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Research on spatial reasoning in mathematics education: Trend and opportunity

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Abstract

Spatial thinking is important in learning Science, Technology, Engineering, and Mathematics. Numerous studies about spatial ability in various fields like mathematics, neuroscience and phycologist considered various factors such as gender, age, or demography. However, a few studies are still about enhancing spatial ability in the context of mediated pedagogies. This study aims to describe spatial research on mathematics education, especially related to the intervention or learning design of spatial reasoning. A bibliometric study is employed to determine the research trend of spatial reasoning, especially related to teaching practice. The review follows a structured design consisting of several stages of the PRISMA method. From 652 documents about spatial in mathematics education gathered from the Scopus data, it is reduced to 40 documents regarding spatial reasoning in mathematics education. Further, only 19 documents about intervention and practice in enhancing spatial reasoning exist. This study may benefit researchers in mathematics education by showing the development and trend of spatial reasoning research and suggesting new directions for future research.

Keywords: bibliometric; SLR; spatial reasoning; intervention

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I. Introduction

Spatial has started to be researched since 1962, and it still has interesting aspects to be studied further until now. Spatial thinking, also so-called spatial ability, spatial skill, visual-spatial representation, or spatial reasoning, is defined by (Lohman et al., 1996, p. 97) as an 'ability to generate, retain, retrieve, and transform well-structured visual images'. So, the core components of the framework of spatial thinking (Ramful et al., 2017) are mental rotation, spatial visualization and spatial orientation (Linn & Petersen, 1985).

Spatial thinking is an important factor in learning science, technology, engineering, and mathematics (Wintarti, 2021), and it affects one's success (Fowler et al., 2021). Humans undeniably interact with spatial models of objects and spatial relations between objects or explore the spatial coordinates of places and spaces in their daily activities (Uttal et al., 2013). Simple examples are how we organize our things, locate an object in a room, draw a map, navigate, transform, and see symmetry (Bruce et al., 2017). Thus, even though spatial activities are not constrained to a particular topic in mathematics, spatial thinking or reasoning ability needs to be trained.

Numerous studies about spatial ability in fields like mathematics, neuroscience and phycologist consider factors such as gender, age, or demography (Bruce et al., 2017). The studies show that spatial ability has a positive correlation with mathematics. Students who perform better in spatial tasks have better achievement on mathematics tests (Wintarti, 2021). However, only some mathematics curricula of every country address spatial as one particular topic should be taught in school. Some countries integrated it into the topic of geometry (Wintarti, 2021). There is research on spatial teaching practice, even though it is still a few.

Digital transformation and technological development bring abundant opportunities to teach mathematics powerfully. Many software and applications can engage students in spatial activities and tasks. These technologies provide a chance to enhance students' spatial thinking abilities. However, a few studies are still about enhancing spatial ability in the context of digitally mediated pedagogies (Fowler et al., 2021). Based on the best knowledge, there has yet to be literature review research to determine the research potential of spatial reasoning. Research on spatial reasoning is needed to fill the existing gap and find new directions. This study aims to describe spatial research on mathematics education, especially related to the intervention or learning design of spatial reasoning. This study may benefit researchers in mathematics education by showing the development and trend of spatial reasoning research and suggesting new directions for future research.

The research questions to be addressed in this study are:

1. How has the trend of spatial reasoning in mathematics education research been from the appearance of the first article until 2023?
2. How has the research trend of spatial reasoning regarding learning intervention over the past 20 years been viewed from the subject, intervention approach and method, related mathematical topics, and the utilized technology?
3. What is the future research opportunity related to spatial reasoning teaching/intervention?

II. Research Method

A bibliometric study (Dong et al., 2012; Kulakli & Osmanaj, 2020; Yang et al., 2017) is employed in this study to find out the research trend of spatial reasoning, especially related to teaching practice. Bibliometrics can make it easier for researchers to search for research trends on a topic more quickly using a website or application. Vos Viewer Excel software and the Scopus database were used in this research. Data was collected from the Scopus database since it includes documents from journals and proceedings considered more relevant and reliable by the scientific communities, as well as for their constancy and periodicity. An online search conducted between 18 and 22 December 2023 was the first step of research. The review follows a structured design with several stages (Figure 1). The PRISMA (Preferred Recording Items for Systematic Review and Meta-analysis) method (Moher et al., 2009) determines the most relevant document to answer each research question. PRISMA steps include identifying, screening, and finding eligible articles and articles that include the topic.

