widodopratama78@unsil.ac.id 1

5002-Article Text-32085-1-2-20260627.docx

Pra EXAM

unsi

Universitas Siliwangi

Document Details

Submission ID

trn:oid:::1:3587392491

Submission Date

Jun 5, 2026, 4:20 PM GMT+7

Download Date

Jun 5, 2026, 4:26 PM GMT+7

File Name

5002-Article_Text-32085-1-2-20260627.docx

File Size

241.7 KB

13 Pages

4,946 Words

32,602 Characters

4% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography
- Quoted Text
- Cited Text
- Small Matches (less than 8 words)

Match Groups

18 Not Cited or Quoted 4%
Matches with neither in-text citation nor quotation marks

0 Missing Quotations 0%
Matches that are still very similar to source material

0 Missing Citation 0%
Matches that have quotation marks, but no in-text citation

0 Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

3% Internet sources
2% Publications
1% Submitted works (Student Papers)

Match Groups

- **18** Not Cited or Quoted 4%
  Matches with neither in-text citation nor quotation marks
- **0** Missing Quotations 0%
  Matches that are still very similar to source material
- **0** Missing Citation 0%
  Matches that have quotation marks, but no in-text citation
- **0** Cited and Quoted 0%
  Matches with in-text citation present, but no quotation marks

Top Sources

3% Internet sources
2% Publications
1% Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	Publication	Fatwiah Noor, Nor Jainah, M. Anwar, Ridha Darmawaty, Mostafa Farouk Abdelale...	<1%
2	Internet	olj.onlinelearningconsortium.org	<1%
3	Internet	icet.fip.unp.ac.id	<1%
4	Student papers	Universitas Negeri Semarang	<1%
5	Publication	Mislia, Agusalim Juhari, Asmayani. "Portrait of Junior High School Teachers' Read...	<1%
6	Internet	ojs3.unpatti.ac.id	<1%
7	Student papers	Syntax Corporation	<1%
8	Internet	e-journal.stkipsiliwangi.ac.id	<1%
9	Internet	www.researchsquare.com	<1%
10	Publication	Lodya Sesriyani, Sri Rahayu. "THE ANALYSIS OF ARTIFICIAL INTELLIGENCE (AI) US...	<1%

11 Internet

ejournal.umm.ac.id <1%

12 Internet

eprints.mdpu.org.ua <1%

13 Internet

pressbooks.openeducationalberta.ca <1%

14 Internet

rsisinternational.org <1%

15 Internet

www.icetol.com <1%

16 Internet

www.seaairweb.info <1%

ETDC Indonesian Journal of Research and Educational Review
Volume 5, No. 3, 2026, pp 1934 - 1946
e–ISSN 2809-3682
p–ISSN 2809-7505
https://doi.org/10.51574/ijrer.v5i3.5002

Mathematics Education Students' Adaptation to the Digital Learning Ecosystem

Agusalim Juhari[1], Sitti Habibah[2]
[1] Pendidikan Matematika, Universitas Negeri Makassar, Indonesia
[2] Administrasi Pendidikan, Universitas, Negeri Makassar, Indonesia

Article Info

Article history:

Received March 29, 2026
Accepted June 03, 2026
Published June 05, 2026

Keywords:

Auditory Learning;
Digital Era;
Higher Education;
Mathematics Education;
Visual Learning.

ABSTRACT

The transition to a Digital Learning Environment (DLE) in mathematics education often highlights a gap between rigid instructional delivery and students' diverse sensory preferences. This study aims to analyze the prevalence of learning styles among mathematics education students at Universitas Negeri Makassar (UNM) and explore their interactions with digital platforms. Employing a descriptive quantitative design, data were gathered via a standardized learning style inventory and a digital engagement questionnaire, then analyzed using descriptive statistics. The results reveal a structured hierarchical distribution dominated by visual learners (45%), followed by multimodal individuals (30%), and auditory learners (25%). These modalities directly dictate technology interaction patterns: visual students excel with dynamic geometry software and video tutorials, whereas auditory learners rely on audio-based discussions and podcasts. Notably, multimodal students exhibit the highest adaptability within Learning Management Systems (LMS) due to their capacity to simultaneously process dual sensory inputs. This research offers critical empirical insights into higher education pedagogy within the Indonesian context. It concludes that a successful digital transition requires a strategic shift toward a Dual-Coding instructional model that harmonizes dynamic visualizations with auditory narratives, thereby fostering an inclusive, adaptive, and highly effective mathematics learning environment.

