinking Aloud Pair Problem-Solving (TAPPS) strategy in enhancing students' mathematical problem-solving behaviour and achievement in linear algebra. Through TAPPS, students are encouraged to articulate their thought processes. The process not only facilitates self-reflection however it encourages collaborative learning, allowing them to share and critique the process in problem-solving.

These findings are consistent with previous studies that emphasize the benefits of collaborative approaches in problem-solving. For instance, research by Björn et al. (2019) and Kumar Shah (2019) demonstrated that when students work together on complex mathematical tasks, they are more likely to develop skills in reasoning and critical analysis, which are essential for tackling challenging topics like linear algebra. By validating the effectiveness of TAPPS, this study contributes to the broader educational literature, offering further evidence of how structured collaborative learning can help students internalize mathematical concepts and refine their problem-solving behaviour and achievement.

4.1 Impact on Problem-Solving Behaviour

The substantial improvement in students' problem-solving behaviours observed in this study provides compelling evidence that the Think Aloud Pair Problem Solving (TAPPS) strategy significantly enhances cognitive engagement with mathematical tasks. By verbalizing students thought processes and collaborating with peers, students became more aware of the strategies they employed during mathematical problem-solving. This collaborative discourse not only facilitated deeper understanding but also encouraged students to critically analyze their own reasoning and that of their peers.

Notably, the most improvements were observed during the reflection stage of the Polya problem-solving model. Students were more likely to check their work meticulously, identify and correct errors, and reassess their solutions after implementing TAPPS. This increased focus on reflection is consistent with constructivist theories that emphasize that learning occurs through active engagement and self-regulation (Olusegun, 2015).

In the context of linear algebra, a discipline often characterized by its abstract nature and structures. The benefits of TAPPS are particularly significant. The structure framework provided by TAPPS enabled students to break down complex problems, think critically, and correct mistakes in real-time. These improvements in behaviour are likely to lead to long-term benefits in students’ ability to approach mathematical problems more systematically, in future contexts.

4.1 Impact on Problem-Solving Achievement

The significant gains in mathematical problem-solving achievement observed in this study further validate the use of the TAPPS as an effective instructional strategy. The increase in mean test scores from pre- to post-intervention indicates that TAPPS not only improved students' ability to reflect on their problem-solving processes but also translated into measurable academic gains. This is an important finding, as it demonstrates that the behavioural changes fostered by TAPPS, such as better planning, more accurate execution of strategies, and increased attention to detail, contributed directly to improved performance on mathematical tasks. The results of this study demonstrate that the TAPPS strategy has a significant positive impact on both students’ mathematical problem-solving behaviour and their achievement in linear algebra.

By scrutinizing pre- and post-mathematical problem-solving achievement tests, it was observed that in the pre-test, students frequently left blank answers and made errors including miscalculations. These findings consistently show that students often encounter difficulties and make mistakes while solving mathematical problems. Chinnappan and Ghazali (2018) and Hassan et al. (2018) found that developing problem-solving skills is one of the primary challenges that students encounter in Malaysia. Students also exhibit numerous errors and misconceptions when solving mathematical problem-solving questions (Md-Ali & Veloo, 2021; Palraj et al., 2017). This study further revealed that before the implementation of the TAPPS, students did not fully utilize the Polya model for problem-solving. The gap between the pre- and post-intervention results demonstrates that the students were uninvolved in maximizing the use of the Polya model before the introduction of the TAPPS.

Additionally, this study found that early intervention revealed students’ difficulty in distinguishing between algebraic expressions and equations. Some students also had poor foundational mathematical knowledge before the TAPPS. The TAPPS strategy not only helped to address these fundamental issues but also provided students with valuable skills, such as text annotation, paraphrasing, metacognition, and critical thinking. These skills not only benefited their problem-solving abilities in mathematics but also improved their overall understanding of linear algebra.

The TAPPS strategy promotes cognitive engagement, collaboration, and reflection, which allows students to develop better problem-solving habits and achieve greater accuracy in their work. The positive changes in students' behaviour and academic outcomes align with constructivist learning theories that emphasize active participation and peer interaction as essential components of knowledge construction (Olusegun, 2015). Moreover, the improvements observed in students' problem-solving behaviour and achievement highlight the importance of teaching strategies that go beyond rote learning and instead focus on fostering deep reflective thinking (Osman et al., 2016).