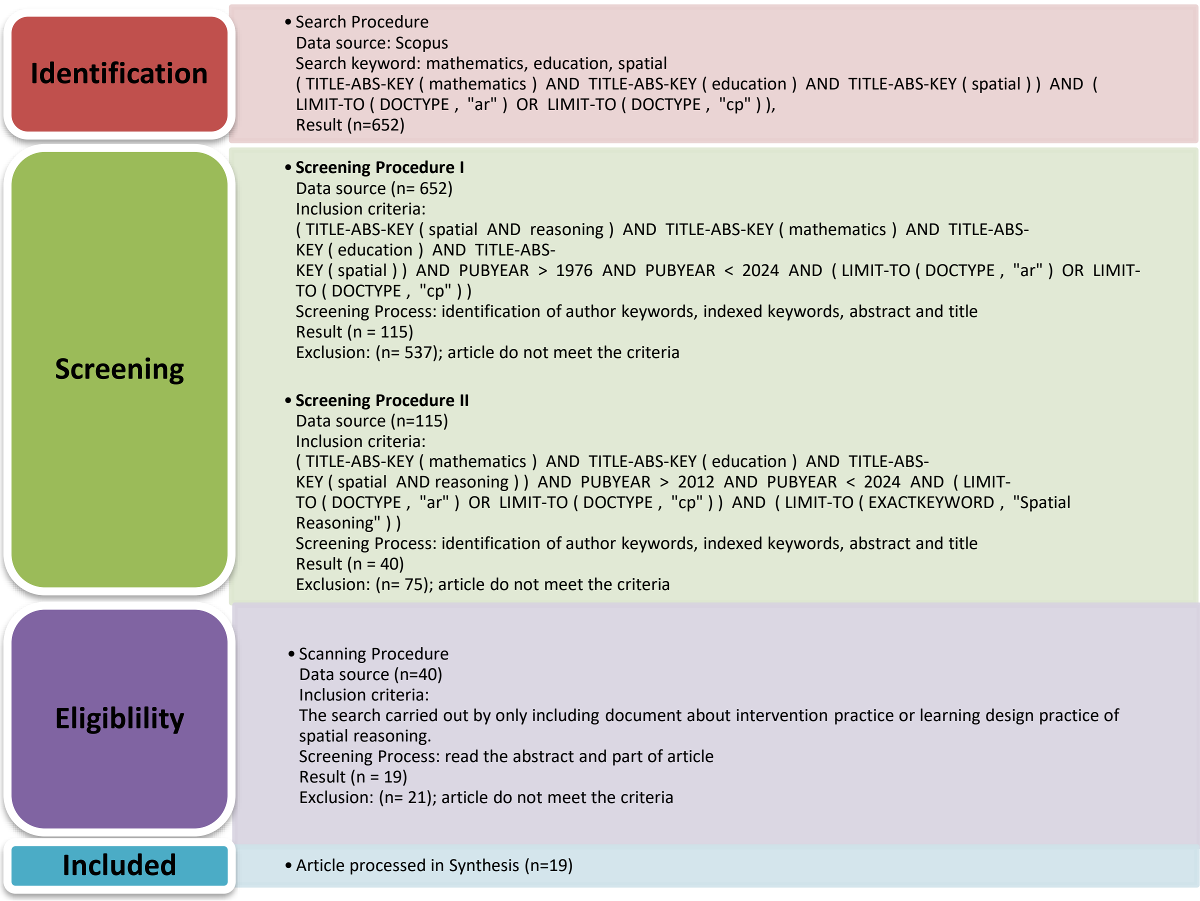

Figure 1. The PRISMA Flow Diagram

The first search attempt was done by inputting the keywords "mathematics", "education", and "spatial". This results in 652 documents, which are then reduced to 115 by adding the keyword "spatial reasoning". Limiting the keyword with exact keywords "spatial reasoning" and limiting the year of the publication to the last decade, then it results in 40 documents. The analysis is performed briefly on the 652 and the 115 documents to get a general trend on spatial and spatial reasoning research. Further, to gain more information about the trend in spatial reasoning over a decade, an analysis has been done on the 40 documents. To answer the last question regarding teaching or intervention design to enhance spatial reason, the documents are sorted into 19 relevant documents to spatial teaching practice and then coded analyses.

The VoSViewer software was utilized to determine the spatial reasoning research trend in the last 10 years (Eck & Waltman, 2020). The analysis employs the co-occurrence of keywords (author's keywords and indexed keywords), which uses a Visualization of Similarities algorithm (VOS) for multidimensional scaling (Putri et al., 2021).