Corresponding Author:

Agusalim Juhari,
Pendidikan Matematika, Universitas Negeri Makassar, Indonesia
Email: agusalimjuhari@unm.ac.id

1. INTRODUCTION

The global education sector is undergoing a structural transformation triggered by the massive integration of digital technology (Wang et al., 2024). This transformation is not simply a shift from offline to online media, but rather the formation of a Digital Learning Ecosystem (DLE) (Al-Ansi et al., 2021). In the context of mathematics education, this change presents unique challenges due to the hierarchical, abstract, and highly precise nature of the discipline (Cotič et al., 2024). Mathematics education students, as future educators, are at the center of this transformation. They are not only required to master mathematical content (Content Knowledge) but also to be able to navigate a complex digital ecosystem involving interactions between software, digital pedagogy, and networked social dynamics (Mishra & Koehler, 2006; Niess, 2018).

Mathematics is often viewed as a complex discipline that requires intensive guidance to understand abstract concepts such as calculus and non-Euclidean geometry (Tall, 2020). However, the shift toward a Digital Learning Environment (DLE) ecosystem has forced students to reorient their learning strategies from conventional face-to-face methods to greater independence (Zimmerman, 2015). This paradigm shift demands strong self-regulated learning skills, requiring students to manage high levels of focus and cognition amidst digital distractions to master complex problem-solving (Broadbent & Poon, 2015; Sáiz-Manzanares et al., 2020).

Furthermore, the challenge in digital mathematics learning has shifted to the in-depth integration of technology and digital literacy (Ilhan et al., 2025; Ng, 2015). Students are not only required to be proficient in using social media but also to be competent in operating dynamic visualization tools such as GeoGebra, Desmos, or MATLAB to analyze previously static mathematical objects (Hohenwarter et al., 2016). Without mastery of these collaborative platforms and computing tools, the risk of a literacy gap will become even more pronounced, hindering students' ability to perform mathematical proofs collectively and independently in the modern era (Drijvers, 2019).

The digital learning ecosystem is not simply an integration of hardware and software, but rather a dynamic environment that unites digital content, communities of practitioners, and technical infrastructure (Goodyear, 2020; Nguyen & Tuamsuk, 2022). For mathematics education students, success in this ecosystem requires adaptation across three fundamental dimensions: technological, pedagogical, and psychological (Chai et al., 2019). Students are required to be able to integrate mathematical software into their thinking processes, simultaneously shifting the teaching paradigm from mere information transmitters to effective facilitators in the digital space (Thomas & Palmer, 2014). Furthermore, psychological readiness is crucial for overcoming math anxiety, which can increase due to technical barriers and social isolation in online learning (Dowker et al., 2016; Ríordáin et al., 2021).

Failure to implement this multidimensional adaptation has the potential to hinder the quality of conceptual understanding and reduce students' cognitive effectiveness (Sweller, 2021). As future educators, the ability to align oneself with the digital ecosystem is no longer an option but a professional imperative to ensure the relevance of learning in the future (Zou et al., 2025). If this transformation is not optimal, students will struggle to design adaptive and inspiring instructional environments for the next generation of students (Köhler et al., 2022). Therefore, mastery of the digital ecosystem is a key foundation for producing competent mathematics teachers in the era of technological transformation.

Although research on online learning is abundant, particularly post-COVID-19, most studies focus solely on the effectiveness of specific platforms or general student satisfaction (Crompton et al., 2021). Still, little research specifically examines the ongoing adaptation process of mathematics education students within a holistic "ecosystem" (Handal et al., 2023). Much of the literature is fragmented, focusing solely on the technical or cognitive aspects. Little has been done to explore how mathematics education students synthesize computational skills and mathematical reasoning skills in a constantly changing digital environment (Hoyles, 2018). This underpins the need for an in-depth study of adaptation in the context of Digital Learning Environments (DLE).

