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The role of mathematical representation in enhancing data and statistical literacy: A systematic review

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Abstract

This study aims to investigate the role of mathematical representations in enhancing data and statistical literacy among students, with a focus on the integration of interactive data visualization. Using a systematic literature review approach, this study analyzed articles from leading international databases published between 2014 and 2024. The findings highlight that mathematical representations, such as graphs, tables, and diagrams, play a significant role in enhancing students' understanding and decision-making abilities. Interactive data visualizations not only enhance conceptual understanding but also engage students in exploratory learning processes. A significant contribution of this study lies in the proposal of an easily accessible open-source technology to bridge the gap in schools with limited resources and integrate mathematical representations into real-world contextual applications. Practical implications include teacher training programs for effective visualization design, curriculum development that emphasizes data literacy, and cost-effective adoption of the technology. Future research should evaluate the long-term impact of this strategy, explore inclusive approaches to address individual differences, and assess the scalability of the proposed solution across educational contexts.

Keywords: *interactive data visualization, pedagogical strategies, constructivist learning, educational technology integration*

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1. Introduction

In the digital era and the industrial revolution 4.0, data literacy has become an important skill needed in various sectors, from economics, technology, to education (Dito & Pujiastuti, 2021; Muliastrini, 2019). The ability to process, analyze, and interpret data is one of the main competencies of students in facing global challenges and the development of data-based technology (Muliani et al., 2021; Serianti et al., 2024). International research also confirms that data literacy is not only an industrial need but also an important aspect in developing critical and analytical thinking skills (Overton & Kleinschmit, 2022; Ridgway et al., 2022).

The increasing need for statistical skills encourages schools and universities to strengthen learning related to data analysis and statistical understanding (Prihastari et al., 2022; Setiawan, 2021). Statistical literacy not only helps students solve math problems but also trains them in making decisions based on data, understanding trends, and making accurate predictions (Takaria & Talakua, 2018; Lukman et al, 2022; Bacangallo et al., 2022; Abulela & Harwell, 2020). Research by Schreiter et al. (2024) shows that the development of technology-based statistical literacy can improve students' analytical skills, especially in visualizing complex data.

One important aspect in developing data literacy is mathematical representation. This representation includes various forms such as graphs, tables, diagrams, and visual models that help students understand the relationship between data and the underlying mathematical concepts (Wulandari & Isnarto, 2023). Effective data visualization can improve students' interpretation and analysis, allowing them to extract important information, identify patterns, and better understand abstract concepts (Herrera et al, 2024; Malesevic et al., 2015). This is reinforced by recent research from Miller et al. (2022), which found that interactively designed data visualizations improve students' interpretation skills by up to 35%.

Although data and statistical literacy are important focuses in modern education, students' data and statistical literacy levels are still low in many countries (Prihastari et al., 2022; Kusmanto, 2017). Many students have difficulty understanding data presented in tables or graphs, and are less able to critically analyze information from various sources (Binali, 2024; Kandeel, 2019; Rahmania & Nuriadin, 2025). For example, a study by Kurnia et el. (2023) showed that only 40% of students at the high school level were able to understand data presented in multidimensional graphs.

One of the factors that causes low data literacy is the lack of integration of mathematical representation in statistics learning in schools (Bacangallo et al., 2022; Man et al., 2022). Statistics learning tends to be more theoretical and less involving students in exploratory activities that utilize visual data representation (Xie et al., 2020). This makes it difficult for students to connect statistical concepts to real-world situations, which ultimately affects their ability to think critically and make decisions based on data (Maryati & Monica, 2021). Garcia (2020) emphasizes the importance of an inquiry-based approach in improving data interpretation skills, but its application in the classroom is still limited.

Research conducted by Garcia (2020) and Miller et al. (2022) highlight the importance of mathematical representation and data visualization, but has not discussed specific pedagogical strategies for integrating these representations into statistics learning. Another study conducted by Schreiter et al. (2024) shows the potential of technology in developing data literacy, but focuses more on high technology that is not always accessible to all schools. Meanwhile, Kurnia et al. (2023) highlight the lack of context-based approaches in statistics learning, especially in connecting data to real-world situations. Furthermore, Ridgway et al. (2022) and Overton and Kleinschmit (2022) focus more on the end result of data literacy without deeply evaluating the learning process that supports it. Another study conducted by Miller et al. (2022) highlights the benefits of interactive data visualization, further research is needed to identify the specific design elements that are most effective in supporting student understanding.

The importance of this research is to improve students' data literacy which is an important skill in the digital era and the industrial revolution 4.0. The low integration of mathematical representations in statistics learning, the lack of affordable technology, and the lack of contextual approaches in learning indicate the need for evidence-based pedagogical strategies. In addition, the development of effective interactive data visualizations can help students understand and analyze data more deeply. This research is important to address global challenges in education by providing innovative solutions that are practically relevant and have a broad impact on curriculum development and education policies.

This research focuses on developing effective pedagogical strategies to integrate mathematical representation, accessible technology application, contextual approach in statistics learning, evaluation of learning process, and interactive data visualization design. Based on the urgency, focus, and objectives of the research, the research questions are:

1. What are the most effective evidence-based pedagogical strategies for integrating mathematical representations, such as graphs, tables, and diagrams, to improve students' data literacy at different levels of education?
2. How can affordable and accessible technologies be applied to effectively support data literacy learning across cultural contexts and educational resources?
3. What features in interactive data visualization significantly improve students' conceptual understanding and analytical skills in statistics learning, based on current research evidence?

