Jurnal Pendidikan Matematika
https://doi.org/10.22342/jpm.v18i3.pp329-348

Primary Student Spatial Reasoning Abilities: Progression and Challenges

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Abstract

Spatial reasoning is essential for success in mathematics and STEM fields, yet it is often overlooked in primary school curricula. This study investigates the levels and progression of spatial reasoning abilities among primary school students in Indonesia, focusing on mental rotation, spatial orientation, and spatial visualization. A cross-sectional study involving 135 students from Year 2, Year 4, and Year 6 used an adapted Spatial Reasoning Instrument. Results showed below-average spatial reasoning abilities overall, with notable improvement with age: Year 2 students averaged a Spatial Reasoning Test Score (SRTS) of 1.66, Year 4 students 2.02, and Year 6 students 2.68. Challenges were identified in tasks requiring multi-step spatial reasoning, spatial language comprehension, and 2D-3D transformations, particularly among younger students. These findings highlight the need for curriculum enhancements and targeted interventions to develop spatial reasoning skills from an early age, improving academic performance in STEM subjects.

Keywords: Spatial Reasoning, Mental Rotation, Spatial Orientation, Spatial Visualisation, Primary Education, Mathematics Education, STEM, Cognitive Development, Educational Interventions

How to Cite: Hasanah, U., Putrawangsa, S., Purwanta, E., Setiawati, F. A., & Purnomo, W. P. (2024). Primary student spatial reasoning abilities: Progression and challenges. *Jurnal Pendidikan Matematika*, *18*(3), 329-348. https://doi.org/10.22342/jpm.v18i3.pp329-348

INTRODUCTION

Spatial reasoning is a cognitive process that forms the basis of spatial skills, which are the ability to navigate and manipulate space (Davis et al., 2015b). These skills are typically divided into three categories (Ramful et al., 2017): spatial visualisation, spatial orientation and mental rotation. Spatial visualisation involves the ability to manipulate or transform spatial information, such as creating, interpreting, using, and reflecting on pictures, images, or diagrams mentally, on paper, or with technological tools to convey information, develop ideas, and enhance understanding (Arcavi, 2003; Lowrie et al., 2017). Spatial orientation, also known as spatial perception or perspective-taking, is the ability to perceive or imagine movement or appearance in space from different locations or viewpoints (Lowrie et al., 2017). Mental rotation, on the other hand, refers to the ability to mentally rotate an object and visualise its spatial properties from different angles as a result of the rotation (Lowrie & Logan, 2018a).

Spatial reasoning skills are critical for understanding and navigating the world around us, and they play a vital role in a wide range of academic and professional fields, especially in mathematics (Hawes et al., 2022; Hegarty et al., 2010; Newcombe, 2010; Putrawangsa et al., 2021; Putrawangsa & Patahuddin, 2022; Stieff & Uttal, 2015; Uttal et al., 2013b). In mathematics learning, for example, spatial reasoning plays a critical role as it provides self-evidence and immediacy, facilitates problem-solving, and promotes the development of mathematical arguments (Arcavi, 2003; Lowrie et al., 2021; Schifter et al., 2008). Research has shown that the employment of spatial reasoning through the use of

Received June 5, 2024; Revised July 25, 2024; Accepted August 14, 2024

spatial representations (e.g., number lines, bars or graphs) in mathematics learning fosters the development of mathematical understanding as they provide visual references for expressing, conjecturing, testing, and refining students' mathematical thinking (Giacomone et al., 2022; Lowrie, 2001; Putrawangsa et al., 2021; Putrawangsa & Hasanah, 2022; Putrawangsa & Patahuddin, 2022; Rivera, 2011).

Despite their importance, spatial reasoning skills are often overlooked in primary school curricula (Bruce et al., 2015; Davis et al., 2015a; Davis et al., 2015b; Davis et al., 2015c). This oversight leads to many students struggling with understanding mathematical concepts that require spatial reasoning, such as geometrical transformations (e.g., translation, rotation, reflection, and dilatation) and with comprehending mathematical ideas presented in spatial representations like Cartesian coordinates, graphs, bars, and maps (Ishikawa & Kastens, 2005). The challenge is particularly pronounced in mathematical tasks involving the transformation between two-dimensional (2D) and three-dimensional (3D) representations (Francis & Whiteley, 2015). This gap in the primary school curriculum highlights the need for a detailed examination of the development and challenges of spatial reasoning in young students, especially primary school students.

To address this need, the present study aims to investigate the level and progression of primary school students' spatial reasoning abilities, focusing on three key constructs: mental rotation, spatial orientation, and spatial visualisation (Ramful et al., 2017). By understanding these abilities and the specific challenges students face, especially in tasks requiring multi-step spatial reasoning and the use of spatial language and representations, we can develop effective educational strategies to enhance these critical skills.

In addition, research indicates that spatial reasoning abilities develop gradually over time, with significant variation among individuals based on age and prior experiences (Okamoto et al., 2015; Uttal et al., 2013a). While older students generally exhibit more advanced spatial reasoning skills due to increased exposure to spatial-related tasks in their curriculum, younger students often struggle with complex spatial tasks. This study specifically examines these developmental differences and challenges within an Indonesian primary school context, where spatial reasoning has been identified as an area needing attention. Therefore, two main research questions were investigated in this study, namely (1) What is the level and progression of students' spatial reasoning abilities at the primary-school level? And (2) What are the difficulties and challenges in reasoning spatially for primary students?