This research offers a novel element through a holistic ecosystem approach that views learning as an organic whole between students, lecturers, and technical infrastructure, going beyond previous studies that tended to focus on the use of a single tool (Bansah & Darko Agyei, 2022; Mukhlis et al., 2024). The primary focus is on adaptability as a metacompetency, exploring shifts in students' cognitive strategies when facing obstacles in mathematical software and how Technological Pedagogical Content Knowledge (TPACK) spontaneously forms through digital dynamics. Specifically, this research highlights the process of adapting to the unique characteristics of mathematics—such as function visualization, symbolic writing, and logical proof—in the digital space, thus providing a more in-depth theoretical contribution than in the social sciences or language contexts.

This research aims to map the profile of mathematics education students' adaptation to Digital Learning Environments (DLE) and identify various supporting and inhibiting factors in this process. Theoretically, this study is expected to contribute a new framework regarding a comprehensive digital adaptation model for the development of future mathematics education literature. Practically, the results of this study provide crucial input for Teacher Training Institutions in designing curricula oriented toward digital resilience, while also equipping lecturers with transformative instructional strategies to encourage students to transition from passive learners to active participants in the digital ecosystem (Redecker, 2017).

Furthermore, this study emphasizes that adapting to technology is not simply a technical choice, but an existential imperative for students to align their academic abilities with the demands of the modern educational world. By raising awareness of the importance of adaptability as a life skill in the era of Industry 4.0 and Society 5.0, this study seeks to provide substantive solutions for the professional development of prospective educators. Through a holistic ecosystem lens, it is hoped that synergy will be created that can minimize competency gaps, so that mathematics education graduates are highly prepared to face the ever-evolving dynamics of instruction

2. METHOD

This study used a quantitative approach with a descriptive design to map the distribution of learning styles and the level of student adaptation in the digital ecosystem. This approach was chosen because the researcher aimed to provide a systematic and factual overview of the phenomenon of visual and auditory learning styles without providing special treatment to subjects. Through this descriptive method, the relationship between students' sensory preferences and their interaction patterns on digital learning platforms can be objectively identified to generate accurate empirical data.

The study population included all active students in the Mathematics Education Study Program at Makassar State University (UNM). Sampling was conducted using purposive sampling or stratified random sampling (depending on the year structure) to ensure representativeness of students who have been exposed to various Learning Management System (LMS) platforms and dynamic mathematics software. The focus on this institution aims to make a specific contribution to the development of mathematics pedagogy in the context of higher education in Indonesia, particularly in the South Sulawesi region.

The data collection instruments consisted of two main validated tools. The first was a standardized learning style inventory adapted to classify students into visual, auditory, or multimodal categories. The second is a digital learning engagement questionnaire using a Likert scale. This questionnaire was designed to measure the frequency of digital media use, tool preferences (such as dynamic geometry software or podcasts), and the level of conceptual understanding students perceived while interacting with digital content.

The data collection procedure was conducted in a hybrid manner, with the instrument distributed through an online survey platform to efficiently reach respondents within their digital environment. The researchers ensured the ethical aspects of the research were met by providing an informed consent form at the beginning of the survey, explaining that participation was voluntary and data would be kept confidential. This process allowed students to provide honest reflections on their learning experiences, use of video tutorials, and participation in digital collaborative discussions.

Data analysis was conducted in two main stages to obtain a comprehensive picture. The first stage used descriptive statistics, including frequency calculations, percentages, and means, to map the distribution of dominant learning styles among students. This analysis aimed to identify general trends, such as the dominance of visual learning styles in the use of geometry software. These statistical results were then presented in tables and graphs to facilitate visual and systematic interpretation of student profiles.

In the final stage, thematic interpretation was conducted to deepen the quantitative findings, particularly regarding how learning styles interact with specific features of the LMS. Researchers analyzed the relationship between "multimodal" tendencies and students' adaptability to various digital instructional modes. This synthesis of quantitative data and thematic analysis aims to generate practical recommendations for dual-coding-based digital content design, which harmoniously integrates visual and auditory elements to improve future instructional effectiveness.

3. RESULTS AND DISCUSSION

Results

This section presents empirical findings regarding the distribution of learning styles among Mathematics Education students at Makassar State University and how these preferences interact with the digital ecosystem. Data is analyzed to uncover the correlation between sensory preferences and the choice of digital tools for understanding mathematical concepts.

Distribution of Student Learning Styles

The results of the learning style inventory, significant variations were found in the way students process mathematical information. The distribution of these learning styles is summarized in the following Table 1.

