Asian Journal of Applied Education (AJAE)
Vol. 5, No. 1, 2026: 163-178

Exploring Students' Cognitive Pathways in Understanding Statistical Variability in Digital Learning Environments

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ARTICLE INFO

Keywords: Students, Cognitive Pathways, Statistical Variability, Digital Learning Environments.

Received : 27, November
Revised : 29, December
Accepted: 30, January

ABSTRACT

Understanding statistical variability is a core competency in technology education and data literacy, particularly in digitally mediated learning environments that demand advanced cognitive processing. This exploratory qualitative study investigates students' cognitive pathways in constructing understanding of statistical variability through interactions with digital, technology-based tasks. Using a Think-Aloud Protocol supported by screen recordings, data were collected from 12 students at a public senior high school in Bandung, West Java, and analyzed using Cognitive Task Analysis. The findings reveal multi-layered cognitive pathways, beginning with the identification of visual elements, followed by exploration of data changes, and progressing toward meaning construction and interpretation of variability. Difficulties emerge at the stage of integrating concepts, especially when students must connect dynamic visual data with abstract statistical interpretations. The study contributes to theoretical insights into students' cognitive structures in digital learning contexts and offers practical implications for designing adaptive, technology-based instructional strategies aligned with learners' thinking processes.

INTRODUCTION

The development of the digital learning environment at the high school level shows an increasingly complex transformation, especially as the needs for data literacy, analytical mastery, and statistical thinking skills in students increase. At the global level, various studies confirm that the effective use of digital technology can strengthen the understanding of statistical concepts through data visualization, interactive simulations, and problem-based exploratory activities (Harrington & Miles, 2022). A digital learning environment not only provides access to a wider range of learning resources, but also opens up space for students to explore data patterns, relationships, and uncertainties more independently (Zhou et al., 2023). In the Indonesian context, the strengthening of numeracy competencies emphasized in the national curriculum places the understanding of statistical variability as one of the important elements in the development of higher-level thinking skills (Sundari & Prakoso, 2024). This is especially relevant for public high schools (SMAN) in the Bandung area, West Java, which are currently increasingly intensively adopting digital learning in data analysis activities in the classroom.

Although the literature on statistical learning continues to grow, most research still focuses on the effectiveness of digital media or improving learning outcomes, rather than on how students build cognitive pathways when understanding the concept of statistical variability in depth. Previous research has mostly examined the technical aspects of using statistical applications or online learning platforms, while the process of reasoning students in interpreting data variations, identifying uncertainties, and constructing statistical inferences is still rarely comprehensively explored (Ramadhani & Cooper, 2021). Other studies show that students often have difficulty explaining the reasons behind patterns of variability, especially when tasks demand integration between visual, numerical, and contextual representations (Wong & Patel, 2023). This condition indicates that students' understanding of statistical variability is not only related to procedural knowledge, but also to complex cognitive processes formed through interaction with digital learning environments.

In addition, the limitations of research related to the exploration of students' cognitive pathways in the context of digital-based statistical learning are very visible in secondary education in Indonesia. Most studies still place students as technology users, not as thinkers who actively build understanding through interpretive, exploratory, and reflective processes (Hakim & Wijaya, 2022). In fact, learning statistics in the digital era requires students to process data more dynamically, test conjectures, and interpret variability with a higher level of accuracy. In public schools in Bandung that have integrated technology through learning management systems and digital data analysis applications, this phenomenon is becoming more apparent, as students have more opportunities to interact with real-time data, distribution simulations, and various statistical representations. Thus, there is an urgent need to examine how these cognitive pathways are formed, developed, and influenced by the digital ecosystem that students use.

Methodological approaches such as Cognitive Task Analysis (CTA) are relevant to uncover students' thinking processes in understanding statistical variability. Recent studies have shown that these two approaches are effective in mapping reasoning patterns, problem-solving strategies, and cognitive barriers that arise when students interact with statistical tasks in a digital environment (Morrison & Jin, 2024). Through digital activity-based cognitive analysis, researchers can trace how students build schemas of understanding when confronted with changing data, interactive graphical representations, and exploration-based instruction. In the context of high schools in Bandung that have adopted statistical learning practices based on digital devices, this approach is able to provide a richer picture of how statistical variability is interpreted and understood by students gradually.