By linking the findings to the notions of schematic spatial reasoning (Hegarty & Kozhevnikov, 1999) and diagrammatic reasoning (Giacomone et al., 2022), this study also seeks to demonstrate the potential impacts on students' mathematical learning and problem-solving abilities. The insights gained can inform curriculum design and teaching practices aimed at fostering spatial reasoning skills from an early age, ultimately improving students' academic performance and future career prospects in STEM fields.

METHODS

The current research is a cross-sectional study since it aims to investigate the prevalence and patterns of spatial reasoning abilities and challenges among several different-year levels of primary students at a single point in time (Creswell & Creswell, 2023; Gilligan-Lee et al., 2021). Students' spatial reasoning abilities were investigated through a spatial reasoning test consisting of three constructs of spatial reasoning skills, namely mental rotation, spatial orientation, and spatial visualisation (Ramful et al., 2017). A separate quantitative approach was employed to answer each research question. The details of the approaches were elaborated on in the data analysis section.

The total number of participants involved in this study was 147 students, 12 of them were involved during the pilot test, and the remaining 135 students participated in the data collection for the current study. The 135 students were taken from six classes in a public primary school in Indonesia, consisting of two classes for each Year 2, Year 4 and Year 6, with the distribution shown in Table 1.

Table 1. The distribution of the participants involved in the study.

Level	Number of participants	Male	Female
Year 2	44	21	23
Year 4	47	28	19
Year 6	44	17	27
Total	135	66	69

The students' spatial abilities were measured through a spatial-ability test (SAT). The test items used in this study were adapted from Ramful et al. (2017)'s spatial reasoning instrument (SRI). As in SRI, three constructs of spatial reasoning measurement were considered in this study, namely mental rotation (MR), spatial orientation (SO), and spatial visualisation (SV). Since the SRI was initially developed for middle school students, we made some adaptations to the SRI test items to make it appropriate to be used for elementary students. The adaptations were conducted in three stages, namely selections, modifications, and elimination, as elaborated in the following paragraphs.

In terms of selections, we first selected 12 items from 30 items in the SRI consisting of 4 MR items, 4 SO items, and 4 SV items. The selection of the items was based on the coverage in measuring the skills in each construct and their complexities. For example, the four items of the mental rotation were selected based on the following considerations: mental rotation of a simple 2D object (1 item), mental rotation of a simple 3D object (1 item), mental rotation of a complex 3D object (1 item) and mental rotation of multiple objects involving textual/contextual information (1 item).

