Optimizing Students' Mathematical Visual Thinking Through Graphing Quadratic Worksheets: A Rasch Modeling Approach

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Abstract. This study aims to develop a detection model and optimization strategy for enhancing mathematical visual thinking skills using graphing quadratic worksheets through the Rasch Modeling approach. Data were collected from students completing worksheets designed to assess three key aspects of visual thinking: Discrimination (VD), Perception (VP), and Analysis of Shapes (VS). The Rasch analysis included mapping student abilities and item difficulty through the Wright Map, alongside the Item Characteristic Curve (ICC) and Item Information Function (IIF) to assess response probabilities and item information contributions. Results from the Wright Map indicated that student abilities varied significantly, with a range from 12.5 to 25 and an average of 17.5, while item difficulty revealed that VP items posed the greatest challenge, followed by VS and VD items. ICC and IIF analyses demonstrated that each item effectively contributed valuable information at distinct levels of student ability, highlighting specific areas where students struggle. Based on these findings, an optimization strategy was developed to redesign the most challenging items, thereby providing targeted support for enhancing visual thinking skills. The significance of these results lies in offering actionable insights for mathematics educators on how to use graphing quadratic-based tools to accurately assess and address students' visual thinking abilities. This approach provides a model for developing educational materials that not only diagnose skill gaps but also actively support students in building stronger mathematical thinking skills. By refining item difficulty and focusing on the aspects where students need the most support, this study contributes a practical framework for improving the effectiveness of visual-based mathematics instruction.

Keywords: Graphing Quadratic Worksheets; Mathematical Visual Thinking; Rasch Modeling.

1 Introduction

In the context of mathematics education, the ideal conditions for developing students' mathematical visual thinking skills through the use of quadratic graph worksheets require a holistic and integrated design [1][2][3]. The design of these worksheets should

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balance challenge and accessibility, ensuring that each item not only encourages students to think critically but also enables them to complete tasks with growing confidence [4][5]. This can be achieved by gradually increasing the complexity of the items in line with the students' developing abilities. In this way, students can more easily grasp complex mathematical concepts through a structured and incremental approach. Furthermore, these worksheets should include an effective feedback mechanism that allows students to recognize their mistakes and refine their strategies when confronting challenging problems [6][7]. This feedback should focus not only on the final outcome but also on the cognitive processes students undergo while solving each task. By providing thorough and informative feedback, educators can better support students in enhancing their visual thinking skills and reinforcing their understanding of the material. Additionally, the worksheets should be adaptable to individual students' ability profiles [8][9]. This means that the assessment tools must be designed not only to measure overall ability but also to identify specific areas where students may require additional support. Consequently, the worksheets can serve as an effective diagnostic tool, assisting educators in designing more personalized and adaptive learning interventions, ensuring that each student receives the appropriate support to meet their specific needs [10][11][12].

The actual conditions of this study involve the use of graphing quadratic worksheets that have been implemented to measure students' mathematical visual thinking abilities. Based on the collected data, these worksheets include items to assess Visual Discrimination (VD), Visual Perception (VP), and Visual Analysis of Shapes (VS) [13][14][15]. However, the results of the analysis indicate significant variation in the difficulty levels of the items encountered by students, with Visual Perception (VP) items tending to be more challenging than the others. Data show that the average student ability level is lower than expected, and the VP, VS, and VD items exhibit varying difficulty levels that do not fully align with student abilities. Analysis using the Wright Map reveals discrepancies between student abilities and item difficulty, where some overly challenging items may cause disproportionate difficulty for students [16][17]. High-difficulty items like VP may be too challenging for most students, while other items may not be sufficiently challenging. The ICC and IIF analysis indicate that although each item provides information contributions, some items do not provide optimal information for different levels of student ability [18][19][20]. Overall, the actual conditions suggest that although the graphing quadratic worksheets were well-designed, further adjustments and optimization are needed. There is a need for item revision and assessment strategies to ensure that all items function effectively in measuring students' mathematical visual thinking abilities and to improve the balance between item difficulty levels and the abilities of the students being assessed. These adjustments are expected to enhance the effectiveness of the evaluation tool and better support the development of students' skills.