III. Results and Discussion

Inputting the source (TITLE-ABS-KEY (mathematics) AND TITLE-ABS-KEY (education) AND TITLE-ABS-KEY (spatial)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")), in total there is 652 documents of spatial research in mathematics education. The first research publication on spatial in mathematics education was in 1962 by Sax, G., and Carr, A., titled An Investigation of Response Sets on Altered Parallel Forms. This article is published in Educational and Psychological Measurement, 22(2), pp. 371–376 and has been cited 16 times.

Furthermore, by inputting this source of code (TITLE-ABS-KEY (spatial AND reasoning) AND TITLE-ABS-KEY (mathematics) AND TITLE-ABS-KEY (education) AND TITLE-ABS-KEY (spatial)) AND PUBYEAR > 1976 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) we get 115 article in total, related to spatial reasoning in mathematics education trough out the time.

The General Trend of Spatial and Spatial Reasoning Research (until 2023)

The first publication about spatial reasoning was published in the Journal of Psychology: Interdisciplinary and Applied, 95(1), pp. 99–104 in 1977 by Eisenberg, T.A., McGinty, R.L. Entitled On spatial visualization in college students. This study investigated the effect of individuals with distinct career orientations and the sex difference in spatial reasoning abilities. To gather the data, a spatial visualization test was administered to 223 mathematics university students in four different types of mathematics courses: calculus, business statistics, remedial mathematics, and mathematics for elementary school teachers. The examination covered four forms of spatial visualization. The results suggest that unexpected sex enrolled in the course (e.g., males in elementary education) scored higher than the expected sex on most of the variables. Sex differences were observed within each of the courses. On three of the four variables, students in the calculus courses scored higher than students in the other courses.

Before 2000, there was no research on spatial reasoning and only a few research on spatial (Figure 2). Both topics were addressed more around 2000 and gradually increased until 2013. One factor affecting this increase is the beginning of mathematics literacy on PISA (Programme for International Student Assessment). PISA started in 2000, and one mathematics literacy addressed in it is about visual, spatial, verbal and numeric information in a graph or map to conclude the information represented (O.E.C.D., 2000). One addressed thinking skill is utilizing the mind's eyes (O.E.C.D., 2003).

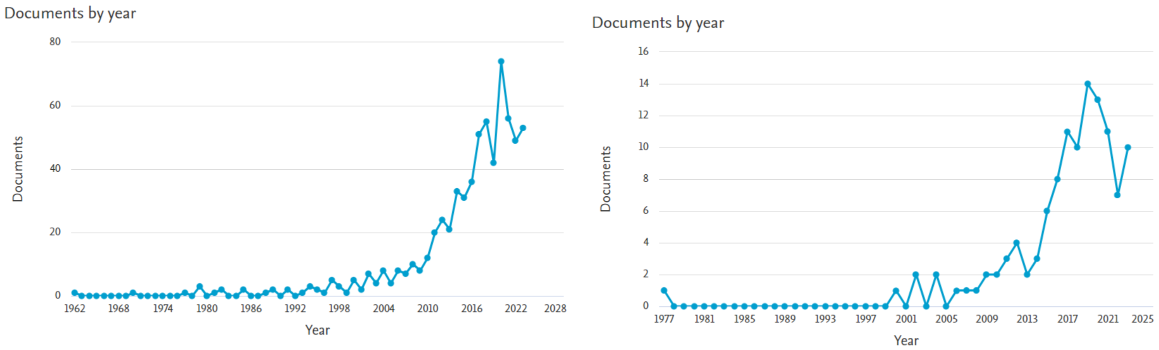

Figure 2. The research trend on spatial in mathematics education (left) and spatial reasoning in mathematics education (right) throughout the years

Further, Figure 2 shows that over the last 10 years (2013 to 2023), the research trend on spatial and spatial reasoning shows a significant increase and reached its peak in 2019 with 19 publication documents on spatial reasoning in total. The significant increase in research about spatial and spatial reasoning, in particular, is affected by PISA. The question given at PISA 2015 is related to Geometry and spatial ability. In 2017, the OECD explicitly wrote that one of the content categories assessed in PISA 2015 is space and shape, closely related to geometry. Space and shape encompass a wide range of phenomena that occur in our visual and physical world, including positions and orientations, representations of objects, decoding and encoding of visual information, and navigation, which is spatial visualization (OECD, 2017). Another factor that triggered the significant increase is the growth in interest in STEM Education. STEM is one of the US's attempts to answer the results of TIMSS (Trends in International Mathematics and Science Study) and PISA 2015. Thus, it is unsurprising that the country with the most research publications on spatial reasoning is the United States (Figure, 3) with 35 publications on spatial reasoning in mathematics education over the last 10 years (2013-2023).