Based on the research questions, this study aims to examine mathematical representations in improving data and statistical literacy, focusing on current trends and research gaps that can still be explored. This study uses a systematic literature review to evaluate mathematical representations in improving data and statistical literacy. This process follows a systematic approach (Xiao & Watson, 2019) and uses PRISMA-P, NVivo for qualitative analysis, and Excel for data management. The reviewed articles were retrieved from Scopus, Web of Science, and ERIC between 2014-2024, thus covering the latest developments in the field. These databases were selected due to their coverage of relevant and high-quality literature, with Scopus and Web of Science widely known for their interdisciplinary coverage, while ERIC has a specific focus on education (Mongeon & Paul-Has, 2016; Bhattacherjee, 2012).

2. Theoretical Framework

In the context of modern education, data literacy is an essential element that supports the development of analytical and decision-making skills. Research shows that data literacy is not only important to meet industry needs but also as a driver of critical thinking skills among students (Overton & Kleinschmit, 2022; Ridgway et al., 2022). In recent decades, various studies have focused on the development of these skills, highlighting the importance of mathematical representations as a tool for visualizing and understanding data.

2.1. Constructivism Theory in Data Literacy

Constructivism theory, first proposed by Jean Piaget (1970) and further developed by Lev Vygotsky (1978), provides a powerful theoretical framework for understanding the development of data and statistical literacy. In the constructivist view, learning is viewed as an active process in which students actively construct and reconstruct knowledge based on their experiences and interactions with the environment. Mathematical representations, such as graphs, tables, diagrams, and other data visualizations, play a critical role in bridging students' understanding from abstract concepts to more concrete, observable information. These representations not only help organize and simplify information, but also strengthen critical and analytical thinking skills. Vygotsky added a social dimension to constructivism through the concept of the Zone of Proximal Development (ZPD), which emphasizes that effective learning occurs when students are guided through support from teachers, peers, or technological tools. In this context, the use of visual representations supported by scaffolding can significantly enhance students' ability to understand and interpret data meaningfully.

2.2. Information Processing Theory

The information processing theory proposed by Atkinson and Shiffrin (1968) provides an important framework in understanding how humans receive, store, and process information received from the environment. In this theory, information is processed through three main stages, namely sensory memory, short-term memory, and long-term memory. In the context of data literacy, this theory is very relevant because it shows that appropriate information representation can affect the effectiveness of learning. One strategy that has proven effective is the use of data visualization, which allows students to grasp complex information more quickly and efficiently than with textual formats alone. Mayer et al.'s (2001) research on multimedia principles supports this idea by showing that the integration of text and visual elements, such as graphs and diagrams, can significantly improve conceptual understanding. This is because the combination of visuals and verbal helps reduce cognitive load and supports information processing in the dual channels possessed by the human memory system. Thus, the use of visualization in data learning not only clarifies information, but also strengthens students' retention and understanding of the material.

2.3. Experiential Learning Theory

Kolb (1984) suggested that effective learning takes place through a cycle of experiences involving four main stages, namely concrete experience, reflective observation, abstract conceptualization, and active experimentation. In the context of data and statistics literacy, mathematical representations including tables, graphs, and mathematical models as well as the use of interactive data visualizations play a crucial role in supporting these stages. Through interactive visualizations, students not only passively observe data, but also actively explore, manipulate, and draw conclusions based on the patterns they find. This allows for a deep and meaningful learning experience. This concept is in line with the findings of Garcia (2020), who emphasized that the inquiry-based learning approach is very effective in improving students' data literacy. Through this approach, students are directly involved in the process of collecting, analyzing, and interpreting data, which ultimately strengthens their ability to understand and use data in real-life contexts.

2.4. Educational Technology Theory

The diffusion of innovation theory proposed by Rogers (2003) provides an important conceptual framework in understanding the process of acceptance and adoption of technology in the context of education. In this theory, Rogers highlights five main characteristics that determine the rate of adoption of an innovation, namely: relative advantage, compatibility, complexity, trialability, and observability. Interactive data visualization technology, as explained by Schreiter et al (2024), can be classified as a form of educational innovation that has significant potential to improve student data literacy. By designing technology that has practical advantages, is easy to use, is in accordance with curriculum needs, and allows for clear trials and observations of the results of its use, the chances of adopting this technology in the educational environment will increase substantially. Therefore, the strategy for implementing innovation in education needs to pay attention to these characteristics so that the technology integration process is effective and sustainable.

2.5. Cognitive Theory in Data Visualization

Cognitivism is one of the main approaches in learning psychology that emphasizes the importance of an individual's internal mental processes, such as attention, perception, memory, and problem solving in understanding, organizing, and reconstructing information. Within this framework, interactive data visualization has a strategic function as a cognitive aid that can strengthen the effectiveness of information processing. Based on the cognitive load theory developed by Sweller (1988), optimally designed visualizations can minimize extrinsic cognitive load, that is, the load that does not directly contribute to core learning, thus allowing students to focus their mental resources on understanding essential material. Interactive visualizations not only simplify the representation of complex information but also help students form more organized mental structures for the data being analyzed. Empirical research conducted by Miller et al. (2022) supports this view with the finding that intuitive and informative visualizations significantly improve students' analytical and interpretive thinking skills, especially in data-based and statistical learning. Thus, the integration of interactive data visualization in the context of cognitivism-based learning is not only relevant but also crucial to foster deeper and more meaningful data literacy.