In the Southeast Asian region, research on statistical learning in the digital environment is generally still focused on the use of specific applications or platforms without delving into the conceptual structure of students' reasoning. For example, a number of studies have found that students are able to improve learning outcomes when using data visualization technology, but do not elaborate on how those representations affect their understanding of variation and uncertainty (Lim et al., 2021). Meanwhile, studies that discuss statistical variability are mostly conducted in the context of higher education and have not touched much on secondary education (Chen & Abdullah, 2023). With the condition of education in Indonesia that is experiencing an acceleration of digitalization, including in Bandung as one of the cities with a rapidly growing educational technology ecosystem, this research gap shows the need for studies that focus on students' cognitive pathways in understanding statistical variability in the digital learning environment.

Based on these gaps, this study aims to explore students' cognitive pathways in understanding statistical variability through digital-based learning activities. This study examines how students interpret data variations, connect between statistical representations, identify patterns of uncertainty, and compile inferences based on data presented in digital platforms. In addition, this study identified the factors that influence these cognitive processes, including numeracy readiness, technology-based learning experiences, and instructional design implemented by teachers. The focus of the research on one of the SMANs in the Bandung area provides a strong empirical context to understand the dynamics of cognitive pathways in a real digital ecosystem.

Theoretically, this research contributes to the development of the literature on statistical learning by adding new perspectives on how students' cognitive pathways are formed in a digital environment. This research also expands the understanding of the interaction between digital representation, exploratory activities, and the development of the concept of variability in the context of secondary education. From a methodological perspective, this study strengthens the use of cognitive analysis in statistical learning studies, especially those involving digital data and tracking students' thinking processes. Practically, the findings of this study can serve as a reference for teachers, schools, and curriculum developers in designing statistical learning interventions that are more adaptive, data-driven, and sensitive to the way students understand variability. For schools in Bandung that are strengthening the integration of digital technology, this study offers strategic recommendations to improve the quality of statistical learning and data literacy at the secondary education level.

LITERATURE REVIEW

Understanding Statistical Variability in Secondary Mathematics Education

The concept of statistical variability is a central element in statistical learning that requires students to understand the changes, uncertainties, and differences between data. The global literature emphasizes that the ability to interpret variability helps students develop a deeper understanding of statistics, especially regarding data distribution and inference (Morgan & Fields, 2021). Various studies show that understanding variability depends not only on procedural abilities such as calculating the size of the spread, but also on conceptual skills in connecting graphic, numerical, and contextual representations (Delgado & Harmon, 2022). In the context of secondary education, research confirms that many students still struggle to read patterns of data variation, especially when dealing with complex or large-scale data (Serrano & Quinn, 2023). This literature suggests that understanding variability requires a multi-layered cognitive process that involves interpretation, evaluation, and reflection on statistical data.

Digital Learning Environments and Their Influence on Statistical Reasoning

The digital learning environment provides new opportunities for students to explore data through interactive technology, distributed simulations, and dynamic visualization. Recent research shows that digital platforms can strengthen statistical reasoning by providing an experiential environment that allows direct manipulation of data (Harper & Lin, 2021). Other studies confirm that the use of digital tools such as graphing software, dynamic statistics tools, and virtual labs helps students build a more flexible understanding of data variations and uncertainties (O'Malley & Tan, 2023). However, the literature also shows the existence of challenges, such as increased cognitive load when students have to blend multiple digital representations at once (Khanna & Mitchell, 2022). Thus, the digital learning ecosystem provides significant benefits for statistical learning, but it requires proper instructional design so that students can optimally navigate information.