Based on Figure 2, the number of studies on spatial reasoning in the past few years until now has not exceeded the number of articles published in 2019. On the other hand, spatial reasoning is needed by every individual because spatial thinking is an important factor in learning Science, Technology, Engineering, and Mathematics (Wintarti, 2021), which are needed when facing the world of work and everyday life. Therefore, much research is needed on spatial reasoning, looking at many cognitive, affective and psychomotor aspects so teachers can apply appropriate strategies to improve spatial reasoning abilities.

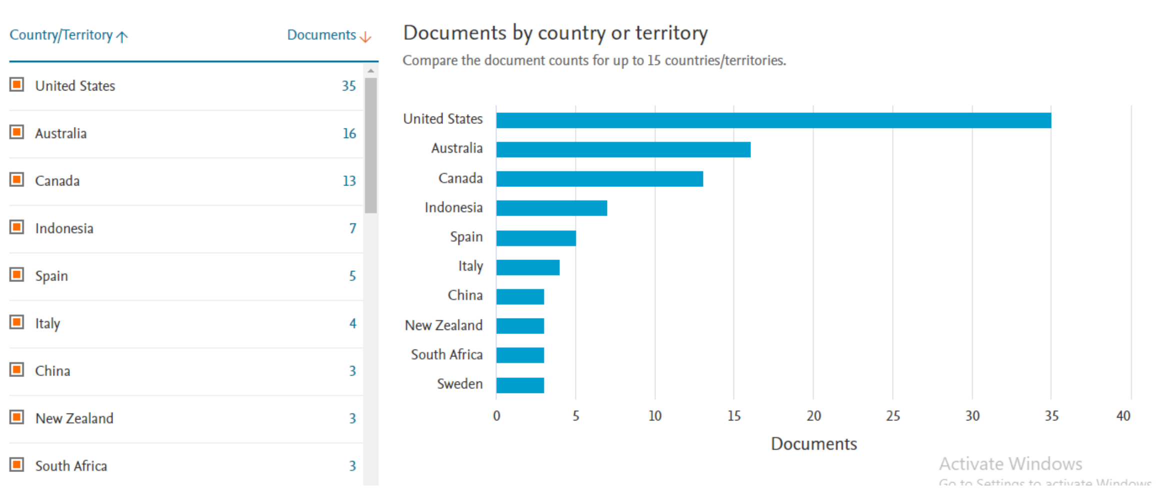

Figure 3. Document on research publication of spatial reasoning in mathematics education by country (2013-2023).

The trend of Spatial and Spatial Reasoning Research Over a Decade (2013-2023)

From 115 documents is then reduced 43 documents of spatial reasoning study published until 2023 by employing (TITLE-ABS-KEY (mathematics) AND TITLE-ABS-KEY (education) AND TITLE-ABS-KEY ((spatial AND reasoning)) AND PUBYEAR > 2012 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (EXACTKEYWORD, "Spatial Reasoning")) and 40 documents in the last 10 years (Figure 4).

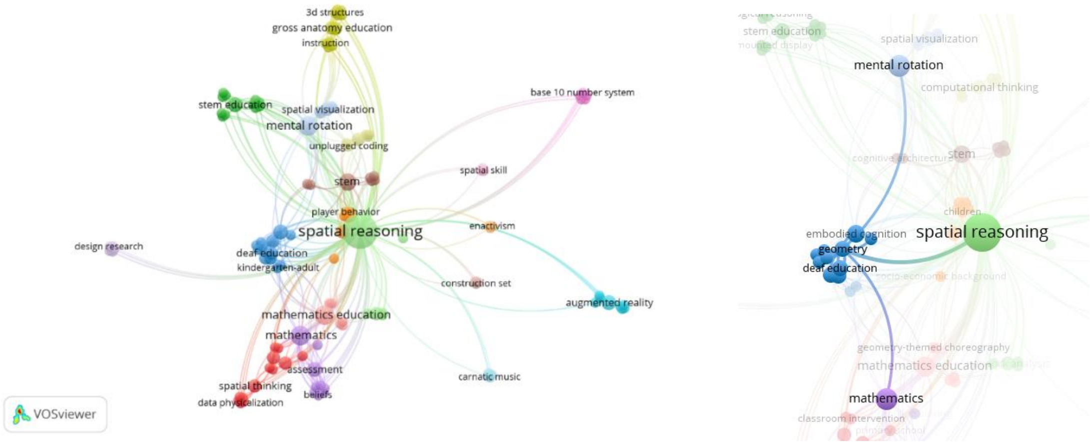

Figure 4. The keywords co-occurrence of 40 documents on spatial reasoning in mathematics education from 2013 to 2023

Figure 4 gives the systematic map of spatial reasoning studies. In the last decade, the research on spatial reasoning has been approached from different aspects. For instance, spatial reasoning related to STEM, studies on spatial and gender differences, studies on intervention and learning design and assessment, and several aspects of spatial reasoning, like mental rotation and spatial visualization. In addition, the research field on spatial reasoning is getting wider since it is not only related to geometry but also widespread in other mathematics topics such as fractions and number lines. As for the subject, it is from primary and secondary students to undergraduate and even disabled students. Further, there is also research on spatial and technology like augmented reality (AR), virtual reality (VR), and Cabri 3D.