2.6. Gaps in the Literature

Previous research has shown that data literacy is an essential skill in the digital age, with mathematical representations, interactive technologies, and context-based approaches playing a critical role in enhancing students' understanding of data. Studies such as Wulandari and Isnarto (2023) and Miller et al. (2022) highlight the effectiveness of data visualization in supporting students' interpretations, while Kurnia et al. (2023) emphasize the importance of connecting learning to real-world contexts. However, there are still gaps in evidence-based pedagogical strategies for integrating mathematical representations, a lack of affordable technology for schools with limited resources, and a lack of contextual approaches that consider local cultural factors. Furthermore, research often focuses on outcomes rather than evaluating the learning process, with little exploration of specific and inclusive data visualization designs. Therefore, research is needed that develops innovative pedagogical approaches, accessible technologies, and comprehensive evaluations of the learning process to ensure that data literacy can be taught effectively across educational levels and contexts.

3. Methodology

3.1. Study Design and Overview

This study aims to identify, screen, and analyze literature on the role of mathematical representation in improving data and statistical literacy. The Systematic Literature Review (SLR) methodology was chosen due to its ability to ensure transparency, replicability, and evidence-based conclusions, which align with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). To achieve these goals, the SLR method is used which allows researchers to find, evaluate, and interpret various relevant previous research results. The use of SLR is considered appropriate to the formulation of the problem and the scope of this research topic. In implementing SLR, there are a number of systematic stages that are passed, namely: formulating research questions, compiling a conceptual framework, determining selection criteria, establishing a literature search strategy, selecting appropriate studies, coding data, assessing study quality, synthesizing findings to answer research questions, and compiling a report on the results of the analysis (Zawacki-Richter et al., 2020).

To support the data collection process, this study also refers to the PRISMA approach, which provides a structured and clear research methodology (Stovold et al., 2014). The PRISMA approach includes four main stages, namely: identification, screening, eligibility determination, and integration or inclusion of studies. The main advantages of PRISMA include its ability to help formulate systematic research questions, set explicit inclusion and exclusion criteria, and analyze publications from scientific databases over a certain period of time. In addition, this approach also facilitates the search for new vocabulary that is relevant in the context of learning (Sierra-Correa & Kintz, 2014).

3.2. Identification

The article search process obtained the Scopus, Web of Science (WoS) and Google Scholar databases using the Publish or Perish 8 application. The search was conducted to obtain as much data as possible related to mathematical representation skills using the search keywords: ("Mathematical Representation" OR "Data Literacy") AND ("mathematical representation" OR "statistics"). Applying these words to avoid biased and non-specific search results on the topic being studied.

3.3. Filtering

The earliest step used in determining the eligibility of an article is to see the relevance between the title and abstract of the study. The selected articles are then shared using the exclusive and inclusive criteria that have been set, as shown in table 1.

Table 1

Inclusion and exclusion criteria

Criteria	Inclusion Criteria	Exclusion Criteria
Type of Literature	Research Journal	Proceedings, serial books, review articles
Language	English and Indonesian	Non English and Indonesian
Range of years	2014 - 2024	Before 2014 and after 2024

To ensure that the selected literature is truly relevant and in accordance with research needs, a screening process is carried out by establishing strict inclusion and exclusion criteria (Kraus et al., 2022). First, only articles from scientific journals were included, because this type of publication generally presents the latest research results that have gone through a peer-reviewed process. In contrast, proceedings, books, book series, book chapters, or articles of the "systematic literature review" type were not included in the analysis. Second, the literature used must be written in English or Indonesian to ensure understanding of the content and expand the reach of the research both nationally and internationally. Literature in languages other than these two languages was not considered. Third, the literature was limited to works published between 2014 and 2024. This time span was chosen because it is considered to reflect the latest developments in the field of mathematics education, especially related to improving students' mathematical representation skills. During this period, many innovative approaches, new learning strategies, and educational policies that focus on developing mathematical representation have been introduced. Therefore, articles published before 2014 were automatically excluded from the selection process. The article selection process was carried out manually by paying attention to the suitability of the title and content of the article with the main focus of the research, namely improving mathematical representation skills in mathematics education. The selected articles must demonstrate strong relevance to the topic and explore it in depth. In addition, the quality of the article is an important consideration, where only articles that have gone through a peer review process, have a valid and clear methodology, and make significant contributions to the study of mathematical representation skills in the context of mathematics education will be included in the analysis.

3.4. Eligibility

This study used a multi-stage screening approach that began with a feasibility selection process. Researchers reviewed each successfully extracted article to ensure compliance with the inclusion criteria. The screening stage began with a search for sources from two main databases using Publish or Perish software, which was 500 articles found. Screening was carried out to eliminate duplicate data. At this stage, 50 articles were eliminated. Screening was carried out to examine the selected years (2014 - 2024) and articles in Indonesian and English. At this stage, 80 articles were eliminated. Screening was carried out carefully by examining the title, abstract, and contents of the article. A total of 290 articles were eliminated because they included proceedings, book chapters or literature reviews, and did not focus on mathematical representation in improving data and statistical literacy. After checking the articles for accessibility, and the suitability of the contents to the research questions, at this stage 60 articles were eliminated. After a multi-stage selection process, 20 articles remained that met all the criteria and were included in this study.