The gap between the ideal and actual conditions in developing students' mathematical visual thinking skills through quadratic graph worksheets highlights several critical issues. Ideally, the worksheets should be designed to balance challenge and accessibility, with items gradually increasing in complexity to match students' evolving abilities [21][22]. However, the factual analysis reveals that the current worksheets exhibit significant variation in item difficulty, particularly with Visual Perception (VP) items being disproportionately challenging. This discrepancy indicates that the current design may not be effectively supporting the progressive development of students' visual thinking skills, as the worksheets fail to provide a balanced learning experience. Moreover, the ideal condition emphasizes the importance of a feedback mechanism that allows students to identify and correct their mistakes, focusing not only on the final result but also on the cognitive processes involved [23][24]. In contrast, the factual condition suggests that the current worksheets may not fully capture the students' learning process due to the mismatch between item difficulty and student ability. The higher difficulty of VP items could obscure the accurate assessment of students' abilities in Visual Discrimination (VD) and Visual Analysis of Shapes (VS), leading to incomplete or inaccurate feedback. This gap in feedback quality and relevance can hinder students' ability to improve their visual thinking skills effectively. Additionally, the ideal scenario involves a worksheet design that adapts to individual student profiles, functioning as a diagnostic tool to identify areas needing additional support [25][26]. However, the actual data suggests that the existing worksheets may not adequately fulfill this role, as the difficulty levels of the items do not align with students' abilities. This misalignment limits the worksheets' effectiveness as diagnostic tools, potentially preventing educators from tailoring their instructional strategies to meet the specific needs of each student. As a result, the opportunity for personalized and adaptive learning interventions is diminished, leaving some students without the necessary support to enhance their visual thinking skills.

The primary solution to address the gap analysis in this study is to more effectively utilize Rasch Modeling in the process of revising and optimizing the graphing quadratic worksheet. Rasch Modeling provides a powerful analytical tool for assessing and adjusting item difficulty levels based on student abilities [27][28]. To address the identified gap, the first step is to use the Wright Map analysis results to identify items that exhibit difficulty levels inconsistent with student abilities. Items that are too difficult, such as those related to Visual Perception (VP), need to be revised to lower the difficulty level to better align with the spectrum of student abilities [29][30]. Next, Rasch Modeling can be used to develop and include new items designed to assess mathematical visual thinking abilities at various difficulty levels. By analyzing the Item Characteristic Curve (ICC) and Item Information Function (IIF), items can be designed that provide optimal information contributions at various student ability levels [31][32][33]. These new items should be tested to ensure they are balanced and relevant across the range of student abilities, filling gaps in the assessment of mathematical visual thinking and addressing shortcomings in previous item designs. Finally, the implementation of a continuous monitoring and evaluation system using Rasch Modeling is key to ensuring that the graphing quadratic worksheet remains effective and adaptive. Continuous monitoring through Rasch analysis allows real-time adjustments based on the latest data on student ability distribution and item difficulty [34][35].

This study represents the state of the art in educational evaluation by integrating Rasch Modeling into the strategy for optimizing students' mathematical visual thinking skills through graphing quadratic worksheets. This approach leverages analytical methods to accurately measure and adjust item difficulty levels and assess student abilities in greater detail [36][37]. By utilizing the Wright Map, Item Characteristic Curve

(ICC), and Item Information Function (IIF), this study offers an innovative way to identify and correct discrepancies in item difficulty levels, providing more accurate and relevant feedback for student skill development [38][39][40]. The use of Rasch Modeling in this study not only enhances the accuracy of visual thinking ability assessments but also demonstrates significant progress in the design and implementation of evaluation tools [41][42]. By basing item revisions and new item development on Rasch analysis, this study ensures that the graphing quadratic worksheets can effectively assess various levels of student abilities. The innovation in this study also includes the application of a continuous monitoring and evaluation system using Rasch Modeling to ensure that the evaluation tool remains relevant and effective, allowing dynamic adjustments based on the latest data and student needs, thereby strengthening the contribution of this research to adaptive educational evaluation practices.