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These results are consistent with those of Stehle and Peters-Burton (2019), who found that collaborative problem-solving strategies enhance student achievement by encouraging deeper cognitive engagement. The present study expands on this by showing that the TAPPS, when combined with the structured framework of the Polya model, can be particularly effective in addressing the challenges of solving linear algebra problems. The practical implications of this finding suggest that incorporating TAPPS into regular mathematics instruction could help reduce the gap in student performance observed in international assessments, such as TIMSS and PISA (Mandasari, 2021).

4.3 Correlation Between Behaviour and Achievement

The observed moderate positive correlation between students' mathematical problem-solving behaviour and their academic achievement illuminates the intricate interplay between cognitive processes and educational outcomes. Students who demonstrated significant improvements in their problem-solving behaviour more likely to achieve higher scores on the mathematical problem-solving achievement test. This empirical finding aligns with the theoretical framework of social constructivism, which posits that learning is not only an individual cognitive process, but also a social one, enhanced by collaboration and interaction (Chuang, 2021). The TAPPS encourages students to articulate their thought processes, engage in dialogue with peers, and refine their approaches through reflection, all of which contribute to better academic outcomes.

Furthermore, this correlation emphasises the critical importance of teaching strategies that go beyond rote memorization or procedural learning. By emphasizing the cognitive processes involved in problem-solving, such as planning, execution, and reflection, TAPPS fosters the development of metacognitive skills. These skills are crucial for success in mathematics and other academic disciplines (Hafizah et al., 2015). These findings suggest that educators should not only enhance students' mathematical knowledge but also improve their problem-solving behaviour for more meaningful learning outcomes. Integrating strategies like TAPPS promotes deeper cognitive engagement and develops higher-order thinking skills, aligning with educational goals that prioritize critical thinking and creativity over rote memorization. Adopting collaborative and reflective teaching methods like TAPPS leads to sustained improvements in student achievement and equips students with essential skills for lifelong learning and real-world problem-solving.

5.0 LIMITATIONS AND FUTURE RESEARCH

Although this study provides valuable insights into the benefits of TAPPS, it is not without limitations. The quasi-experimental design, which is effective in capturing pre- and post-intervention changes, lacks the control provided by a randomized controlled trial. The relatively small sample size (30 students) and specific focus on one school in Johor may limit the generalizability of the findings to other educational settings. Additionally, the study focused exclusively on linear algebra, and it remains to be seen whether the positive effects of the TAPPS would be observed in other areas of mathematics or different age groups.

Future research should address these limitations by employing larger and more diverse samples and exploring the impact of TAPPS on other mathematical topics. It would also be beneficial to investigate the long-term effects of TAPPS on students' problem-solving abilities, and whether the improvements observed in this study can be sustained over time. Furthermore, qualitative studies examining the experiences of students and teachers with TAPPS could provide deeper insights into the mechanisms underlying its effectiveness.

6.0 CONCLUSIONS

This study aimed to explore the effects of the thinking-aloud pair problem-solving (TAPPS) strategy on students' mathematical problem-solving behaviour and achievement in linear algebra. The findings indicate that the TAPPS significantly improves both problem-solving behaviour and achievement, with a moderate positive correlation between the two variables. Students who participated in the TAPPS became more reflective and strategic in their approach to solving mathematical problems, which translated into measurable improvements in their academic performance. The practical implications of this study are clear: TAPPS offers a promising approach to enhancing mathematical problem-solving skills, particularly in challenging subjects, such as linear algebra. By fostering collaboration, reflection, and critical thinking, the TAPPS helps students engage more deeply with mathematical concepts and develop the metacognitive skills necessary for success in mathematics. Educators are encouraged to integrate TAPPS into their instructional practices to support students in becoming more effective problem-solvers. While this study provides strong evidence for the benefits of TAPPS, future research should continue to explore its broader applications across different mathematical domains and educational contexts. With further investigation, TAPPS has the potential to become a widely adopted strategy for improving mathematical education and closing the performance gaps in mathematics, both in Malaysia and internationally.

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