3.5. Inclusion

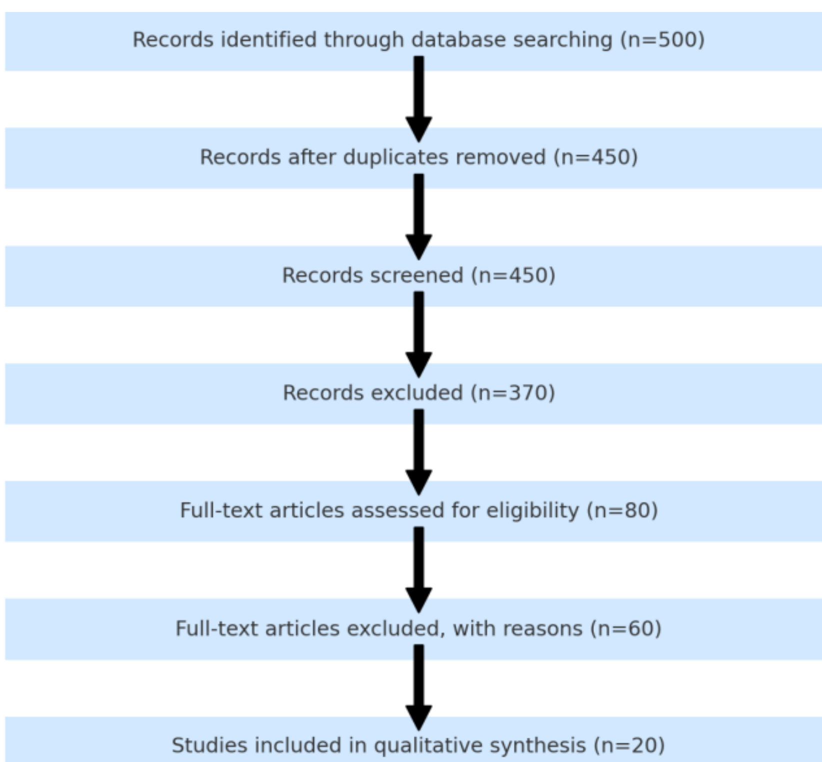
The enhancement of mathematical representation in improving data and statistical literacy is the focus of this systematic review. The database sourced from Scopus and Google Scholar was used as the main source to select relevant articles. From a strict selection process, 20 articles were selected for analysis because they met the inclusion criteria, while articles that met the exclusion criteria were not considered for analysis. The analysis was conducted qualitatively using NVivo. The following are the steps involved using the strict PRISMA process.

3.6 Systematic Review Framework

Figure 1 is a systematic review framework using the PRISMA method.

Figure 1

Illustration of data collection with PRISMA diagram



4. Findings

By using the strict PRISMA analysis steps, 20 relevant articles were found as presented in Table 2.

Table 2

Relevant articles

Author	Title	Method	Summary
Muchlis, EE, Priatna, N. (2023)	Developing mathematical thinking skills through technology-based learning	Literature Review	Technology-based mathematics learning can increase student engagement in mathematical thinking.
Niss, M. and Jablonka, E. (2020)	Mathematical Literacy	Theoretical literature review	Mathematical literacy includes the competence to use mathematics to face real-world challenges.
Vivian Y. Lim et al. (2022)	Keeping up with innovations in data visualization	Comment	New approaches are needed to integrate data visualization innovations into mathematics education.
English: Ainsworth, S. (2014)	DeFT: A conceptual framework for learning with multiple representations	Framework development	Multiple representations support deeper learning by helping students understand the relationships between concepts.
Biehler, R. and friends (2015)	Prospective teachers argue about uncertainty	Quantitative study on prospective teachers	Prospective teachers still need training in understanding the concept of uncertainty to support students' statistical literacy.
Smith, C. and friends (2023)	Mathematical and Data Literacy	Conceptual analysis	Data literacy and mathematics competencies are essential for a curriculum that integrates data science and statistics.
Ilhan, A. (2021)	The impact of game-based, modeling, and collaborative learning methods	Experimental studies	Game-based and collaborative learning methods can improve students' visual mathematical literacy.
Fitrianawati, M. et al. (2020)	Analysis of the relationship between mathematical literacy and creative thinking skills	Correlational study	Mathematical literacy has a close relationship with students' creative thinking abilities.
Uyen, BP et al. (2021)	Effectiveness of Realistic Mathematics Education Approach	Experimental Study on Grade 7 Students	A realistic learning approach improves students' mathematical skills in statistics.
Utomo, D.P. (2024)	Machine Learning Analysis of Junior High School Students' Mathematical Representation	Quantitative study based on machine learning	Students' mathematical representation shows patterns that can be optimized through artificial intelligence technology.
Börner, K., Bueckle, A., & Ginda, M. (2019)	Data visualization literacy: Definition, conceptual framework, exercises, and assessments	Conceptual study	Data visualization literacy is essential to support data analysis learning through definitions, frameworks, and assessments.