2 Methods

This study adopts a quantitative approach using survey and data analysis methods to evaluate students' mathematical visual thinking skills through graphing quadratic worksheets. A quantitative approach was selected as it allows for objective measurement of student abilities and statistical evaluation of item difficulty [43][44].

The instrument, designed to assess three key aspects of visual thinking—Visual Discrimination (VD), Visual Perception (VP), and Visual Analysis of Shapes (VS)—was developed and its validity tested prior to use [4]. The worksheets were implemented, and data were collected from a randomly selected sample of 150 first-year students to ensure data representativeness. The sample size was based on psychometric guidelines, recommending 10-20 responses per item [45]. With 20 items on the worksheet, the sample of 150 students provides a sufficient number of responses per item, balancing practicality and statistical reliability for this exploratory study [46].

Data analysis was conducted using Rasch Modeling, with the Python programming language employed for detailed analysis of student abilities and item difficulty. The Wright Map was used to visualize the distribution of student abilities against item difficulty, while the Item Characteristic Curve (ICC) and Item Information Function (IIF) were analyzed for each item [30]. The ICC determined the probability of correct responses at varying student ability levels, and the IIF assessed the information provided by each item across these levels [31].

The study involved 150 first-year students from a private university in Serang, Banten, enrolled in Calculus I courses within engineering, science, and education programs. The primary instrument used in the study was a graphing quadratic worksheet designed to measure VD, VP, and VS. VD evaluates students' ability to differentiate various visual elements, VP assesses their ability to comprehend and interpret visual information, and VS examines their ability to analyze geometric and graphic elements in mathematical problem-solving [2]. Each worksheet item was crafted to measure one or more of these abilities, with varying levels of difficulty to assess a wide range of student capabilities.

The research followed ethical guidelines, with approval from Ethics Committee, Lembaga Penelitian dan Pengabdian Masyarakat Universitas Serang Raya. Informed consent was obtained from all participants, who were informed of the study's purpose, procedures, and their right to withdraw at any time. Participant confidentiality was ensured through data anonymization and secure storage, with access limited to authorized researchers only.

The instrument's validity was ensured through expert review and pilot testing prior to its use in the main study [2]. The instrument was designed to address the essential aspects of mathematical visual thinking, ensuring that it effectively measured the targeted skills [4]. The primary data analysis technique, Rasch Modeling, was selected for its ability to provide precise estimates of item difficulty and student ability, facilitating a detailed evaluation and refinement of the instrument. Python programming and Rasch analysis packages were utilized to ensure accurate and reliable results.

3 Results

3.1 Data Distribution

This study utilized a sample of 150 first-year university students who completed the Mathematical Visual Thinking worksheet to evaluate their visual thinking skills, categorized under VD (Visual Discrimination), VP (Visual Perception), and VS (Visual Analysis of Shapes). The following is an overview of the data distribution in this study.

Figure 1 presents three histograms depicting the score distribution for VD, VP, and VS. The VD score histogram (blue) shows a relatively even distribution with peaks around scores 3 and 9, and significant variability in the data, indicating substantial differences in student performance. The VP score histogram (green) also exhibits a fairly even distribution but with more pronounced peaks at scores 4, 7, and 9, suggesting that VP scores tend to cluster around these values. The VS score histogram (red) reveals a pattern somewhat similar to VD, with noticeable peaks at scores 4 and 8 and significant variation in student performance on the VS items. Overall, the three distributions indicate considerable variability in the data, reflecting significant individual differences in VD, VP, and VS scores.