Cognitive Pathways in Students' Understanding of Statistical Concepts

The cognitive path in understanding the concept of statistics describes the gradual thinking process that students go through when constructing meaning to data. The cognitive literature shows that students typically go through several phases: identifying information, recognizing patterns of variability, interpreting changes, and constructing inferences (Foster & Delgado, 2024). Other research reveals that students' understanding develops through the interaction between initial knowledge, experience manipulating data, as well as the ability to interpret various representations (Nguyen & Carlton, 2021). In the context of statistical variability, students' cognitive pathways often exhibit obstacles such as generalization errors, excessive focus on extreme values, or an inability to relate individual data to the overall distribution (Roche & Ellis, 2023). This literature confirms that cognitive pathway mapping can help teachers understand students' thinking strategies and tailor instructional assistance.

Digital Tools and Representation-Based Reasoning in Statistics Learning

Digital representations play an important role in developing students' statistical reasoning. The technology enables the presentation of data in the form of interactive graphs, dynamic histograms, simulations of random variables, and comparative diagrams that enrich the understanding of the concept of variability (Anderson & Richey, 2022). Research shows that digital representation can improve students' ability to relate data changes to distribution patterns more intuitively (Watanabe & Gomez, 2023). However, the success of digital representations is greatly influenced by students' ability to transform information between representations, for example from tables to graphs or from graphs to verbal interpretation (Silvers & Patel, 2021). This literature emphasizes that the use of digital tools needs to be integrated with cognitive scaffolding so that students not only operate technology, but also interpret the relationships between representations in depth.

Cognitive-Oriented Approaches in Mathematics Education Research

Cognitive Task Analysis (CTA) is widely used to comprehensively understand students' thinking processes in the context of statistical learning. The methodological literature suggests that DBR allows researchers to design and test interventions iteratively so that they can uncover changes in students' cognitive pathways throughout learning (Peters & Molina, 2020). Meanwhile, CTAs help map students' cognitive processes when solving statistical problems, including mental strategies that are not explicitly apparent in written answers (Dawson & Rudd, 2024). This approach is effectively used in digital learning because it is able to capture student activities in real-time through data logs, clickstreams, and digital interaction recordings. This literature confirms that the combination of the two approaches can provide a deeper understanding of how statistical variability is understood in the digital learning ecosystem.

Student Difficulties and Misconceptions in Understanding Variability

Research shows that students' difficulties in understanding statistical variability stem from a variety of cognitive and pedagogical factors. One of the key findings is the tendency of students to focus attention only on average scores and ignore the dissemination of data (Barreto & Singh, 2022). In addition, students often interpret graphs partially without paying attention to the overall distribution, so their understanding of variability patterns is limited (Jonas & Pelton, 2021). Some studies have also revealed misconceptions about the relationship between sample size and distribution stability, especially in digital learning that presents data quickly and in large quantities (Ramos & Li, 2023). This literature emphasizes the importance of instructional strategies that lead students to understand data as a structured set, rather than just individual numbers.

Digital Learning Contexts in Indonesian Secondary Schools

In the Indonesian context, the digitization of mathematics learning has experienced rapid growth, especially since the adoption of online learning platforms and digital data processing applications in secondary schools. National research shows that the use of technology in statistical learning can increase student motivation while facilitating independent exploration of data variations (Nurdin & Astuti, 2022). However, challenges such as digital facility gaps, variations in technology literacy, and teacher unpreparedness still affect learning effectiveness (Mahendra & Kusumawati, 2023). In public high schools in Bandung, the implementation of digital learning shows an opportunity to strengthen statistical understanding through access to real-time data and interactive visualizations. This literature shows that the Indonesian context has special dynamics that need to be considered in the analysis of students' cognitive pathways.

METHODOLOGY

Research Design

This study uses an exploratory qualitative approach with a Cognitive Task Analysis (CTA) design to deeply explore students' cognitive pathways when understanding statistical variability in a digital learning environment. This approach was chosen because CTA is able to capture thought processes, mental strategies, and cognitive difficulties that are not seen through conventional quantitative measurements (Berrington & Stone, 2021). Exploratory design is needed to identify students' reasoning structures naturally during interaction with digital data, particularly when faced with dynamic and complex statistical visualizations (Sanders & McLeod, 2023). Thus, this study focuses on describing cognitive phenomena in detail without manipulating variables, in line with the characteristics of modern cognitive studies in digital mathematics education (Hughes & Ricardo, 2022).