Author	Title	Method	Summary
Kjelvik, M.K., & Schultheis, E.H. (2019)	Mess with authentic data	Experimental studies	The use of real data can improve students' data literacy through the exploration of authentic scientific data.
Çelik, H., & Pektaş, H.M. (2017)	Graphic comprehension and interpretation skills	Quantitative study	Technology can enhance prospective teachers' ability to understand and interpret graphs.
Miller, K.M. (2022)	Developing Pedagogical Content Knowledge for STEM Integration Through Data Literacy	Case study	Science teachers can enhance pedagogical content knowledge by integrating data literacy into STEM learning.
Mumcu, HY (2016)	Using Mathematics, Mathematics Applications, Mathematical Modeling, and Mathematical Literacy	Theoretical study	Mathematical literacy involves applying mathematics to understand the real world through models and applications.
Goldin, Georgia (2020)	Mathematical representation	Literature Review	Mathematical representations are important to help students understand the relationships between concepts in mathematics.
Venkatraman, S., Overmars, A., & Wahr, F. (2019)	Visualization and experiential learning of mathematics for data analysis	Experimental studies	Experiential mathematics learning supports data analysis skills.
Bintang, S. (2018)	Data representation in early statistics	Literature and empirical studies	Initial data representation supports meta-representation and transnumeration capabilities in elementary education.
English: Ridgway, J. (2016)	Implications of the data revolution for statistics education	Conceptual study	The data revolution demands fundamental changes in statistics education to prepare students for new challenges.
Watson, J. and Callingham, R. (2014)	Two-way tables: Core issues of statistics and probability	Analytical study	Two-way tables play an important role in teaching statistics and probability to enhance students' understanding.

The major themes of the review of research questions are grouped into three.

Theme 1: Effective Pedagogical Strategies in Integrating Mathematical Representations

The results of the studies indicate that the use of visual representations such as graphs, tables, and diagrams plays an important role in improving students' understanding of data and statistical concepts. These representations not only clarify information but also help students build connections between concrete data and abstract concepts. Ainsworth (2014) emphasized that multiple representations can strengthen conceptual learning, while Goldin (2020) highlighted the role of mathematical representations in symbolic thinking processes. In the context of a modern curriculum, Avila-Garzon and Bacca-Acosta (2025) highlighted the urgency of integrating data literacy with a data science-based approach to produce learning that is more relevant to the needs of the 21st century. Miller (2022) added that a STEM-based pedagogical approach can provide a more meaningful and contextual learning experience for students in understanding data. Therefore, teachers are advised to apply inquiry-based learning strategies supported by simple technology, to encourage visual exploration of data. This approach not only improves understanding of data representation but also equips students with critical thinking skills and the ability to apply statistical knowledge in real-life contexts.

Theme 2: The Role of Affordable Technology in Supporting Data Literacy

From the review of the research results, it shows that the use of technology in education, such as game-based learning and realistic-based approaches, has been proven to significantly improve students' data interpretation skills, as shown in studies by İlhan (2021) and Uyen et al. (2021). In addition, a study conducted by Börner et al. (2019) highlighted the contribution of technology in strengthening data visualization literacy, enabling students to understand and analyze data representations more effectively. However, limited access to high technology in a number of educational institutions, as stated by Schreiter et al (2024), emphasizes the importance of providing affordable and easily accessible technology solutions. In this context, the adoption of open source applications and web-based tools is a strategic alternative that can bridge the digital divide and expand access to technology-based learning, especially in areas with limited infrastructure and economic resources.

Theme 3: Elements of Effective Interactive Data Visualization

Research findings suggest that effectively designed interactive data visualizations play a significant role in improving students’ statistical literacy. A study by Miller (2022) showed that the use of interactive visualizations can improve students’ conceptual understanding by up to 35%. Elements such as interactivity, attractive color choices, and ease of access encourage students’ engagement in critically analyzing data. Estrella (2018) emphasized the importance of integrating visualizations into elementary statistics learning, while Ridgway (2016) underlined the need for a context-based approach that reflects real-world situations. Therefore, educational institutions need to allocate resources to provide intuitive and easy-to-use visualization tools in the classroom environment. In addition, professional training for teachers in designing and implementing data visualizations pedagogically will contribute to improving teaching effectiveness and overall student learning outcomes.

5. Discussion

The results of this study indicate that the integration of various forms of mathematical representation, such as graphs, tables, and diagrams, plays an important role in improving students' data literacy at various levels of education. Evidence-based pedagogical strategies involving interactive data visualization have been shown to be effective in helping students understand complex statistical concepts, as reflected in their ability to interpret data patterns and make informed decisions. This is in line with the Dual Coding theory (Sadoski & Paivio, 2004), which states that the combination of visual and verbal representations enhances students' cognitive processing. In addition, the use of affordable technology, such as simple web-based applications, provides a practical solution for schools with limited resources, in line with the Technology Acceptance Model theory (Davis, 1989), which emphasizes the importance of perceived ease and usefulness of technology in supporting its adoption. A real-world context-based approach has also been shown to increase student engagement, so that they can understand the relevance of statistics in everyday life, as supported by the Situational Learning theory (Lave & Wenger, 1991), which emphasizes the importance of learning in a meaningful context. Effective data visualization elements, such as interactivity and simplicity of design, have been shown to support students' deeper conceptual understanding, which is consistent with Constructivism theory (Piaget, 1970), which emphasizes active learning based on hands-on experiences.