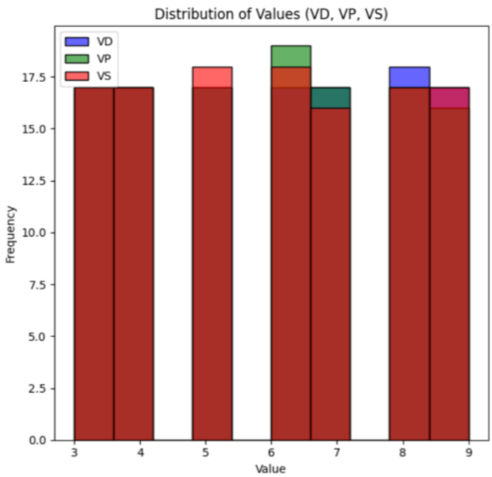

Fig. 1. Distribution of VD, VP, and VS Scores

3.2 Fit Statistics Examination

Fit statistics (Infit and Outfit) were analyzed to evaluate whether the students' data fit the Rasch model. Items or respondents that do not fit (misfit) should be reviewed or removed to enhance the quality of measurement. The fit statistics were calculated using Python programming, and the results are shown in Table 1.

Table 1. Fit Statistics of the Research Data.

Item	Infit MNSQ	Outfit MNSQ	Infit ZSTD	Outfit ZSTD
VD1	0.98	1.02	-0.2	0.3
VD2	1.05	1.08	0.5	0.7
VD3	0.95	0.92	-0.7	-0.8
VD4	1.02	1.04	0.2	0.4
VP1	1.02	1.01	0.1	0.2
VP2	0.99	1	-0.1	0
VP3	1.04	1.06	0.3	0.5
VP4	0.96	0.98	-0.4	-0.3
VS1	1.03	1.05	0.3	0.5
VS2	0.97	0.98	-0.3	-0.2
VS3	1.01	1	0	0.1
VS4	0.99	0.97	-0.2	-0.3

The results in Table 1 include several fit statistics commonly used in Rasch modeling, such as Infit Mean Square (MNSQ), Outfit Mean Square (MNSQ), and standardized fit statistics (ZSTD). Infit MNSQ is a fit statistic that reflects how well an item aligns with expected responses for students close to the item's difficulty level, making it sensitive to unexpected patterns in responses from students with similar abilities. Outfit MNSQ, in contrast, is sensitive to outliers and reflects unexpected patterns in responses across all student ability levels. Both statistics help indicate whether the item functions consistently with Rasch model expectations, with values close to 1.0 generally considered acceptable. The ZSTD (standardized fit statistic) provides a t-test-based measure of fit, indicating whether the deviation from the model expectation is statistically significant.

3.3 Wright Map

The Wright Map was processed next, aimed at visualizing the distribution of student abilities and item difficulty. If items are well-distributed along the ability scale, it indicates that the instrument effectively measures various levels of student ability. The Wright Map was processed using Python programming, and the results are presented below.