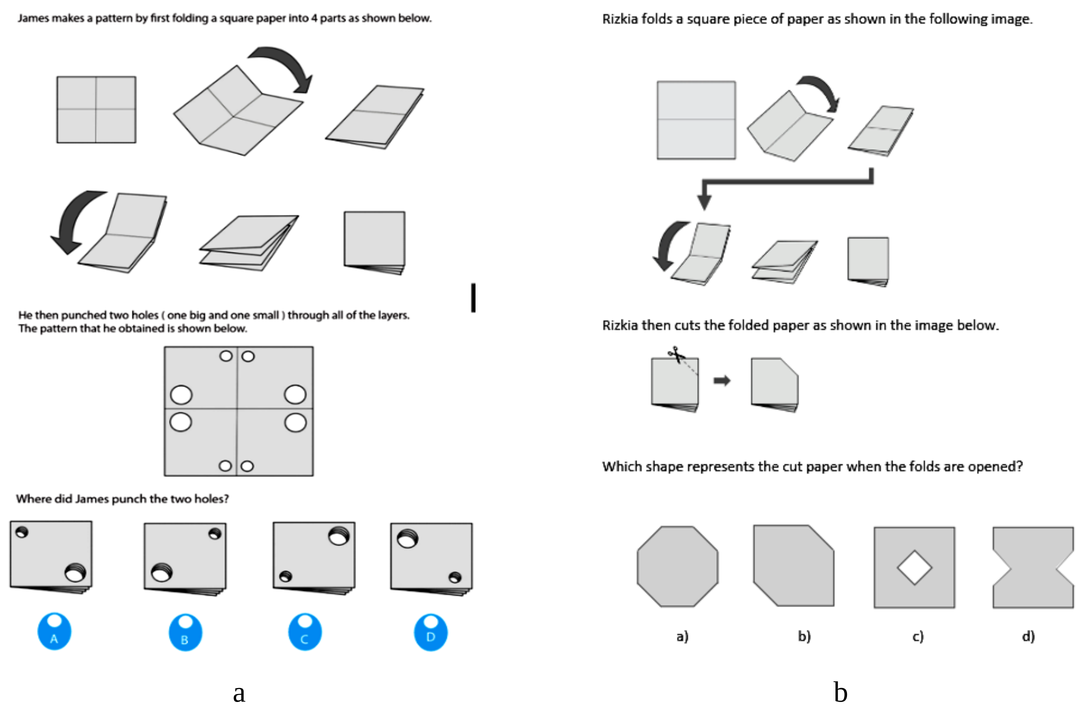


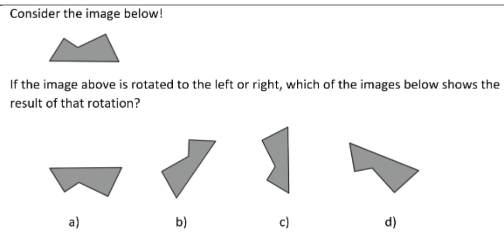
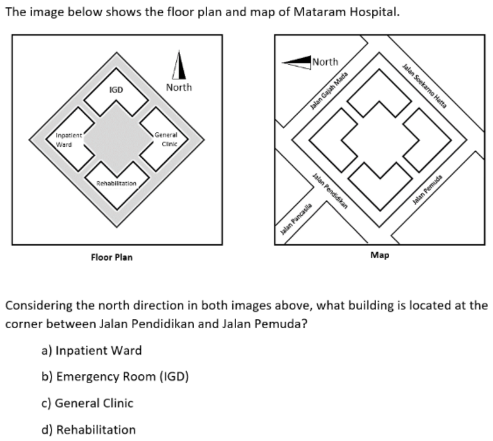
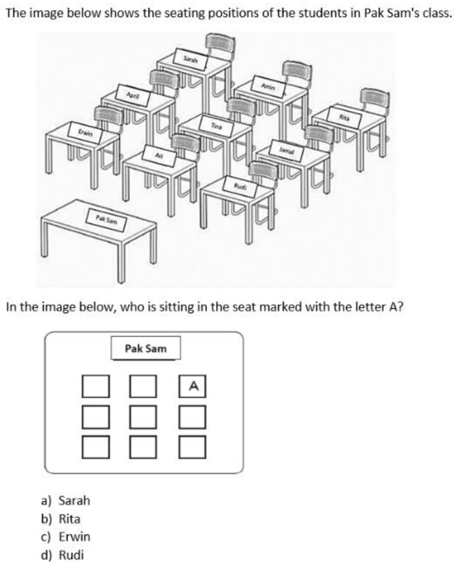
Figure 1. Test item modification: (a) the original version and (b) the modified version

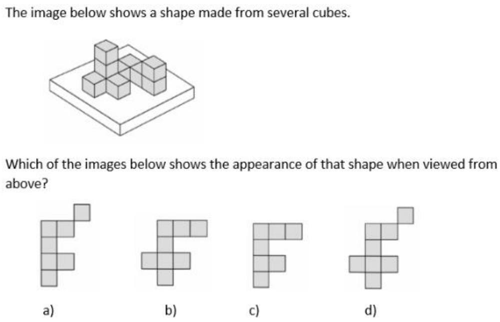
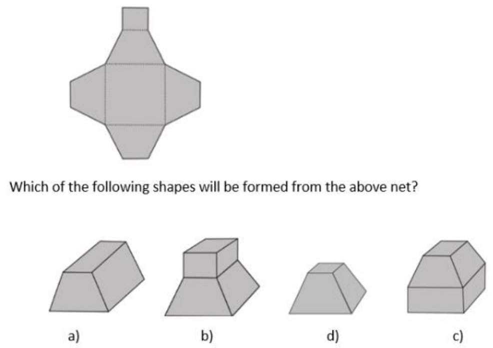
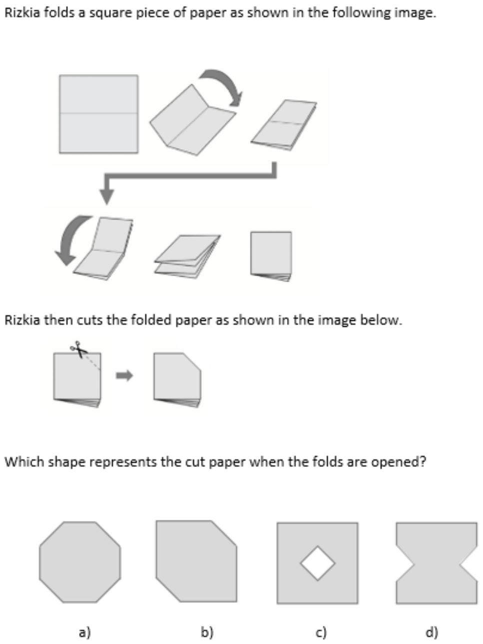
In terms of modification, the 12 selected items were then slightly modified to reduce their complexity to meet the level of the primary students. Figure 1a, for example, shows the original test item from SRI for a spatial visualisation item (see Ramful et al., 2017). It requires students to not only visualise the multiple folding processes but also imagine the spatial effects of folded and unfolded states of the paper with multiple holes within the area of the paper. The item was slightly modified to reduce its complexity by focusing on the spatial effect of cutting on one edge of the folded paper (see Figure 1b).

In the elimination process, the 12 modified items were initially tested on primary students to check their readability and suitability for the primary student level. In this pilot test, twelve year-three primary students were involved (7 males and five females). The findings from the pilot test were used as the final consideration in selecting the final set of test items for the current study, where six items were eligible and selected for use in this study (see Table 2). The six items represent the three constructs of spatial reasoning skills (i.e., two items for each mental rotation, spatial orientation, and spatial visualisation) and cover various aspects of spatial reasoning in each construct (e.g., single-object rotation and multiple-object rotation).

Considering the rigorous process of developing test items elaborated above, we were convinced that the selected items could be used to assess primary students' spatial reasoning abilities. The assembly of the final test items was based on both theoretical and practical considerations. The test constructs and the items were taken from the existing reputable test instruments (i.e., Ramful et al., 2017). Then, they were slightly modified to meet the level of targeted subjects. The modified items were then empirically tested to check their legibility for the targeted subjects and to eliminate less appropriate items.