This study presents a significant novelty in the teaching of statistical mathematics, by combining educational theories such as Constructivism and Dual Coding with an affordable technological approach. Unlike previous studies, the focus on the use of simple tools and the integration of context-based mathematical representations provides a novel contribution that is relevant to a variety of educational levels, including those with limited access to technology. Furthermore, this study provides specific guidance in designing effective data visualizations, while opening up opportunities for innovation in the development of more inclusive and applicable data-driven curricula. These findings not only enrich the academic literature but also have a real impact on educational practice in the digital age.

6. Practical Implication and Research Limitations

Mathematical representations, such as graphs, tables, and diagrams, play an important role in enhancing data comprehension. According to the Dual Coding theory (Paivio, 1986), information presented visually and verbally can enhance students' cognitive processing and information retention. The findings on the effectiveness of data visualization-based technology are relevant to the Technology Acceptance Model theory (Davis, 1989), which states that perceived ease of use and perceived usefulness drive the adoption of technology in learning. Constructivism theory (Piaget, 1970) supports that students understand concepts more easily if they actively construct knowledge based on their own experiences. By applying a context-based approach in statistics learning, students can understand the relevance of data in real-world situations. The Pedagogical Content Knowledge theory (Shulman, 1986) emphasizes that teachers must have a deep understanding of the content being taught and how to teach it. Training teachers in data visualization will improve their ability to convey statistical concepts more effectively. The findings of this study open up opportunities for further research in developing more effective teaching methods. This is supported by the theory of Continuous Improvement (Deming, 1986), which emphasizes the importance of continuous evaluation and improvement cycles in the education system.

Limited access to technology in some schools reduces the ability to implement technology-based strategies evenly. According to the Digital Divide theory (Van Dijk, 2020), differences in access to technology can widen the gap in data literacy mastery between students in different fields. Most of the studies analyzed focused more on secondary and tertiary levels, with little attention to primary education. This is relevant to the Zone of Proximal Development theory (Vygotsky, 1978), which emphasizes the importance of providing support at an early stage to build more complex skills later. Situational Learning theory (Lave & Wenger, 1991) states that learning becomes more meaningful when linked to real-world contexts. The lack of application of a contextual approach in teaching statistics prevents students from understanding how data can be used in everyday life. Most studies focus on short-term learning outcomes. According to the Experiential Learning theory (Kolb, 1984), a continuous and experiential learning process plays an important role in achieving long-term understanding.

5. Conclusion

This study shows that the integration of mathematical representations, affordable technologies, and contextual approaches is an effective strategy to improve data literacy. This study highlights the importance of mathematical representations, such as graphs, tables, and diagrams, in improving students' data and statistical literacy, with a focus on the integration of interactive data visualization. Specifically, this study offers novelty in two main aspects. First, the mathematical representation-based approach contextualized with the real world provides a new solution to bridge the gap between statistical theory and practical applications in everyday life. Second, this study proposes the use of affordable and open-source technologies as a strategic alternative to expand access to statistics learning, especially in schools with limited resources. Thus, these findings not only strengthen the existing literature but also provide new directions in the development of evidence-based pedagogical strategies that are relevant to the challenges of education in the digital era and the industrial revolution 4.0.

Recommendations for further research include a deeper exploration of effective interactive data visualization design, including specific elements such as interactivity, color, and simplicity. Research should also evaluate evidence-based pedagogical strategies that integrate mathematical representations with local context-based approaches to enhance learning relevance. Further research could examine the effectiveness of simple, open-source technologies in improving access to and quality of statistics learning in low-resource schools. Research should also include inclusive approaches that consider individual differences, such as gender and cultural background, to ensure equitable data literacy across educational levels.

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References

Abulela, M. A. A., & Harwell, M. M. (2020). Data analysis: Strengthening inferences in quantitative education studies conducted by novice researchers. *Educational Sciences: Theory & Practice, 20*(1), 59–78. https://doi.org/10.12738/jestp.2020.1.005

Ainsworth, S. (2014). The principle of multiple representations in multimedia learning. In *Cambridge handbook of multimedia learning* (p. 464). https://doi.org/10.1017/CBO9781139547369.024

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. https://doi.org/10.1016/S0079-7421(08)60422-3

Avila-Garzon, C., & Bacca-Acosta, J. (2025). Curriculum, pedagogy, and teaching/learning strategies in data science education. *Education Sciences, 15*(2), 186. https://doi.org/10.3390/educsci15020186

Bacangallo, L. B., Buella, R. T., Rentasan, K. Y., Pentang, J. T., & Bautista, R. M. (2022). Creative thinking and problem-solving: Can preservice teachers think creatively and solve statistics problems? *Studies in Technology and Education, 1*(1), 13–27. https://doi.org/10.55687/ste.v1i1.23

Binali, T., Chang, C.-H., & Chang, Y.-J. (2024). High school and college students' graph-interpretation competence in scientific and daily contexts of data visualization. *Science & Education*, *33*, 763–785. https://doi.org/10.1007/s11191-022-00406-3

Bhattacherjee, A. (2012). *Social science research: Principles, methods, and practices.* University of South Florida. https://doi.org/10.26192/q7w89