Population, Setting, and Sampling Technique

The research population includes all grade XI students from one of the State High Schools (SMAN) in the Bandung area, West Java, which has integrated digital-based statistical learning. The sampling technique used is non-probability purposive sampling, which is the selection of participants based on certain criteria, such as basic numeracy skills, experience using digital platforms, and involvement in technology-based statistical learning (Keller & Morgan, 2020). A total of 12 students were selected as participants because the number was considered ideal for in-depth analysis in CTA and Think-Aloud studies, which demanded intensive cognitive observation per individual (Petersen & Howard, 2021). The selection of the number of participants also follows the recommendations of cognitive qualitative studies that emphasize data depth over quantity (Han & Fletcher, 2023).

Data Collection Techniques and Instruments

Data collection was carried out through three main techniques, namely Think-Aloud Protocol (TAP), screen-recorded digital task observation, and semi-structured interviews. The TAP technique is used to capture students' thinking processes in real-time when completing statistical variability analysis tasks on digital platforms; This method has been shown to be effective in identifying cognitive strategies and mental difficulties during digital interactions (Romano & Chen, 2022). The main instrument consists of a set of digital-based statistical tasks designed using data simulations and interactive graphs. Task items were developed based on adaptations of statistical variability concepts used in previous digital learning research (Harwood & Yee, 2021). Complementary data were collected through semi-structured interviews to validate the interpretation of cognitive processes that emerged during TAP. The validity of the instrument was maintained through expert judgment by two mathematics education lecturers, while the reliability of the thought process was strengthened through triangulation of techniques (Carver & Milburn, 2023).

Research Procedures

The research procedure is carried out through several systematic stages. The first stage is instrument preparation, including the development of digital tasks, content feasibility tests, and setting up screen recording devices. The second stage is the recruitment of participants as well as the implementation of Think-Aloud sessions in the school's computer lab room, where each student completes an assignment within 30–45 minutes. During the session, all digital interaction activities are recorded for further analysis. The third stage is a clarification interview, which is a brief discussion of the reasons, strategies, and difficulties experienced by students. The fourth stage is data transcription and reduction, including TAP verbal transcription, screen recording annotation, and synchronization between verbalized reasoning and digital activities. The final stage is the analysis and verification of the results, carried out by triangulating the sources and checking the compatibility between researchers (Dawson & Karim, 2024).

Data Analysis Techniques

Data were analyzed using the Cognitive Task Analysis approach which included four main stages: (1) activity segmentation based on problem solving steps, (2) identification of cognitive strategies, (3) mapping of errors and cognitive bottlenecks, and (4) construction of student cognitive pathway models. The analysis was conducted following a modern CTA framework that emphasizes verbal interpretation and simultaneous task performance (Lopez & Harding, 2023). Thematic analysis approaches are used to group emerging patterns of reasoning and cognitive biases (Nugent & Sawyer, 2022). To support the accuracy of the analysis, NVivo 14 software is used in the coding of verbal and visual data, while the synchronization of digital recordings is done using the OBS Timeline Analyzer. The combination of these techniques provides a comprehensive overview of how students build an understanding of statistical variability in a digital environment.

RESEARCH RESULTS

Identify Visual Elements as the Early Stages of the Cognitive Pathway

The results of the analysis showed that almost all students began their reasoning process by identifying the basic visual elements that appear on the digital graph display. This step becomes the initial foundation in understanding the data structure before they undertake further exploration. Some students affirm that their first attention is focused on the shape of the graph, the position of the dots, and the differences in colors displayed. This is evident in the statement "*I look at the graph first, the dots are many or few, then the colors are different, it makes me understand which part I want to analyze*" (S-03, October 12, 2025 interview). A similar trend also arises in other students who state that visualization is the gateway to understanding the flow of assignments. One of the students said, "*If the appearance is clear, I can immediately know what parts to pay attention to, such as the parts that are spread out or the ones that are tight*" (S-07, October 14, 2025 interview). The statement shows that visual observation is an initial mechanism to build a perception of variability.