Table 2. The spatial reasoning test items and their characteristics

Construct	Item	Description/Characteristic
Mental Rotation 1 (MR1)		This item requires students to investigate spatial changes in an object as a result of a rotation, namely the change in the appearance of an object due to a rotation clockwise or anti-clockwise.
Mental Rotation 2 (MR2)		This item requires students to investigate spatial changes on multiple interconnected objects simultaneously, including their relative positions and locations, as a result of a rotation, namely the change in the appearance, location and position of a set of interconnected objects due to a rotation clockwise or anti-clockwise. Moreover, this item requires the students to process textual/contextual information presented in the item in relation to the spatial changes.
Spatial Orientation 1 (SO1)		This item requires students to view the appearance of a set of objects from a different perspective with a directed or indicated reference (e.g., Pak Sam's position). It requires considering the position or location of the targeted object with respect to other objects.
Spatial Orientation 2 (SO2)		This item requires students to view the appearance and simultaneously the structure of a set of objects

Construct	Item	Description/Characteristic
		from a different perspective without a directed or indicated reference (i.e., the students decide their own reference). It requires not only considering the position or location of the targeted object with respect to the other objects but also the structure of the units constructing the objects.
Spatial Visualization 1 (SV1)		This item requires students to investigate the spatial movements or changes of a set of objects with a single-degree movement or change (e.g., investigating a spatial change in a paper as a result of folding the paper once).
Spatial Visualization 2 (SV2)		This item requires students to investigate the spatial movements or changes of a set of objects with multiple-degree movements or changes (e.g., investigating a spatial change in a paper as a result of folding the paper multiple times consecutively).

With respect to the research questions, two separate methods of assessing students' responses to the given test were employed, namely the levelling method (to identify students' spatial reasoning level and progression) and the rating method (to assess students' difficulties in reasoning spatially). Regarding the first method, we employed Ramful et al. (2017) method of scoring a spatial reasoning test consisting of three steps. The first was scoring students' responses in each item for each construct into 1 or 0 for correct and incorrect responses, respectively. The second was counting the construct score by averaging the item scores in each construct. Finally, the measure of an individual's or group's spatial abilities was generated by summing the construct scores from those three spatial reasoning constructs. By applying the method above, the score of the spatial reasoning abilities in this study falls in the interval between 0 and 6. We then partitioned the interval into ten equal sections (see Table 3) where the length of each section was 0.6 (*Note*. 0.6. was generated from dividing the maximum score of the spatial reasoning test by the number of the intended partitions, which is 6/10=0.6). We employed these levels to indicate students' spatial reasoning abilities at each year's level and to investigate the progress of students' spatial reasoning abilities throughout the years.

Table 3. The level of students' spatial reasoning ability based on the spatial reasoning test score (SRTS)

Level	SRTS Interval	Description
Level 10	$5.40 \leq SRTS \leq 6.00$	Very high score
Level 9	$4.80 \leq SRTS < 5.40$	High score
Level 8	$4.20 \leq SRTS < 4.80$	Moderately high score
Level 7	$3.60 \leq SRTS < 4.20$	Above intermediate score *
Level 6	$3.00 \leq SRTS < 3.60$	Slightly above intermediate score
Level 5	$2.40 \leq SRTS < 3.00$	Slightly under intermediate score
Level 4	$1.80 \leq SRTS < 2.40$	Under intermediate score
Level 3	$1.20 \leq SRTS < 1.80$	Moderately low score
Level 2	$0.60 \leq SRTS < 1.20$	Low score
Level 1	$0.00 \leq SRTS < 0.60$	Very low score

Note. *) The intermediate score of the spatial reasoning test score (SRTS) is 3.

Meanwhile, in the rating method, students' difficulties in dealing with the test items were rated by counting the mean or average score of each item. The items having relatively small mean scores were considered challenging for the students and the other way around. We then referred to the characteristics of the items presented in Table 2 to seek for explanation or the possible rationale underpinning those challenges.

RESULTS AND DISCUSSION

The results of students' performance on the spatial reasoning test were displayed in two sections. Following each section, we discussed the findings in relation to the relevant literature to highlight the theoretical contributions or significance of the current study.

In the first section, students' performance on the given spatial test was displayed. The main point of this coverage is to provide an overview of the students' spatial reasoning abilities throughout the years within the three spatial constructs (i.e., mental rotation, spatial orientation, and spatial visualisation). These data were used as the basis to highlight students' spatial reasoning level and the progression of their spatial reasoning abilities throughout the years.

The second section displayed students' difficulty rate in dealing with the spatial reasoning test, construct by construct and item by item. These data were used to emphasise students' challenges in performing spatial reasoning and to show that students of different ages encountered slightly different forms of spatial challenges.

Level and Progression of Students' Spatial Reasoning Abilities

The spatial reasoning test shows some interesting findings. The overall score of the spatial reasoning abilities of the participating students was 2.12, setting them in Level 4 from the ten levels (see Table 4 and Table 3). It is surely far from the highest level (i.e., Level 10 with $5.40 \leq \text{SRTS} \leq 6.00$) or even below the medium level (i.e., Level 5 with $2.40 \leq \text{SRTS} < 3.00$). This finding suggests that the students' spatial reasoning abilities were apprehensive and needed attention.

Table 4. Students' spatial reasoning test scores throughout the years

Spatial constructs	Year 2	Year 4	Year 6	Overall
Mental rotation score (MRS) *	0.59	0.64	0.95	0.73
Spatial orientation score (SOS) *	0.41	0.77	0.86	0.68
Spatial visualisation score (SVS) *	0.66	0.62	0.86	0.71
Spatial reasoning test score (SRTS) **	1.66	2.02	2.68	2.12

Note. *) The construct scores were obtained by averaging item scores obtained in each construct. **) SRTS is obtained by summing the scores of the three contracts of spatial reasoning skills (Ramful et al., 2017).