Table 1. Learning Style Profile of Mathematics Education Students

Learning Style Categories	Frequency (f)	Percentage (%)	Trends in Key Digital Tools
Visual	68	45%	GeoGebra, Desmos, Video Tutorials
Auditory	38	25%	Math Podcasts, Group Discussions (Voice)
Multimodal (V-A)	45	30%	Integrated LMS, Interactive Webinars
Total	151	100%	

The data shows that most students (45%) have a visual preference. This aligns with the characteristics of mathematics, which relies heavily on graphical representations, diagrams, and spatial symbolism. However, an interesting finding is the emergence of a multimodal group (30%), indicating that nearly a third of students have the flexibility to switch between sensory modes. This group was found to have a higher level of resilience to changes in the Learning Management System (LMS) interface used at UNM.

Learning Style Percentage Graph

This graph focuses on the percentage distribution of each learning style category to see which group is most dominant, as shown in Figure 1.

```
(%) Percentage of Students
 50% |
 45% |      +---------+
 40% |      |  45%    |
     |      |         |
 35% |      |         |
 30% |      |         |          +---------+
 35% |      |         |          |  30%    |
     |      |         | +---------+ |         |
 20% |      |         | |  25%    | |         |
 15% |      |         | +---------+ |         |
 10% |      |         | |         | |         |
  5% |      |         | |         | |         |
  0% +------+---------+---+---------+-+---------+
          Visual          Auditory     Multimodal (V-A)
```

Figure 1. Learning Style Percentage

The empirical data presented in Figure 1 delineates the percentage distribution of students across three distinct learning style categories, illustrating a clear hierarchical preference among the respondents. Specifically, the visual learning style emerges as the most prominent paradigm, accounting for 45% of the total student population. This is sequentially followed by the multimodal (Visual-Auditory) learning style at 30%, while the auditory learning style represents the least prevalent cohort, constituting only 25% of the sample. These statistics reveal a substantial leaning toward visually oriented information processing, as nearly half of the students demonstrate a primary reliance on sight-based stimuli to comprehend, process, and retain educational content effectively. Conversely, the smaller proportion of purely auditory learners implies that traditional, lecture-heavy instruction might only optimally accommodate a quarter of the classroom cohort, whereas a combined 75% of the students possess either a strict or partial reliance on visual aids.

The clear dominance of both visual and multimodal learning styles—cumulatively representing three-quarters of the sample—necessitates a paradigm shift toward a highly integrated multimedia instructional approach. Students within the multimodal bracket possess cognitive flexibility to concurrently process visual representations and verbal explanations, thereby bridging the gap between abstract concepts and concrete understanding. Consequently, to maximize pedagogical efficacy and address the widespread preference for visual stimuli, educators are strongly encouraged to move away from monotonous auditory delivery. Instead, the systematic incorporation of dynamic visual tools, such as infographics, conceptual maps, and illustrative presentation slides, should be meticulously paired with explicit oral discourse. Designing such inclusive learning environments ensures that instructional delivery directly aligns with the dominant cognitive preferences of the student body, thereby fostering higher academic engagement and comprehension.

Comprehensive Graph: Frequency Distribution and Digital Tools

The matrix graph below in Figure 2 combines the number of students (frequency) and maps the ecosystem of the main digital tools they use according to their learning style characteristics.