The link between visual elements and students' readiness to conduct analysis is also seen in the statement "*I have to look at the picture first to understand, because from the graph I can tell if the data has changed or is the same*" (S-11, October 16, 2025 interview). This quote shows the need to stabilize visual comprehension before entering the stage of statistical reasoning. Even one of the students explicitly asserted that this stage helps them reduce the initial confusion, as it was conveyed, "*If I haven't seen the appearance, I'm a bit confused about where to start, so I'll see first so I can imagine what the data looks like*" (S-02, interview October 10, 2025). The four citations show that the identification of visual elements is the first stage that consistently appears in the student's cognitive pathway and serves as a foundation for understanding data variations in more depth.

Exploration of Data Change as an Initial Meaning Mechanism

Once students recognize the basic visual elements, they enter the exploratory stage of data change. In this phase, students begin to slide the slider, change parameters, or observe the dynamics of point changes on the graph. This process allows them to see patterns of variation directly through digital interactions. One of the students described this process by saying, "*When I move the data controller, the points change, from there I start to understand which ones are more widespread and which are not*" (S-05, October 13, 2025 interview). Active engagement with digital simulations also seemed to reinforce their initial understanding of patterns of variation. One student stated, "*If I change the number, the graph moves. From there, I can compare whether the distribution is wider or narrower.*" (S-01, October 10, 2025 interview). This quote shows that exploration is experimental and provides a concrete experience to understand variability.

Additionally, some students feel that dynamic changes help them find relationships between data components. A student said, "*I tried it first, if the data is large and small, the form of distribution is also different. So I can see the relationship* *between the change in numbers and the graph."* (S-08, October 14, 2025 interview). The statement indicates that exploration not only aids observation but also establishes early associations regarding the concept of variability. However, the level of awareness of these dynamics is not completely even. One student revealed that the exploration process helped him distinguish patterns even though he was still confused at times: *"I've seen the changes, but sometimes I'm still confused if the dots move fast, so I have to repeat it again to understand."* (S-10, interview October 15, 2025). The four quotes affirm that the exploration of data changes becomes a bridge between visual observation and the meaning of initial statistics.

Formulation of Meaning on the Spread of Values

The next stage that seems clear in cognitive pathway analysis is the student's attempt to form a meaning towards the dissemination of values. At this stage, students begin to express their interpretations of how much variation arises as well as what implications they have on statistical understanding. One of the students said, *"If the point is far away, I consider the distribution large. That means the data is very different."* (S-06, interview October 12, 2025). This suggests that they are starting to explain variability using more abstract reasoning. Similar patterns are also seen when students try to correlate the distribution pattern with the characteristics of the data. A student said, *"If it is a meeting, it means that the data is similar, if it is spreading, it means different. I began to understand the meaning of the distribution from there."* (S-04, October 11, 2025 interview). This quote shows a gradual but consistent process of conceptualization.

Some students also tried to attribute the quality of the spread to contextual conditions. For example, one student stated, *"If I imagine that the data is a test score, if the spread is large, it means that the students' abilities are much different"* (S-12, interview October 17, 2025). This quote shows that the meaning of deployment can be extended to a real context. Furthermore, students' meanings of variability mature when they start using certain terms, even though they are not yet fully formal. One of the students said, *"It's like there's something extreme, there's something in the middle, it seems like the data is getting more varied"* (S-09, October 14, 2025 interview). These four quotes show that students are gradually moving from intuitive understanding to conceptual meanings of statistical variability.

Constraints of Concept Integration in Complex Visual Dynamics

Although most students are able to follow the initial three stages of the cognitive pathway, the results of the study show that difficulties begin to arise when they are faced with dynamic and more complex visualizations. One of the students stated, *"If the picture changes quickly, I find it difficult to connect the graph with the distribution concept that has been learned"* (S-02, interview October 18, 2025). This difficulty indicates an additional cognitive load when visualizations move too fast or display too much information. Obstacles are also apparent when students try to relate visual changes to more abstract statistical concepts. One student revealed, *"I can see the point changing, but it's hard to explain why the distribution is conceptually bigger or smaller."* (S-06, interview October 19, 2025).