Although the overall spatial reasoning test score was alarming, there was a stable progression in students' spatial reasoning abilities throughout the years (see Figure 2). The students in Year 2 were able to score 1.66, positioning them in Level 3. A slightly better result is shown by the students in Year 4, where they obtained 2.02 SRTS, putting them in Level 4. Meanwhile, Year 6 students obtained the highest SRTS among the other two groups, which was 2.68, placing them in Level 5. Thus, the development of spatial reasoning abilities among the primary students expanded from Level 3 (SRTS 1.66) to Level 5 (SRTS 2.68), where the disparity between the lowest and the highest scores in Year 2 and Year 6, respectively, was relatively appreciable (i.e., 1.02 points).

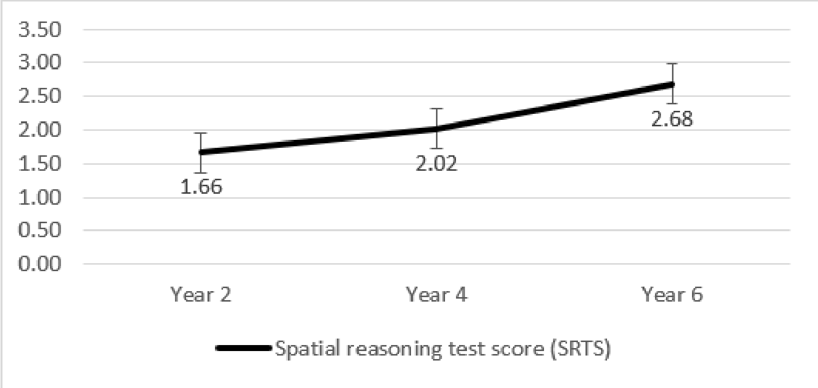


Figure 2. The progression of primary students' spatial reasoning abilities throughout the years

Like the overall tendency, the trends of students' spatial performance in each construct show positive development throughout the years, although some constructs experienced fluctuations (see Figure 3). While spatial visualisation scores experienced instability, mental rotation and spatial orientation scores show stable progressions throughout the years. The average score of the students' mental rotation was initially 0.59 in Year 2 and gradually increased to 0.64 in Year 4 before a significant growth in Year 6, reaching 0.95 (i.e., the highest construct score among three constructs throughout the years), see Table 4. Like mental rotation, spatial rotation scores increased progressively, starting from 0.41 in Year 2 (i.e., the lowest construct score among three constructs throughout the years) to 0.77 in Year 4 and finally reaching 0.86 in Year 6. Unlike the previous two constructs, spatial visualisation scores experienced instability, although they showed positive development over the years. At year 2, it was 0.66 (i.e., the highest score among the three constructs in the same year), but then dropped to 0.62 in Year 4 (i.e., the lowest score among the three constructs in the same year) before sharply increasing to 0.86 at Year 6.

The progression rate of spatial reasoning abilities among the three constructs varied. Among the three constructs, the progression rate of spatial orientation was the highest, where the discrepancy of the construct score between Year 2 and Year 6 reached 0.45 (i.e., 0.86 – 0.41, see Table 4). In contrast, spatial visualisation experienced the slowest progression rate, which was only 0.20. Meanwhile, mental rotation scores show a moderate development speed which is 0.36.

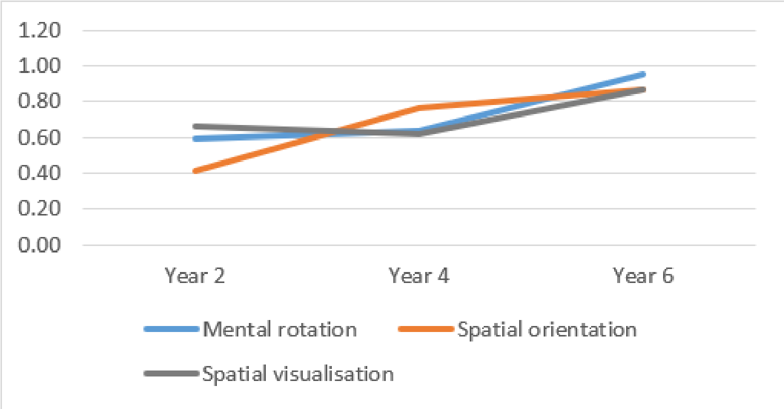


Figure 3. The trends of students’ spatial reasoning abilities in the three constructs of spatial reasoning skills

Overall, the findings of the current study suggest that the primary students’ spatial reasoning abilities were apprehensive, especially in the context of Indonesian students. One of the reasons for the alarming findings is the fact that school curricula throughout the world, including in Indonesia, pay little attention to students’ spatial reasoning development (Bruce et al., 2015; Davis et al., 2015a; Davis et al., 2015b; Davis et al., 2015c; Lowrie & Logan, 2018b; Woolcott et al., 2022) since spatial reasoning is critical for students’ academic achievement and future careers (Hawes et al., 2022; Hegarty et al., 2010; Newcombe, 2010; Putrawangsa et al., 2021; Putrawangsa & Patahuddin, 2022; Stieff & Uttal, 2015; Uttal et al., 2013b), these concerning findings warrant the attention of educational policy-makers and practitioners in designing school curriculum and implementing learning strategies that priorities the enhancement of students' spatial reasoning abilities.