Clustering colour (Figure 4) shows several clustering on spatial reasoning in mathematics education research. Briefly look, it shows that the clustering is the use of technology (AR, VR), research approach (DR), mathematical topics (geometry, number), subject (deaf individual, primary, secondary, etc.), intervention or learning approach (i.e. STEM), and cognitive aspect of spatial reasoning like mental rotation, visualization, embodied etc.

Research About Intervention in Spatial Reasoning

The 24 documents gathered are then reduced to 19 by excluding the research that is not a practical intervention. The 19 documents collected are mostly an intervention study of spatial reasoning in primary education (code: PRIM). The other intervention is for secondary "SEC" education (9 out of 19 studies), and for undergraduate "UNDRG" students, there are 6 documents related (Table 1).

Furthermore, Table 1 shows that the mathematical integrated topics are Geometry (2D and 3D shape, space shape, navigation and reference), Data and its representation, Fraction, robotic, and spatial ability training such as mental rotation, spatial visualization, and spatial reference. The method employed is Design-Based Research (i.e. Bruce et al., (2023). Experimental studies and mixed methods. Theories addressed in the 19 documents are related to spatial reasoning spatial skills, including mental rotation, spatial visualization, spatial reference, and theory of embodied cognition (i.e. Augello et al., 2018)

The learning approach and method used are Realistic Mathematics Education RME (Chandrawati et al., 2023) and the Experience-Language-Pictorial-Symbolic-Application ELPSA (Lowrie et al., 2021). Carnatic music (Raja & Bhalla, 2021), Dance activities (An et al., 2021), a design module data physicalization activities (Zhu & Klapwijk, 2023), and classroom activities of fraction (Bruce et al., 2023), and activities on mental rotation (Moen et al., 2020).

Since the sophisticated development of technology offers opportunities to enhance spatial reasoning as well as help the students to represent the visualization of geometrical objects in particular, several studies in the 19 documents also employed integrated technology in the learning design or intervention to promote and enhance spatial reasoning. The technology used in the learning design, such as technology-enhanced STEM (Fowler et al., 2022; Winter et al., 2019), Augmented Reality media (Bairaktarova et al., 2019; Pangestu & Setyaningrum, 2020), graphic sketches app (Bairaktarova et al., 2019; Eloy et al., 2020), Buildagram (Eloy et al., 2020), a spatial reasoning mathematics program (J. Mulligan et al., 2020; J. et al., 2013), 3D geologic block diagrams (Gagnier et al., 2017), eye-movement visual guidance protocol (Roach et al., 2019), activities learning with Cabri 3D (Hartatiana et al., 2017), the "A me gli occhi" project, a virtual reality game (Freina & Bottino, 2016), a geometry program that incorporates 2D and 3D mental rotations (Bruce & Hawes, 2015), new learning model using robotic (Augello et al., 2018).

Table 1. Research about intervention in spatial reasoning

Authors	Title	Year	Code
Chandrawati A.E., Johar R., Elizar E.	Spatial reasoning skills of year 5 elementary school students through realistic mathematics education	2023	PRIM, RME, GEO, Exp (OneSht)
Zhu C., Klapwijk R.	Thinking Spatially About Data: A Developing Framework to Understand Children's Spatial Reasoning in Data Physicalization	2023	PRIM, DMod-Physiclization Act, DATA
Bruce C.D., et.al.	Leveraging Number Lines and Unit Fractions to Build Student Understanding: Insights from a Mixed Methods Study	2023	PRIM, DAct, FRAC, DBR
Fowler S., et.al.	Technology-enhanced learning environments and the potential for enhancing spatial reasoning: A mixed methods study	2022	SEC, DMP-Tech-STEM, SR, MixM
Raja V., Bhalla D.O.	Impact of Carnatic music training on the mathematical ability of children	2021	PRIM, Msc,
An S.A., Tillman D.A., Hachey A.C.	Off the paper and into the dance: Investigating Preservice Elementary Teachers' experiences with dynamic spatial reasoning choreography tasks	2021	UNDG, DNCE (Lego WS), GEO-Post
Lowrie T. et al.	The Impact of a Spatial Intervention Program on Students' Spatial Reasoning and Mathematics Performance	2021	SEC, ELPSA, SpatTrain
Moen K.C., et.al.	Strengthening spatial reasoning: elucidating the attentional and neural mechanisms associated with mental rotation skill development	2020	UNDG, MATLAB act, Spat-MR
Pangestu A., Setyaningrum W.	Instructional media for space geometry based on augmented reality to improve students' spatial reasoning	2020	SEC, AR, space-GEO
Eloy A., et.al.	Buildagram: A constructionist environment for spatial reasoning	2020	PRIM, BLDGRM, Dig.Tools, GEO-3D
Mulligan J., et.al..	Evaluating the impact of a Spatial Reasoning Mathematics Program (SRMP) intervention in the primary school	2020	PRIM, SRMP, GEO 2D-3D
Winter V. et.al.	A computer scientist teaches gen Ed math	2019	UNDGR, COMPT PROG, MATH