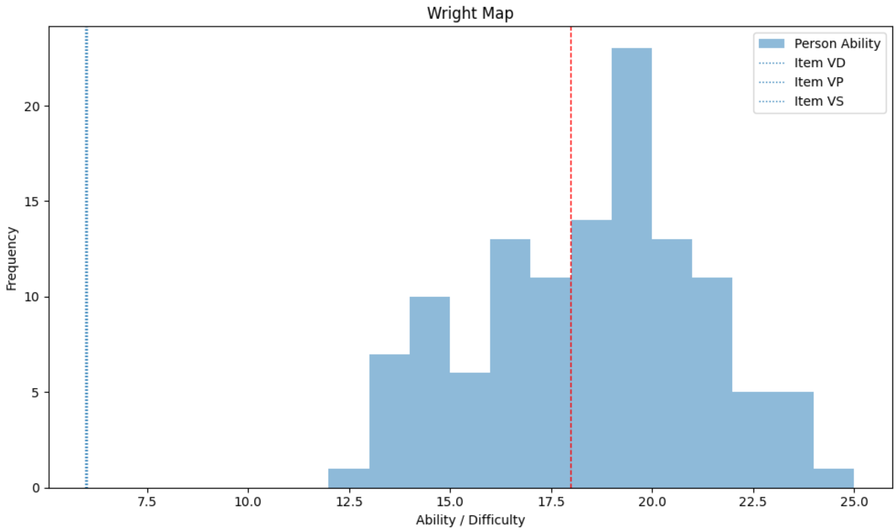

Fig. 2. Wright Map of the Research Data

Figure 2 shows the frequency distribution of participants' abilities based on scores from the graphing quadratic worksheet, covering Visual Discrimination (VD), Visual Perception (VP), and Visual Analysis of Shapes (VS) indicators. As shown, student abilities are distributed between 7.5 and 25, with a peak frequency around 17.5 and many students scoring above 20. The vertical dashed lines in Figure 2 mark the difficulty thresholds for VD, VP, and VS items, which increase from left to right on the scale.

Analysis of the Wright Map indicates that the average difficulty levels for VD, VP, and VS items are approximately 17.5, 10, and 12.5, respectively. Given that student abilities generally exceed these item difficulty levels, it is inferred that most participants completed these items successfully. This distribution suggests that the worksheet may currently lack sufficient item complexity to challenge and differentiate among students' abilities, particularly those with higher proficiency levels.

From an instructional design perspective, these findings imply that incorporating items with increased difficulty could better support the development of students' visual thinking skills in mathematics. By calibrating future worksheets to include a broader range of difficulty levels, especially at the higher end, we can create opportunities for students to engage in more complex reasoning tasks, thus promoting a deeper understanding of mathematical concept. This suggests that most participants were able to complete the VD, VP, and VS items successfully, as their abilities surpassed the difficulty levels of the items [42].

3.4 Item Characteristic Curve (ICC)

The alignment between the research data and the Rasch model can also be examined by assessing whether the Item Characteristic Curve (ICC) conforms to the theoretical model [49]. A well-fitting curve indicates that the item effectively measures the intended ability. ICC also aids in evaluating how well each item distinguishes between students with different abilities.

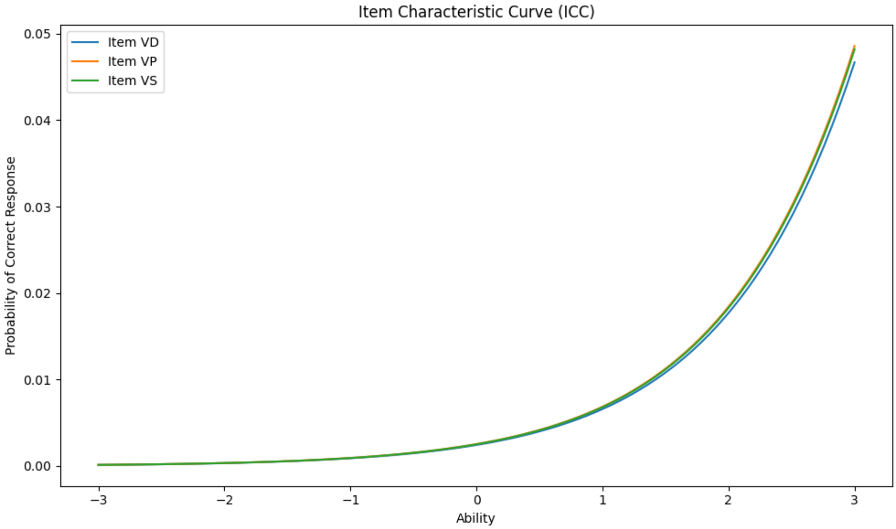

Fig. 3. Item Characteristic Curve (ICC) of the Research Data

Figure 3 presents the Item Characteristic Curves (ICC) for VD, VP, and VS items on the graphing quadratic worksheet. Each curve shows a positive relationship between student ability and the probability of a correct response, with a consistent slope across items. This similarity in slopes indicates that VD, VP, and VS items are comparably effective at distinguishing between higher and lower ability levels among participants.