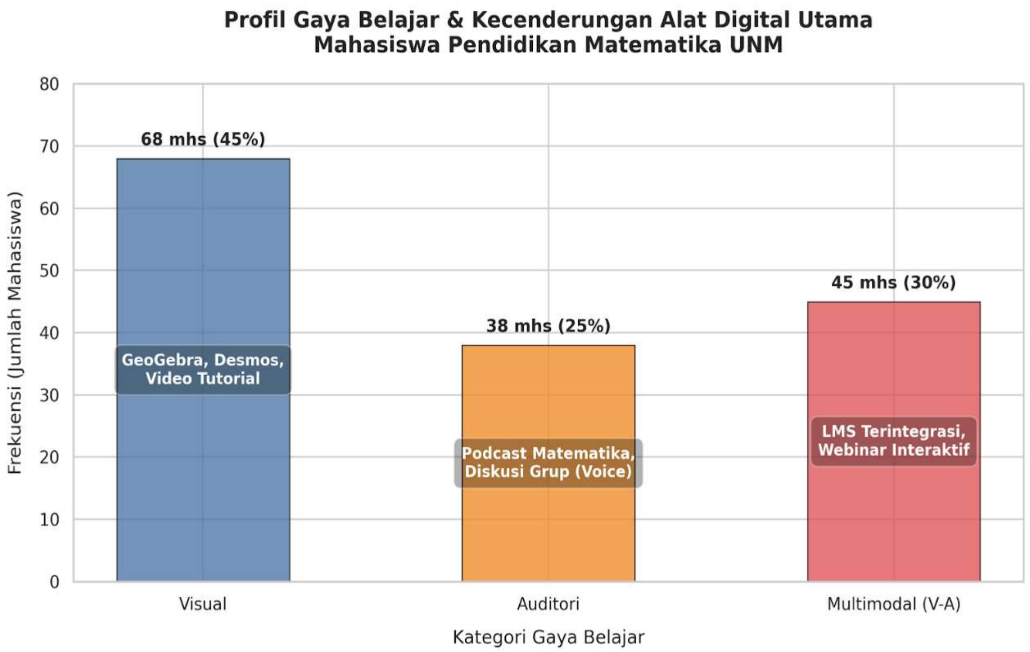

Figure 2. Frequency Distribution and Digital Tools

The empirical data illustrated in Figure 2 delineates a comprehensive profile of learning styles alongside the corresponding digital tool ecosystems utilized by mathematics education students at UNM. Quantitative analysis reveals that the visual learning style stands as the most dominant modality, accounting for 45% of the total cohort with a frequency of 68 students. This substantial preference is structurally followed by the multimodal (Visual-Auditory) learning style, which encompasses 30% of the sample size (45 students), while the auditory learning modality constitutes the smallest proportion at 25% (38 students). These findings highlight a distinct hierarchical distribution, indicating that a combined 75% of the student population relies heavily or partially on visual stimuli to process complex academic material. These distribution patterns are crucial to cognitive trend, suggesting that traditional text-only or purely auditory delivery methods may fail to engage most of the modern classroom cohort effectively.

Beyond mere statistical frequencies, the data demonstrates a clear alignment between specific learning style characteristics and student choices in digital media integration. For instance, the dominant visual cohort predominantly relies on dynamic visualization software and graphic-heavy materials, specifically GeoGebra, Desmos, and tutorial videos, to conceptualize mathematical abstractions. Conversely, the multimodal group engages seamlessly with collaborative and blended learning environments, favoring integrated Learning Management Systems (LMS) and interactive webinars that simultaneously deliver verbal and visual information. Meanwhile, the auditory minority optimizes voice-centric platforms, including mathematics podcasts and group voice discussions, to reinforce their comprehension. Consequently, these insights suggest that designing an effective mathematics curriculum requires a deliberate shift toward hybrid multimedia frameworks. By systematically integrating interactive visual software with collaborative LMS features, educators can cultivate an inclusive digital ecosystem that directly corresponds to the diverse cognitive preferences mapped across the student body.

Interaction of Learning Styles with Digital Platforms

This study further explores how these learning styles manifest in the use of specific digital tools to solve complex mathematical problems.

Table 2. Relationship of Learning Styles with Digital Platform Engagement

Adaptation Dimension	Visual (M)	Auditory (M)	Multimodal (M)	Sig. (p)
Use of Dynamic Software	4.82	3.12	4.55	< 0.05
Audio/Vocal Discussion Participation	2.45	4.65	4.10	< 0.05
Video Tutorial Effectiveness	4.70	3.50	4.85	< 0.05
LMS Navigation Ability	3.90	3.85	4.75	< 0.05

The dominance of students with a visual learning style was significantly evident in the use of Dynamic Geometry Software (DGS), with the highest score (M=4.82). For this group, the ability of software like GeoGebra to manipulate geometric objects in real time became a crucial tool for bridging complex mathematical abstractions. These dynamic visualizations enabled them to transform theoretical concepts into tangible graphical representations, thus facilitating the internalization of mathematical structures that were previously difficult to visualize statically.