Bairaktarova D., van Den Einde L., Bell J.E.	Using digital sketching and augmented reality mobile apps to improve spatial visualization in a first-year engineering course	2019	UNDRG, SKETCHAP-AR, SPAT
Roach V.A., et.al.	Guiding Low Spatial Ability Individuals through Visual Cueing: The Dual Importance of Where and When to Look	2019	UNDRG, EYE-MOV TRACK, MRot
Augello A., et.al.	Improving spatial reasoning by interacting with a humanoid robot	2018	PRIM, HUMROBT, SPAT, EMBODI
Gagnier K.M., et.al.	Comprehending 3D Diagrams: Sketching to Support Spatial Reasoning	2017	UNDRG, GEOBLCK Diag., STEM
Hartatiana, Darhim, Nurlaelah E.	Student's Spatial Reasoning through Model Eliciting Activities with Cabri 3D	2017	SEC, MEA CABRI3D, GEO (ln. Agl.)
Freina L., Bottino R.	Visual thinking skills training in support of STEM education	2016	PRIM, VRGme, Spat
Bruce C.D., Hawes Z.	The role of 2D and 3D mental rotation in mathematics for young children: What is it? Why does it matter? Moreover, what can we do about it?	2015	PRIM, MYCprog., GEO (2D 3D) MR

From these results, the technology used to develop spatial reasoning still focuses on AR, VR, and Cabri. The use of technology has a significant impact on improving students' spatial reasoning abilities (Javaheri et al., 2022). Further research using other media is needed to improve students' spatial reasoning abilities.

Future Research on Intervention for Enhancing Spatial Reasoning

From 19 documents about learning design and intervention, there are attempts to enhance students' spatial reasoning, from primary to undergraduate. The attempt is made through classroom activities that either directly address spatial reasoning or enhance it by integrating it into other topics such as geometry, fractions, data and robotic building activities. However, it still leaves space for further research, especially integrating spatial reasoning into the curriculum and making a local instructional theory. This would benefit countries whose mathematics curriculum needs to address spatial reasoning, like Indonesia. Another room is to stand spatial reasoning with another cognitive aspect, like computational thinking.

In terms of research methods, since different terms refer to spatial reasoning, it will give wider results by searching with more keywords such as spatial education, spatial thinking, spatial ability, or spatial skills. The search could also be done in several databases, not only Scopus. Thus, the border image and spatial trend could be produced.

Using software for bibliometric analysis makes it very easy for researchers to find the position of the topic to be researched. Researchers can look for gaps in what previous researchers have researched. However, Bibliometrics also has areas for improvement, such as doubts regarding the ability of bibliometric methods to analyze abstract concepts such as research quality (Ismail et al., 2012). It does not differentiate between case reports and higher-impact articles (Choudhri et al., 2015).

IV. Conclusion

The research on spatial and spatial reasoning began to be more addressed around 2000 and gradually increased until 2013. Over the last 10 years (2013 to 2023), the research trend on spatial and spatial reasoning shows a significant increase and reached its peak in 2019, with 19 publication documents on spatial reasoning in total. The significant increase in research about spatial and spatial reasoning, in particular, is affected by PISA and the significant increase in the growth interest in STEM Education.

In the last decade, the research on spatial reasoning has been approached from different aspects. There are several clusters on spatial reasoning in mathematics education research, such clusters of the use of technology (AR, VR), research approach (DR), mathematical topics (geometry, number), subject (deaf individual, primary, secondary, etc.), intervention or learning approach (i.e. STEM).