However, there was a positive progression where their spatial reasoning abilities improved gradually with respect to their ages (i.e., getting better as they get older), although the different aspects of spatial development may progress at varying rates. This finding is in line with other studies highlighting that age is one of the significant factors contributing to the development of young children’s spatial reasoning abilities (Fujita et al., 2020; Gilligan-Lee et al., 2021; Hodgkiss et al., 2021; Okamoto et al., 2015). Gilligan-Lee et al. (2021), for example, found that age has an impact on the development of spatial language in children, where the production and comprehension of spatial language in older children are superior to that of their younger peers. Moreover, Fujita et al. (2020) identified that older children demonstrate a more advanced level of spatial maneuvers than their younger counterparts when confronted with tasks related to spatial reasoning in mathematics.

However, we believe that age was not the only factor contributing to the development of spatial reasoning among children. The findings of the current study suggest that students’ prior learning experiences are another potential factor that influences the progression of students’ spatial reasoning capacities. It is because the older students (e.g., Year-6 students) had been exposed more intensively to spatial-related subjects in their learning experiences (e.g., learning geometry) compared to the younger group (e.g., Year-2 students). Many studies also suggested that students' prior knowledge is another factor known to impact students' spatial reasoning abilities (Bower et al., 2020; Jirout & Newcombe, 2015; Lowrie et al., 2019; Uttal et al., 2013b). For instance, Lowrie et al. (2019) identified that the children who had a prior learning experience of spatial visualisation, such as working with building blocks, had a substantial progression in their spatial reasoning skills compared to a control group.

Difficulties and Challenges in Reasoning Spatially for Primary Students

We investigated students' difficulties and challenges in reasoning spatially by examining their difficulties in dealing with the given spatial reasoning test items. There were six items used to measure students' spatial reasoning, and each construct was evenly measured by two items. The level of difficulty for an item was generated by averaging students' scores in the item. Meanwhile, the level of difficulties for a construct was determined by averaging the average scores of the two items representing the construction, as each construct was measured by two items. The results of the measurements were presented in Figure 4 and Figure 5 for the constructs and the items, respectively. The smaller the average scores, the more difficult the item or the construct for the students, and the other way around.

In general, the level of difficulties of the three constructs was relatively similar throughout the years, although noticeable differences were identified in each year level. Spatial orientation (SO) was slightly more challenging for the students (i.e., 0.34) compared to the other two constructs (see Figure 4). It was the most challenging spatial task for Year 2 students, while it was the most manageable task for Year 4 students and considered a moderate task for Year 6 students. In contrast, mental rotation was considered the most manageable spatial task compared to the other two constructs. It was a moderate task for Year 2 and Year 4 students and the most manageable task for Year 6 students. Spatial visualisation was considered to have a moderate level of difficulty for the students. It was the most manageable task for Year 2, but it was the most difficult task for Year 4 and was a relatively moderate task for Year 6.

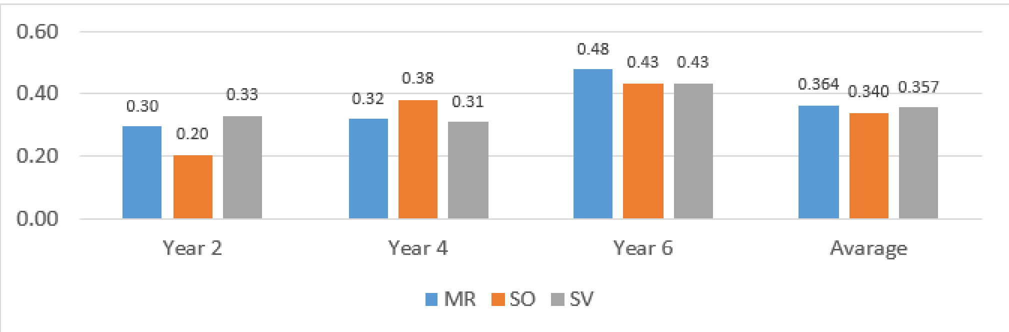


Figure 4. Level of difficulties in the three constructs of the spatial reasoning test

Note. Mental Rotation (MR), Spatial Orientation (SO) and Spatial Visualisation (SV). The smaller the scores, the more difficult the constructs.

If each item was considered, a noticeable pattern of findings was revealed. The second item of mental rotation (MR2), together with the second item of spatial orientation (SO2) and spatial visualisation (SV2), were among the most challenging spatial tasks for the students throughout the years (see Figure 5). In contrast, the first item of the mental rotation (MR1) was the most familiar spatial task, together with the first item of both spatial orientation (SO2) and spatial visualisation (SV2). These findings suggest that the first spatial items in each construct were relatively more familiar for the students compared to the second items.

It was found that the characteristics of the items supplied the complexity level of the items. Referring to Table 2, the first items in each construct (i.e., MR1, SO1, and SV1) measured relatively simpler spatial reasoning tasks (e.g., one-step spatial reasoning) compared to the second items (i.e., MR2, SO2, and SV2) which required multi-step spatial reasoning and maneuvers. The first item relatively asked the students to observe and do a single step of spatial maneuver with less engagement with spatial languages and spatial representations. MR1, for example, simply asked the students to mentally rotate a simple object where intensive spatial language and representation processing were not stimulated or necessary to do so.