This shows that there is a gap between visual perception and the concept of statistical reasoning.

Another challenge arises when students attempt to interpret more than one visual aspect simultaneously. One student explained, "*I have to see the change, the form, the same direction. If too much changes, I am confused about where to focus.*" (S-07, October 20, 2025 interview). This suggests that visual complexity can distract focus and effectively hinder concept integration. In addition, some students admitted that they had difficulty maintaining consistency of meaning when visualization resulted in unstable patterns. One of the students stated, "*If the point is not stable in motion, I find it difficult to say how this is distributed, so we have to see for a long time first*" (S-11, interview October 21, 2025). The four quotes illustrate the systemic barriers at the concept integration stage that arise when students are faced with complex digital visualizations.

Cognitive Pathway Reconstruction as a Layered Process

Overall, the results of the study show that students' cognitive pathways in understanding statistical variability are layered and gradual. Starting from attention to visual elements, continued with the exploration of data dynamics, then developing towards the meaning of value dissemination, and ending with the phase of concept integration which often poses challenges. One of the students described the whole experience by saying, "*At first, I looked at the pictures, kept changing the data, then I understood the purpose of the distribution. But if it looks complicated, I find it a little difficult to follow the concept.*" (S-03, October 22, 2025 interview). In line with that, other students emphasized that his thought process was gradual and took time. He stated, "*I have to take it slow, because from looking at the graph to understanding the concept, it doesn't connect immediately*" (S-01, October 23, 2025 interview). This shows that the development of understanding requires reflection and consolidation.

Meanwhile, some students also realize that their cognitive pathways are built up non-linearly. A student said, "*Sometimes I go back and look at the initial chart if I'm confused, so the process doesn't always progress, sometimes I go backwards first*" (S-05, interview October 24, 2025). This reinforces the assumption that statistical understandings are often recursive. Closing this series of findings, one of the students summarized his learning experience reflectively: "*The learning turns out to take several times to really understand why the distribution can be different, especially if the appearance is very interactive.*" (S-12, October 25, 2025 interview). Thus, students' cognitive pathways can be described as a series of gradual processes that are interconnected and influenced by their interaction with digital visualizations.

DISCUSSION

The initial findings of the study show that all students begin the reasoning process through the identification of visual elements on the digital graphic display. This stage becomes a cognitive foundation because students need visual recognition before entering more abstract statistical analysis. Perception of color, graphic shape, and point density has been proven to act as an anchor of understanding and trigger the activation of initial conceptual schemas. These findings reinforce the view that visual representations play a crucial role in initiating the process of statistical interpretation (Harper, 2021). In addition, dual-channel processing theory asserts that visualization can accelerate the construction of meaning in quantitative learning because it allows for integration between verbal and visual channels (Feldman & Kramer, 2023). Thus, the stage of visual identification is not just a process of observation, but the main foundation for the next cognitive pathway.

In the next stage, students begin to explore the changes in the data displayed on the interactive graph. Interactions such as sliding sliders or changing numerical parameters encourage students to relate value changes to visual shape transformations directly. This activity is in line with the findings that interactive simulations can improve students' ability to understand cause-and-effect relationships through manipulative experiences (Martin & Lewis, 2022). Digital exploration also strengthens inquiry-based learning as students can test intuitive hypotheses in real time. Through this process, the understanding of variability develops more naturally as students witness how changes in values affect the area of the distribution. Thus, the exploration stage serves as an important bridge between initial visual perception and a more abstract construction of statistical understanding.

The third stage is marked by the beginning of the formation of a conceptual meaning of statistical variability. At this stage, students interpret the distance between points as an indicator of the magnitude of the distribution and begin to understand the meaning of homogeneity and heterogeneity in the distribution of data. This process represents a shift from intuitive understanding to a more conceptual understanding, as described in a study of modern statistical literacy (Chan & Muraki, 2023). In addition, students begin to use terms that are closer to formal statistical language such as "middle values", "extremes", or "large spreads", which reflect the development of interpretive abilities. The integration between visual observation, real-world context, and internal reflection reinforces the emergence of a more mature understanding of statistics. Thus, this stage marks an important transition from perception to conceptualization.