There are attempts to enhance students' spatial reasoning, from primary to undergraduate. The attempt is done through classroom activities that either directly address spatial reasoning or enhance it by integrating it into other topics such as geometry, fractions, data and robotic building activities. However, it still leaves space for further research on it, especially integrating spatial reasoning into the curriculum and making a local instructional theory of it. Another room is to stand spatial reasoning with another cognitive aspect, like computational thinking.

References

An, S. A., Tillman, D. A., & Hachey, A. C. (2021). Into the dance: Investigating preservice elementary teachers' experiences with dynamic spatial reasoning choreography tasks. *Research in Dance Education*, *22*(1), 17–37.

Augello, A., Città, G., Gentile, M., Infantino, I., Guardia, D. La, Manfré, A., & Allegra, M. (2018). Improving spatial reasoning by interacting with a humanoid robot, Smart Innovation, Systems and Technologies. *Intelligent Interactive Multimedia Systems and Services*, *76*(10), 151–160.

Bairaktarova, D., Einde, L. Van Den, & Bell, J. (2019). Using digital sketching and augmented reality mobile apps to improve spatial visualization in a first-year engineering course. *ASEE Annual Conference & Exposition*.

Bruce, C. D., Davis, B., Sinclair, N., McGarvey, L., Hallowell, D., Drefs, M., & Woolcott, G. (2017). Understanding gaps in research networks: using "spatial reasoning" as a window into the importance of networked educational research. *Educational Studies in Mathematics*, pp. *95*, 143–161.

Bruce, C. D., Flynn, T., Yearley, S., & Hawes, Z. (2023). Leveraging number lines and unit fractions to build student understanding: insights from a mixed methods study. *Canadian Journal of Science, Mathematics and Technology Education*, *23*(2), 322–339.

Bruce, C. D., & Hawes, Z. (2015). The role of 2D and 3D mental rotation in mathematics for young children: What is it? Why does it matter? Moreover, what can we do about it? *ZDM Mathematics Education*, *47*(3), 331–343.

Chandrawati, A. E., Johar, R., & Elizar, E. (2023). Spatial reasoning skills of year 5 elementary school students through realistic mathematics education. *AIP Conference Proceedings*.

Choudhri, A. F., Siddiqui, A., Khan, N. R., & Cohen, H. L. (2015). Understanding bibliometric parameters and analysis. *Radiographics*, *35*(3), 736–746. https://doi.org/10.1148/rg.2015140036

Dong, B., Xu, G., Luo, X., Cai, Y., & Gao, W. (2012). A bibliometric analysis of solar power research from 1991 to 2010. *Scientometrics*, *93*(3), 1101–1117.

Eck, N. J. Van, & Waltman, L. (2020). *VOSviewer Manual*. University of Leiden.

Eloy, A., Cruz, D., Thennakoon, K., & Grant, W. (2020). Buildagram: a constructionist environment for spatial reasoning. *Proceedings of the 2020 ACM Interaction Design and Children Conference: Extended Abstracts*, 280–283.

Fowler, S., Cutting, C., Kennedy, J., Leonard, S. N., Gabriel, F., & Jaeschke, W. (2022). Technology-enhanced learning environments and the potential for enhancing spatial reasoning: A mixed methods study. *Mathematics Education Research Journal*, *34*(4), 887–910.

Fowler, S., Cutting, C., Kennedy, J. P., Leonard, S., Gabriel, F., & Jasechcke, W. (2021). Technology-enhanced learning environments and the potential for enhancing spatial reasoning: a mixed methods study. *Mathematics Education Research Journal*, *1*(3). https://doi.org/https://doi.org/10.1007/s13394-021-00368-9

Freina, L., & Bottino, R. (2016). A visual thinking skills training in support of STEM education. *10th European Conference on Games Based Learning: ECGBL 2016*, 224–231.

Gagnier, K. M., Atit, K., Ormand, C. J., & Shipley, T. F. (2017). Comprehending 3D diagrams: Sketching to support spatial reasoning. *Topics in Cognitive Science*, *9*(4), 883–901.

Hartatiana, Darhim, & Nurlaelah, E. (2017). Student's spatial reasoning through model eliciting activities with Cabri 3D. *Journal of Physics: Conference Series*, *895*(1). https://doi.org/10.1088/1742-6596/895/1/012075

Ismail, S., Nason, E., Marjanovic, S., & Grant, J. (2012). Bibliometrics as a tool for supporting prospective R&D decision-making in the health sciences: strengths, weaknesses and options for future development. *Rand Health Quarterly*, *1*(4), 11.