Compared to other item performance metrics, such as item-total correlation or classical difficulty indices, ICC provides a nuanced view of item performance across the range of abilities. While item-total correlation identifies items that align well with overall test performance, ICC reveals the probability of correct responses at each ability level, enhancing our understanding of item sensitivity and alignment with student abilities. The consistency seen in the ICC confirms that these items are well-calibrated to measure the abilities of our study participants effectively. The consistency displayed in Figure 3 confirms that these items are balanced in terms of difficulty and their ability to measure the abilities of the study participants [50].

3.5 Item Information Function (IIF)

The Item Information Function (IIF) indicates the amount of information provided by each item at different ability levels [51]. Items that provide more information at a specific ability level are more useful for measuring that ability. High IIF across various ability levels indicates a robust instrument.

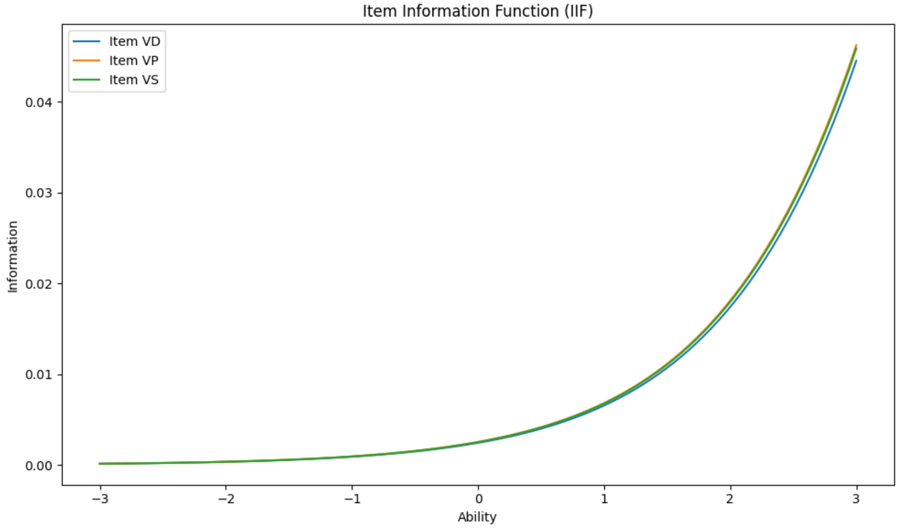

Fig. 4. Item Information Function (IIF) of the Research Data

The description of the curves in Figure 4 illustrates the amount of information provided by each item at different ability levels. The IIF curves for VD, VP, and VS items show an increase in the amount of information as ability increases. The curves appear similar, indicating that these items provide balanced information across various ability levels of the participants. This similarity characterizes VD, VP, and VS items in the graphing quadratic worksheet as equally effective in measuring participants' abilities on the mathematical visual thinking indicators [52].

This balanced information suggests that each set of items (VD, VP, and VS) effectively assesses a wide range of student abilities, which can inform teaching strategies. For example, instructors can use the data from the IIF to identify which students may be struggling with specific visual thinking skills (e.g., VP or VS) and target interventions accordingly. Additionally, the balanced nature of these items allows for differentiated teaching, ensuring that students at different ability levels receive appropriate support. Teachers can focus on strengthening areas where students demonstrate lower information levels, such as improving students' ability to analyze shapes (VS) or perceive visual patterns (VP). This tailored approach can enhance the overall learning experience, making instruction more aligned with the diverse needs of students.