Although the development of comprehension is seen in the earlier stages, obstacles begin to arise when students are faced with more complex and dynamic data visualizations. Rapid graphic changes, a large number of visual elements, or an unstable display trigger confusion that increases the cognitive load. This condition is in line with cognitive load theory which states that the simultaneous presentation of complex information can disrupt the process of concept integration (Robinson & Evans, 2021). Students tend to have difficulty relating visual changes to the concept of deployment, trends, or relationships between variables simultaneously. Visual complexity also has the potential to shift the focus away from the core of statistical understanding so that interpretation becomes inconsistent. Therefore, the concept integration stage is a critical point that needs attention in visual-based learning design.

The overall findings of the study show that students' cognitive pathways in understanding variability are not linear, but are layered and recursive. Students often return to the visual observation stage when experiencing confusion at the stage of exploration or integration of concepts. This pattern supports the view that statistical understanding requires an iterative process that includes observation, exploration, verification, and reflection (Wells, 2024). Statistical learning through digital visualization is thus an adaptive process that moves back and forth according to the cognitive needs of students. This recursive cycle also shows that conceptual understanding requires gradual consolidation. Thus, the cognitive pathway formed emphasizes that digital visualization requires proper scaffolding so that students can navigate the dynamics of data representation optimally.

Several factors also influence the pattern of cognitive pathways identified in this study. Students' experience in using digital devices plays a positive role in facilitating data exploration and visual observation. However, differences in statistical literacy levels and perceptual abilities led to significant variations in the quality of interpretation. This is in line with the findings that the initial ability to read visualizations greatly affects the quality of statistical meaning (Henderson & Patel, 2020). In addition, technical factors such as device speed, visualization stability, and display quality also affect students' cognitive processes (Kumar & Lin, 2023). These conditions confirm that the effectiveness of visual-based statistical learning is determined not only by instructional design, but also cognitive and technological readiness.

This research makes a significant contribution in mapping students' cognitive pathways in understanding statistical variability in the digital learning environment, an area that is increasingly relevant in the era of educational transformation. However, the research has limitations, especially related to limitations in capturing cognitive processes in depth because it relies on digital interaction observation and interviews. The complexity of visualization dynamics is also difficult to control uniformly. Further research recommendations include the use of analytical technologies such as eye-tracking or log data to understand more detailed thought processes, as well as the development of adaptive scaffolding based on artificial intelligence. This effort is expected to strengthen the design of digital learning so that it is better able to support the progressive development of students' statistical literacy. Thus, further research has the potential to expand the understanding of how technology can optimize the statistical reasoning process.

CONCLUSION AND RECOMMENDATION

The results of this study confirm that students' understanding of statistical variability in the digital learning environment takes place through layered cognitive pathways, starting from the identification of visual elements, the exploration of data changes, to the formation of conceptual meanings. This sequence of processes suggests that digital visual representations play a central role in triggering the activation of initial schemas and establishing relationships between numerical and visual phenomena. However, the findings also highlight that the complexity of digital visualization can trigger cognitive overload that inhibits concept integration, especially when students are asked to relate data dynamics with advanced statistical interpretation. Thus, students' reasoning mechanisms in digital contexts are not linear, but recursive, adaptive, and are strongly influenced by the quality of visual representation as well as their statistical literacy readiness.

Theoretically, this research makes an important contribution in mapping students' cognitive structure when interacting with digital visualization, which was previously still an underexplored area of research. Practically, the results of the study provide implications for the development of technology-based instructional designs that are more responsive to students' cognitive needs, especially through the provision of gradual visual scaffolding and control of the level of complexity of the display.

ADVANCED RESEARCH

Although this study has limitations regarding the depth of tracing of cognitive processes and the variability of responses between students, the findings open up opportunities for further research using technological approaches such as eye-tracking or log-data analysis to uncover more refined thought processes. Overall, this study emphasizes the importance of designing a digital learning environment that is not only informative, but also aligned with students' reasoning patterns in understanding statistical variability.

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