In contrast, the second item in each spatial construct required the students to do multiple-step spatial maneuvers with high engagement with spatial languages and spatial representations. For example, MR2 required the students to mentally rotate multiple objects simultaneously, where the students had to consider multi-layers of spatial changes and relations involved in the spatial maneuvers both within an object or between objects. Here, they need to be aware of the changes in the position and locations of the objects in relation to other objects as the result of the spatial maneuvers (e.g., the position of IGD in relation to Pancasila Street after rotating the map 45 anti-clockwise). Furthermore, this item required the students to process spatial information presented in languages (e.g., north and between) that enhanced the complexity of this item. On top of that, this item was presented in the form of a map, a two-dimensional representation of real three-dimensional objects, where research found that processing this type of spatial representation is one of the young students' challenges (Francis & Whiteley, 2015; Ishikawa & Kastens, 2005; Lowrie, 2002). With all those complexities, it is not surprising that this item became the most challenging item for the students throughout the years, especially for younger students, Year-2 and Year-4 students (see Figure 5).

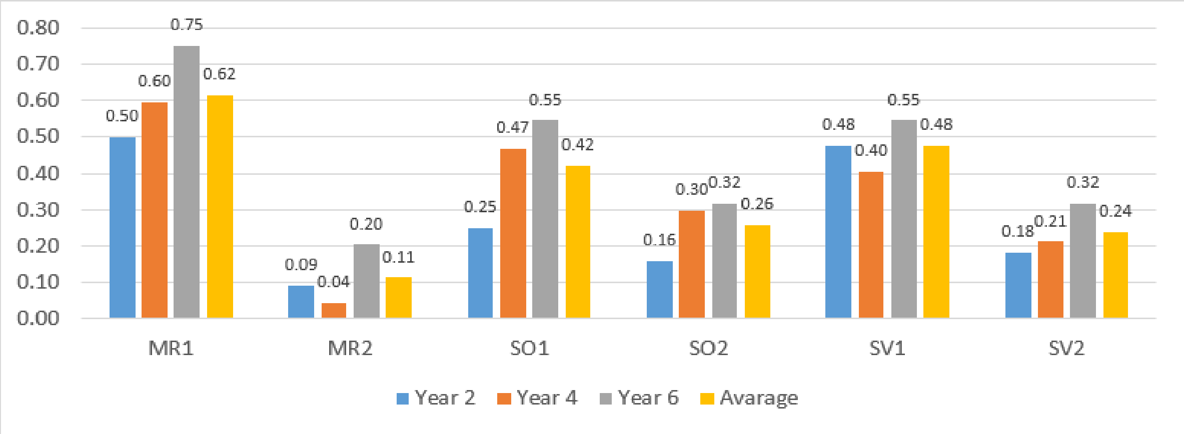


Figure 5. Level of difficulties in the six items of the spatial reasoning test

Note. Mental Rotation (MR), Spatial Orientation (SO) and Spatial Visualisation (SV). The smaller the scores, the more difficult the items.

Primary students' difficulties and challenges in reasoning spatially identified in this study are in line with assertions made by other previous studies about young children's challenges in dealing with spatial reasoning, spatial language and spatial representations. Francis and Whiteley (2015) and Lowrie (2002), for example, highlight that some children struggle in performing spatial maneuvers when interpreting or transforming a two-dimensional (2D) representation to its three-dimensional (3D) real object represented by the representation. In this study, we also identified similar challenges where most of the students struggled to deal with spatial tasks that required them to imagine and interpret two-dimensional spatial information to its real three-dimensional situation (e.g., MR2). In interpreting a rotating map (i.e., MR2), for example, the students (especially the younger age, Year 2 and 4) were hardly able to identify the spatial changes on the map (i.e., position and location) when the map was rotated anti-clockwise. Furthermore, this spatial task required the students to activate their spatial languages (e.g., left, right, north, south, behind, in front, etc.) as they were dealing with the changes of position and location of objects as the result of a rotation. Understanding and using spatial language is essential for spatial reasoning, but it can be challenging for primary school students, especially younger students (Gilligan-Lee et al., 2021). These complexities embedded in the task are probably the rationales why this task was the most difficult task for the students, especially for the younger age (see Figure 5), where inappropriate interpretation of spatial representations could diminish students' problem-solving processes (Boonen et al., 2014).

While many studies have confirmed young students' difficulties in spatialising 2D-to-3D transformation, the findings of the current study added further assertions that young children also struggle in reasoning spatially about 3D-to-2D transformation. In dealing with SO2, for example, many students were not able to appropriately interpret the 3D spatial structure into a 2D representation (see Figure 5). Similarly, students' responses to SV2 indicated that many students struggled to identify the effect of 3D manipulations on a 2D representation. Students' challenges in reasoning spatially on linking between 2D and 3D spatial representation identified in this study are probably one of the justifications underlying students' challenges in interpreting real-life information presented in a spatial model, such as a map or flow chart (Ishikawa & Kastens, 2005).