Javaheri, H., Lehmann, J., Altmeyer, K., M'Ller, L. M., Br'nken, R., & Lukowicz, P. (2022). Design of augmented reality-based environment to promote spatial imagination for mathematics education in elementary school. *UbiComp/ISWC 2022 Adjunct - Proceedings of the 2022 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2022 ACM International Symposium on Wearable Computers*, 274–277. https://doi.org/10.1145/3544793.3560380

Kulakli, A., & Osmanaj, V. (2020). *Global research on big data about artificial intelligence (A bibliometric study: 2008-2019)*.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, *56*(6), 1479–1498. https://doi.org/https://doi.org/10.2307/1130467

Lohman, D. F., Dennis, I., & Tapsfield, P. (1996). *Human abilities: Their nature and measurement*.

Lowrie, T., Harris, D., Logan, T., & Hegarty, M. (2021). The impact of a spatial intervention program on students' spatial reasoning and mathematics performance. *The Journal of Experimental Education*, *89*(2), 259–277.

Moen, K. C., Beck, M. R., Saltzmann, S. M., Cowan, T. M., Burleigh, L. M., Butler, L. G., Ramanujam, J., Cohen, A. S., & Greening, S. G. (2020). Strengthening spatial reasoning: elucidating the attentional and neural mechanisms associated with mental rotation skill development. *Cognitive Research: Principles and Implications*, *5*(1). https://doi.org/10.1186/s41235-020-00211-y

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of Internal Medicine*, *151*(4), 264–269.

Mulligan, J. T., & Mitchelmore, M. C. (2013). Early awareness of mathematical patterns and structures. In L. D. E. & J. T. Mulligan (Ed.), *Reconceptualizing early mathematics learning* (pp. 29–45). springer. https://doi.org/https://doi.org/10.1007/978-94-007-64408

Mulligan, J., Woolcott, G., Mitchelmore, M., Busatt, S., Lai, J., & Davis, B. (2020). Evaluating the impact of a Spatial Reasoning Mathematics Program (SRMP) intervention in the primary school. *Mathematics Education Research Journal*, *pp. 32*, 285–305.

OECD. (2000). *Measuring student knowledge and skills: The PISA 2000 assessment of reading, mathematical and scientific literacy*.

OECD. (2003). The PISA 2003 Assessment Framework: Mathematics, Reading, Science and Problem Solving, Knowledge Skills. In *OECD Publishing*.

OECD. (2017). *PISA for Development Assessment and Analytical Framework: Reading, Mathematics and Science, Preliminary Version*.

Pangestu, A., & Setyaningrum, W. (2020). Instructional media for space geometry based on augmented reality to improve students' spatial reasoning. *Journal of Physics: Conference Series*, 012058.

Putri, C. R., Soleh, S. M., Saregar, A., Anugrah, A., & Susilowati, N. E. (2021). Bibliometric analysis: Augmented reality-based physics laboratory with VOSviewer software. *Journal of Physics: Conference Series*, 012056.

Raja, V., & Bhalla, D. O. (2021). Impact of Carnatic music training on the mathematical ability of children. *Early Child Development and Care*, *191*(12), 1911–1921.

Ramful, A., Lowrie, T., & Logan, T. (2017). Measurement of spatial ability: Construction and validation of the spatial reasoning instrument for middle school students. Assessment. *Journal of Psychoeducational*, *35*(7), 709–727. https://doi.org/https://doi.org/10.1177/0734282916659207

Roach, V. A., Fraser, G. M., Kryklywy, J. H., Mitchell, D. G., & Wilson, T. D. (2019). Guiding low spatial ability individuals through visual cueing: The dual importance of where and when to look. *Anatomical Sciences Education, 12(1), 32-42.*, *12*(1), 32–42.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., & Warren, C. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402. https://doi.org/https://doi.org/10.1037/a0028446

Wintarti, D. (2021). *Developing Indonesian Grade 8 Students' Spatial Ability To Support Mathematics Learning*.

Winter, V., Love, B., Friend, M., & Matthews, M. (2019). A Computer Scientist Teaches Gen Ed Math. *International Conference on Computational Science and Computational Intelligence (CSCI)*, 793–799.

Yang, L., Sun, T., & Liu, Y. (2017). A bibliometric investigation of flipped classroom research from 2000-2015. *International Journal of Emerging Technologies in Learning*, *12*(6), 178–186. https://doi.org/https://doi.org/10.3991/ijet.v12i06.7095

Zhu, C., & Klapwijk, R. (2023). Thinking Spatially About Data: A Developing Framework to Understand Children's Spatial Reasoning in Data Physicalization. *Proceedings of IDC 2023 - 22nd Annual ACM Interaction Design and Children Conference: Rediscovering Childhood*, 537–542.