On the other hand, students with auditory tendencies (M=4.65) demonstrated strong resilience through optimizing collaborative communication within the digital ecosystem. Research findings indicated that this group was more effective in understanding concepts through vocal interaction and active dialogue than simply reading modules in PDF format. For them, digital discussion spaces and audio-based media such as educational podcasts became the primary means for deconstructing mathematical ideas through interactive debates and oral explanations.

The most crucial finding in this study highlights the superiority of multimodal students, particularly in the aspect of navigating the Learning Management System (LMS), with a score of M=4.75. This group demonstrated superior adaptability in simultaneously integrating visual and auditory instruction through a dual-coding mechanism. This ability demonstrates that multimodal students are significantly more resilient in digital environments that often experience information overload, enabling them to effectively manage various digital content formats to support successful learning.

15

The results of this study confirm that the transition to digital learning often creates an "adaptation gap." Students with a dominant learning style tend to experience obstacles when digital platforms do not accommodate their preferences. For example, auditory learners often feel isolated in online courses that rely solely on text and static graphics.

The findings regarding the effectiveness of the multimodal group provide strategic implications for lecturers at Makassar State University to immediately abandon the one-size-fits-all learning approach. Adapting to the digital ecosystem now requires instructional design that explicitly applies the principles of Dual-Coding Theory. In this context, the integration of verbal and non-verbal representations within a single digital workflow is no longer merely an aesthetic complement, but a key prerequisite for ensuring mathematics students' cognitive effectiveness in processing complex information in the digital age.

Practically, the use of video tutorials that combine dynamic visualizations with substantive narrative explanations has proven to be the most inclusive instructional medium. For mathematics education students in Makassar, the success of this adaptation rests not only on technical mastery of the technology, but also on their ability to align internal cognitive processes with the external stimuli provided by the digital ecosystem. Therefore, providing content that accommodates various learning modalities is key to creating a learning environment that is adaptive, relevant, and capable of facilitating deep mathematical understanding. This research has successfully demonstrated that there is significant diversity in learning styles that determine how students interact with technology. Digital inclusivity in mathematics education can be achieved if curriculum developers and lecturers are able to present content that facilitates both visual and auditory pathways in a balanced manner, thereby fostering broader adaptability for all students.

Discussion

11

The findings of this study reveal that mathematics education students' adaptation to the digital learning ecosystem (DLE) is not simply a technical issue, but rather a complex cognitive process influenced by sensory preferences. The following discussion examines the relationship between field findings and relevant theoretical frameworks.

Visual Dominance and Multimedia Cognitive Theory

The finding that 45% of students have a visual predilection aligns with the Cognitive Theory of Multimedia Learning (CTML) developed by Richard Mayer (Mayer, 2014). Mayer states that visual and auditory channels have limited capacity, but appropriate integration of the two can improve information retention (Mayer & Moreno, 2003).

In the context of UNM students, the high use of dynamic geometry software such as GeoGebra suggests that visual students engage in more effective "mental imagery" when mathematical objects can be manipulated digitally (Ruthven, 2018). This supports a previous study by Ziatdinov and Rakuta (2022), which emphasized that dynamic digital environments help students overcome mathematical abstraction through representational visualization.

Challenges for Auditory Students in a Tech-Heavy Environment

One crucial finding in this study is the reliance of auditory students on podcasts and vocal group discussions (25% of respondents). This indicates a barrier to adaptation when the digital ecosystem focuses solely on static text modules (Clark & Mayer, 2016).

This phenomenon can be explained through Vygotsky's Social Constructivism Theory, which states that auditory learners require "scaffolding" through verbal dialogue to reach the Zone of Proximal Development (ZPD) (Mishra, 2023). This study supports research by Lee and Kim (2023), who found that students with auditory learning styles often experience cognitive overload in digital learning platforms that lack synchronous interaction or vocal narration (Sweller et al., 2011).

Multimodal Resilience and Cognitive Flexibility

This study found that multimodal students (30%) had the highest level of adaptation to various Learning Management Systems (LMS). Their ability to simultaneously synchronize visual and auditory input provides an advantage in navigating complex digital ecosystems (Sankey et al., 2010). Theoretically, this relates to Allan Paivio's Dual-Coding Theory, which argues that information processed through two channels (verbal and visual) is more strongly retained in long-term memory (Paivio, 2014). The ability of multimodal students at UNM to "switch modes" without losing cognitive focus indicates that they have developed Cognitive Flexibility, a skill that Spiro et al. (2021) argues is crucial in navigating unstructured and technology-heavy learning environments (Jonassen et al., 2005).