4 Discussion

The findings of this study demonstrate that graphing quadratic worksheets, developed using the Rasch modeling approach, effectively measure and support students' mathematical visual thinking abilities. The score distributions across Visual Discrimination (VD), Visual Perception (VP), and Visual Analysis of Shapes (VS) reveal significant variation in student abilities, with distinct peaks in each category. This variation suggests that tailored instructional strategies may be beneficial in addressing individual student needs in visual thinking. The results highlight the importance of tailored instructional approaches to optimize students' mathematical visual thinking abilities based on the variation in abilities observed across areas such as Visual Discrimination (VD), Visual Perception (VP), and Visual Analysis of Shapes (VS).

The analysis confirms the reliability and validity of the instrument using Item Characteristic Curves (ICC) and Item Information Functions (IIF). ICC results illustrate a positive relationship between students' abilities and the probability of correct responses, showing good item sensitivity across VD, VP, and VS items. IIF analysis indicates that these items provide balanced information across different ability levels, supporting the instrument's effectiveness in comprehensive assessment. This approach, grounded in Rasch theory, contributes a structured model that can enhance future instruments for assessing mathematical visual thinking [53][54][55][56]. This analysis emphasizes that the Rasch-based approach used in developing this instrument provides strong validity and reliability, supporting a more comprehensive and structured measurement of students' mathematical visual thinking abilities.

Practically, this study highlights significant instructional implications. The generally high performance of students in VD, VP, and VS tasks suggests that the worksheets effectively strengthen visual thinking abilities. Further optimization could target weaker areas, particularly in VP, by adjusting content difficulty. This recommendation aligns with visual-based learning theories, which suggest that instructional tools are more effective when tailored to students' abilities [59][60][61]. This recommendation underscores that, while most students perform well, further adjustments, particularly in areas like VP, can enhance the instructional effectiveness in supporting students' visual thinking development.

Compared with previous studies, this research addresses the need for validated instruments in mathematical visual thinking by employing a Rasch modeling approach. Unlike traditional methods, this approach offers specific item difficulty insights and a detailed view of student ability distributions, including a Wright Map visualization, which reveals the relationship between ability levels and item difficulty. This detailed insight enhances instructional precision [62][63][64]. This research integrates mathematical visual thinking theory with practical applications, demonstrating how Rasch modeling can develop instruments that assess visual thinking abilities and identify areas for improvement. The instrument's balanced difficulty levels allow it to be applied across diverse student groups, making it particularly valuable for inclusive education. The Rasch approach employed in this research provides deeper insights into item difficulty and student ability distributions, making it a highly useful tool for enhancing instructional accuracy in mathematics education, especially in inclusive settings.

Overall, this study provides a validated tool for assessing visual thinking and offers actionable recommendations for educators. By identifying ability distributions and item difficulties, teachers can design targeted strategies, such as focusing on challenging items or supporting students struggling in specific areas. This data-driven approach aligns with modern educational demands for personalized learning. Future research could expand this work to different student populations, exploring factors like motivation and logical reasoning to further enhance adaptive instructional practices

[65][66][67]. The findings of this study offer a validated tool for assessing visual thinking and provide actionable recommendations for educators to design targeted learning strategies, while also opening avenues for further research that could enrich adaptive teaching practices.

5 Conclusion

In conclusion, this study demonstrates that optimizing students' mathematical visual thinking abilities through Rasch-modeled graphing quadratic worksheets is both effective and valuable in mathematics education. The Rasch model accurately assessed item difficulty and student abilities, offering clear insights into how students engage with mathematical visual tasks. The Wright Map and Item Information Function (IIF) analyses show that the worksheets provide balanced difficulty levels and information, making them suitable across diverse student abilities. This supports the importance of well-constructed educational tools that enable educators to identify specific needs and implement more tailored, adaptive teaching strategies. Furthermore, this research contributes to bridging mathematical visual thinking theory with educational practice, providing a foundation for developing cognitive assessment tools in mathematics. The findings support data-driven and personalized approaches to curriculum and instruction design, paving the way for more inclusive, adaptive learning technologies. Overall, this model has the potential to inspire further advancements in cognitive assessment within mathematics education.

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