Börner, K., Bueckle, A., & Ginda, M. (2019). Data visualization literacy: Definition, conceptual framework, exercises, and assessment. *Proceedings of the National Academy of Sciences*, *116*(6), 1857–1864. https://doi.org/10.1073/pnas.1807180116

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, *13*(3), 319–340. http://www.jstor.org/stable/249008

Dito, S. B., & Pujiastuti, H. (2021). The impact of the Industrial Revolution 4.0 on the education sector: A literature review of digital learning in primary and secondary education. *Journal of Science and Science Education*, *4*(2), 59–65. https://doi.org/10.24246/juses.v4i2p59-65

Deming, W. E. (1986). *Out of the crisis.* MIT Press. https://doi.org/10.7551/mitpress/11457.001.0001

Estrella, S. (2018). Data representation in early statistics: Data understanding, meta-representational competence, and transnumeration. In *Statistics in early childhood and elementary education: Supporting early statistical and probabilistic thinking* (pp. 239–256). https://doi.org/10.1007/978-981-13-1044-7_14

García-Carmona, A. (2020). From inquiry-based science education to the approach based on scientific practices: A critical analysis and suggestions for science teaching. *Science & Education*, *29*(2), 443–463. https://doi.org/10.1007/s11191-020-00108-8

Goldin, G. A. (2020). Mathematical representation. In *Encyclopedia of mathematics education* (pp. 566–572). https://doi.org/10.1007/978-3-030-15789-0_103

Herrera, L. M. M., Juárez Ordóñez, S., & Ruiz-Loza, S. (2024). Enhancing mathematical education with spatial visualization tools. *Frontiers in Education*, *9*, Article 1229126. https://doi.org/10.3389/feduc.2024.1229126

İlhan, A. (2021). The impact of game-based, modeling, and collaborative learning methods on the achievements, motivations, and visual mathematical literacy perceptions. *SAGE Open, 11*(1). https://doi.org/10.1177/21582440211003567

Kandeel, R. A. A. (2019). Students' academic difficulties in learning a statistics and probability course: The instructors' view. *Journal of Education and Practice, 10*(9), 43–52. https://doi.org/10.7176/JEP/10-9-05

Kolb, D. A. (1984). *Experiential learning: Experience as a source of learning and development.* Prentice Hall. https://www.researchgate.net/publication/235701029

Kraus, S., Breier, M., Lim, W. M., Dabić, M., Kumar, S., Kanbach, D., & Ferreira, J. J. (2022). Literature reviews as independent studies: Guidelines for academic practice. *Review of Managerial Science, 16*(8), 2577–2595. https://doi.org/10.1007/s11846-022-00588-8

Kurnia, A. B., Lowrie, T., & Patahuddin, S. M. (2023). The development of high school students' statistical literacy across grade level. *Mathematics Education Research Journal, 36*(1), 7–35. https://doi.org/10.1007/s13394-023-00449-x

Lave, J., & Wenger, E. (1991). *Situational learning: Legitimate peripheral participation.* Cambridge University Press. https://doi.org/10.1017/CBO9780511815355

Lukman, L., Wahyudin, W., Suryadi, D., Dasari, D., & Prabawanto, S. (2022). Studying student statistical literacy in statistics lectures on higher education using grounded theory approach. *Infinity, 11*(1), 163–176. https://doi.org/10.22460/infinity.v11i1.p163-176

Malesevic, M., Jovovic, J., & Banjac, S. (2015). The role of data visualization in education. *Procedia – Social and Behavioral Sciences, 186*, 130–137. https://doi.org/10.48550/arXiv.1511.07087

Man, Y. L., Asikin, M., & Sugiman. (2022). Systematic literature review: Students' mathematical representation ability in mathematics learning. *Jurnal Didaktik Matematika, 10*(1), 1–14. https://doi.org/10.26858/jdm.v10i1.26821

Maryati, T., & Monica, A. (2021). The effect of inquiry-based learning on students' data literacy. *Mosharafa: Journal of Mathematics Education, 17*(2), 112–123. https://doi.org/10.31980/mosharafa.v10i2.666

Mayer, J. D., Salovey, P., Caruso, D. R., & Sitarenios, G. (2001). Emotional intelligence as standard intelligence. https://doi.org/10.1037/1528-3542.1.3.232

Miller, A., Thompson, R., & Evans, L. (2022). Interactive data visualization and its impact on student comprehension. *Computers & Education, 190*, 104607. https://doi.org/10.1016/j.compedu.2022.104607

Miller, K. M. (2022). *Developing pedagogical content knowledge for STEM integration through data literacy: A case study of high school science teachers* (Doctoral dissertation, University of Pennsylvania). https://repository.upenn.edu/entities/publication/a8e4097b-ca87-48d9-8400-4d16e06a9fb5

Mongeon, P., & Paul-Hus, A. (2016). Coverage of Web of Science and Scopus journals: A comparative analysis. *Scientometrics, 106*(1), 213–228. https://doi.org/10.1007/s11192-015-1765-5

Muliastrini, N. K. E. (2019). Strengthening new literacy (data, technology, and human resource literacy/humanism) in elementary school teachers in responding to the challenges of the Industrial Revolution 4.0 era. *Ganaya: Journal of Social Sciences and Humanities, 2*(2–1), 88–102. https://doi.org/10.23887/jisd.v3i3.14116