The Implications of The Findings to Mathematics Learning

We drew the implications of the findings of the current study by discussing the notion of schematic spatial reasoning and diagrammatic reasoning in mathematics learning. Schematic spatial reasoning abilities relate to the ability to recognise spatial relations and transformations and employ those abilities to think, understand, and communicate ideas and relations (Hegarty & Kozhevnikov, 1999). We often utilise schematic spatial reasoning to visualise abstract concepts presented in written or verbal forms to see the relations and understand the situations. For example, we employ number lines to understand number relations (Putrawangsa & Hasanah, 2022) or bar models to grasp part-whole relationships in percentages (Putrawangsa et al., 2021). Schematic spatial reasoning is critical in mathematics problem-solving as spatial representations are widely used in mathematics problem-solving processes (Hegarty & Kozhevnikov, 1999; Putrawangsa et al., 2021), and the inability to perform this reasoning potentially hampers students' mathematics development (Hegarty & Kozhevnikov, 1999). Meanwhile, diagrammatic reasoning can be defined as a type of reasoning that is used to grasp, manipulate, and assess information presented in a diagram (or diagrams), a visual representation of objects or concepts that can be used to communicate, analyse, or solve problems (Bakker & Hoffmann, 2005; Giacomone et al., 2022). Diagrammatic reasoning is often used in domains that involve the investigation of spatial relations and transformation among physical objects, and it is critical in mathematics problem-solving (Giacomone et al., 2022), especially in statistics (Bakker & Hoffmann, 2005). It helps students to make sense of concepts, data, or information presented in visual forms, such as diagrams, flowcharts, or graphics.

The link between schematic spatial reasoning and diagrammatic reasoning is intimate. As both deal with visual representations of mathematics, both reasoning consider spatial reasoning as a critical cognitive process in processing spatial information and relations presented in visual forms (Giacomone et al., 2022; Tessler et al., 1996). Therefore, deficiency in spatial reasoning abilities potentially hinders students' schematic spatial reasoning and diagrammatic reasoning, which consequently hampers the development of students' mathematics literacy and problem-solving skills, especially in geometry and statistics where concepts, data and information are intensively and extensively presented in visual forms.

As elaborated in the previous sections, the current study shows that most of the students throughout the years experienced difficulties in investigating spatial changes involving multiple spatial relations and maneuvers. Item MR2, for example, requires the students to examine the changes in the positions and locations of multiple objects presented on a map that are rotated simultaneously. Meanwhile, item SV2 requires the students to investigate spatial changes presented in a flowchart as the result of multiple spatial maneuvers (e.g., folding a paper recurrently). These spatial weaknesses potentially impede both students' schematic spatial reasoning and diagrammatic reasoning abilities, which are critical in developing mathematics understanding and enhancing problem-solving skills. This implies that if students do not develop adequate spatial reasoning skills, it could result in various negative impacts on their progression in mathematics learning, especially in mathematics learning that intensively and extensively uses visual representations, such as learning about statistical concepts.

CONCLUSION

In the current study, we aimed to address two main research questions: (1) What is the level and progression of students' spatial reasoning abilities at the primary-school level? and (2) What are the difficulties and challenges in reasoning spatially for primary students? To answer these questions, we developed a spatial reasoning test by adapting a model of spatial reasoning instrument and tested it on 135 primary students across three different year levels (Year 2 = 44, Year 4 = 47, and Year 6 = 44). We employed a method of scoring that classified the scores into ten sections to assess students' spatial reasoning levels in each group and their progression across the three-year levels. Furthermore, we clarified students' challenges in spatial reasoning by measuring the level of item difficulties. Linking to the characteristics of the items, the difficulty level in each item informed the typical challenges students face in spatial reasoning.

This study highlights several important points. In relation to the first research question, the findings show that the spatial reasoning abilities of the primary students involved in this study were concerning. School curricula and classroom learning practices that pay little attention to students' spatial reasoning development could contribute to their inadequate spatial abilities. These findings should be a warning for educational policymakers and practitioners to pay more attention to the development of students' spatial reasoning abilities, as these capacities are critical for students' academic success and future careers. The findings suggest the importance of integrating spatial reasoning as a pedagogical approach to promoting learning, especially for STEM-related subjects.

However, there was a positive progression throughout the years, with students' spatial reasoning abilities improving gradually with age. Nevertheless, age was not the only factor contributing to the progression of the students' spatial reasoning. The students' prior learning experiences potentially impacted the development of their spatial reasoning abilities, as older students (e.g., Year-6 students) had been more intensively exposed to spatial-related subjects in their learning experiences (e.g., learning geometry) compared to the younger group (e.g., Year-2 students). These findings suggest the importance of providing adequate spatial-related prior experiences through spatial interventions to enhance the rate of students' development of spatial reasoning.

In relation to the second research question, there were no substantial differences in students' spatial performance among the three constructs of spatial reasoning, although there were differences in difficulty rates among the constructs. Instead, the characteristics of the spatial tasks were the major factor contributing to students' challenges in performing spatial reasoning. For example, most students, especially the younger groups, struggled with spatial tasks that required them to perform multi-steps of spatial reasoning and maneuvers simultaneously, involving processing spatial languages and spatial relations presented in a spatial representation (e.g., a map or flow chart). However, comprehending this type of spatial skill is necessary to support students' learning where spatial representations are intensively used, such as in learning mathematics. These findings suggest the importance of nurturing students' spatial reasoning from an early age to support them in processing more complicated spatial reasoning tasks that benefit their academic achievement and future career.

ACKNOWLEDGMENTS

Writing this paper would be impossible without support from many parties. Thank you to the students and teachers of SDN 3 Kuripan, Lombok Barat, NTB who were involved during the data collection. Special thanks to our colleagues both at Universitas Negeri Yogyakarta and the University of Canberra for their feedback and insight inspiring this study, and to the Indonesia Endowment Funds for Education (LPDP) who found this study.

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