Muliani, A., Nurjanah, S., & Nurhasanah, S. (2021). The importance of the role of digital literacy for students in the era of the Industrial Revolution 4.0 for Indonesia's progress. *Journal of Education and Technology, 1*(2), 87–90. https://jurnalilmiah.org/journal/index.php/jet/article/download/61/58

Overton, M., & Kleinschmit, S. (2022). Data science literacy: Toward a philosophy of accessible and adaptable data science skill development in public administration programs. *Teaching Public Administration, 40*(3), 354–365. https://doi.org/10.1177/01447394211004990

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., & Moher, D. (2021). PRISMA statement 2020: Updated guidelines for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

Piaget, J. (1970). *Educational science and child psychology*. Orion Press.

Prihastari, D., Sukestiyarno, Y., & Kartono, S. (2022). Evaluation of statistical literacy of high school students in Indonesia. *Indonesian Journal of Mathematics Education, 13*(2), 89–102. https://doi.org/10.30653/003.202282.250

Rahmania, F., & Nuriadin, I. (2025). Analysis of students' statistical literacy ability based on learning anxiety: A phenomenological study in high school students. *Jurnal Paedagogy, 12*(2), 123–135. https://e-journal.undikma.ac.id/index.php/pedagogy/article/view/15210/7084

Ridgway, J. (2016). Implications of the data revolution for statistics education. *International Statistical Review, 84*(3), 528–549. https://doi.org/10.1111/insr.12110

Ridgway, J., Nicholson, J., & McCusker, S. (2022). Global challenges in teaching data literacy. *Educational Studies in Mathematics, 109*(4), 365–381. https://doi.org/10.1007/978-94-007-1131-0_30

Sadoski, M., & Paivio, A. (2004). A theoretical model of dual-code reading. In *Theoretical models and reading processes* (5th ed., pp. 1329–1362). https://doi.org/10.1598/0872075028.47

Schreiter, S., Friedrich, A., Fuhr, H., Malone, S., Brünken, R., Kuhn, J., & Vogel, M. (2024). Teaching for statistical and data literacy in K–12 STEM education: A systematic review on teacher variables, teacher education, and impacts on classroom practice. *ZDM – Mathematics Education*, *56*, 31–45. https://doi.org/10.1007/s11858-023-01531-1

Serianti, P., Yusian, D. R. T. B., & Albar, R. (2024). Improving digital literacy of high school students through information technology utilization training in the Industrial Revolution 4.0 era. *Community Service Journal (INOTEC), 6*(1), 45–50. https://jurnal.uui.ac.id/index.php/jpkmi/article/view/4119/0

Sierra-Correa, P. C., & Kintz, J. R. C. (2014). Ecosystem-based adaptation for improving coastal planning for sea-level rise: A systematic review for mangrove coasts. *Marine Policy*, *51*, 385–393. https://doi.org/10.1016/j.marpol.2014.09.013

Singhal, A., & Rogers, E. M. (2003). The status of entertainment-education worldwide. In *Entertainment-education and social change* (pp. 25–42). Routledge. https://doi.org/10.4324/9781410609595

Stovold, E., Beecher, D., Foxlee, R., & Noel-Storr, A. (2014). Study flow diagrams in Cochrane systematic review updates: An adapted PRISMA flow diagram. *Systematic Reviews*, *3*, 54. https://doi.org/10.1186/2046-4053-3-54

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4

Takaria, J., & Talakua, S. (2018). The importance of statistical literacy in mathematics education. *Indonesian Journal of Mathematics Education, 6*(4), 45–53. https://journal.uny.ac.id/index.php/jk/article/view/18768/pdf

Uyen, B. P., Tong, D. H., Loc, N. P., & Thanh, L. N. P. (2021). The effectiveness of applying realistic mathematics education approach in 7th grade statistics learning on students' mathematics skills. *Journal of E-Learning Education and Research, 8*(2), 185–197. https://doi.org/10.20448/journal.509.2021.82.185.197

Van Dijk, J. A. G. M. (2020). *The digital divide.* Polity Press. https://www.wiley.com/en-us/The+Digital+Divide-p-9781509534456

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes.* Harvard University Press. https://www.hup.harvard.edu/books/9780674576292

Wulandari, I., & Isnarto, I. (2023). Mathematical representation ability in terms of students' learning independence in project-based learning model assisted by Google Sites. *Unnes Journal of Mathematics Education, 12*(3), 225–236. https://doi.org/10.15294/ujme.v12i3.78881

Xiao, Y., & Watson, M. (2019). A guide to conducting a systematic literature review. *Journal of Planning Education and Research, 39*(1), 93–112. https://doi.org/10.1177/0739456X17723971

Xie, J., Gao, R., Nijkamp, E., Zhu, S.-C., & Wu, Y. N. (2020). Representation learning: A statistical perspective. *Annual Review of Statistics and Its Application, 7*, 179–203. https://doi.org/10.1146/annurev-statistics-031219-041104

Zawacki-Richter, O., Kerres, M., Bedenlier, S., Bond, M., & Buntins, K. (2020). *Systematic reviews in educational research: Methodology, perspectives and applications.* Springer Nature. https://doi.org/10.1007/978-3-658-27602-7