Reorienting Pedagogy: Digital Inclusivity in Mathematics

The results of this study critique digital learning practices, which are often "one-way" or overly reliant on visualization (O'Keeffe et al., 2020). There is an urgent need to create inclusive instructional designs (Rose, 2018). Linking with a study by Haciomeroglu (2020) on the learning style profiles of prospective teachers, this research at UNM emphasizes that lecturers must provide "dual-track" content. This means that sophisticated graphic visualizations must be accompanied by in-depth narrative (auditory) explanations. Mathematics education students' adaptation to the digital ecosystem will be optimal if the environment accommodates diverse learning styles, thereby minimizing the learning gap that occurs during the transition from traditional to digital methods (Loewus, 2021).

Implications for Higher Education in Indonesia

The context of Makassar State University, as one of the leading LPTKs in Eastern Indonesia, demonstrates that digital adaptation is inseparable from digital infrastructure and literacy. However, our findings emphasize that internal factors (learning styles) are as important as external factors (technology). This is in line with research by Cahyono et al. (2024), integrating local wisdom into auditory delivery can also be an effective adaptation strategy for students in this region to strengthen their understanding of mathematical concepts through the cultural context of verbal exchange.

The synthesis of the empirical findings and theories above confirms that successful adaptation in the digital learning ecosystem depends heavily on synchronizing media design with the learner's sensory profile. Multimodal learners emerged as the most adaptable group, while visual and auditory learners require more specific design interventions to optimize their cognitive potential in digital spaces.

4. CONCLUSION

This study successfully mapped the dynamics of Mathematics Education students' adaptation to the Digital Learning Environment (DLE) at Makassar State University by identifying the role of learning styles as a significant determinant. Findings indicate that diverse learning styles—dominated by visual (45%), followed by multimodal (30%), and auditory (25%)—directly influence students' interaction patterns with technology, with visual students excelling in the use of dynamic geometry software, while auditory students were more resilient through audio-based discussions. Specifically, multimodal students demonstrated the highest level of adaptability in navigating the complexities of the Learning Management System (LMS) thanks to their ability to simultaneously integrate visual and auditory input. As a pedagogical implication, this study confirms that an effective transition to a digital ecosystem requires a shift in instructional strategies toward a Dual-Coding model that aligns dynamic visualizations with auditory narratives to create an inclusive and adaptive mathematics learning environment.

Lecturers and curriculum developers in higher education institutions are advised to construct varied and comprehensive digital content by avoiding reliance on a single sensory mode. This strategy can be implemented through video tutorials that integrate dynamic visualizations with substantive narrative explanations, as well as digital collaborative discussion spaces to bridge the adaptation gap among various learner profiles. By adopting this multimodal approach, institutions can create a more inclusive and effective learning ecosystem to support students' cognitive transformation in the digital age

14

REFERENCES

Al-Ansi, A., et al. (2021). Analyzing the development of digital learning ecosystems in higher education. *Education and Information Technologies*, 26(6), 7243–7265. https://doi.org/10.1007/s10639-021-10555-5

Bansah, A. K., & Darko Agyei, D. (2022). Perceived convenience, usefulness, effectiveness and user acceptance of information technology: evaluating students' experiences of a Learning Management System. *Technology, Pedagogy and Education*, *31*(4), 431-449. https://doi.org/10.1080/1475939X.2022.2027267

Broadbent, J., & Poon, W. L. (2015). Self-regulated learning strategies & academic achievement in online higher education learning environments: A systematic review. *The Internet and Higher Education*, 27, 1–13. https://doi.org/10.1016/j.iheduc.2015.04.007

Chai, C. S., et al. (2019). Surveying and modeling students' motivation and self-regulation in cyber-physical learning environments. *Educational Technology Research and Development*, 67(6), 1431–1453. https://doi.org/10.1007/s11423-019-09687-2

Clark, R. C., & Mayer, R. E. (2016). *E-learning and the science of instruction: Proven guidelines for consumers and designers of multimedia learning* (4th ed.). John Wiley & Sons. https://doi.org/10.1002/9781119232605

Cotič, M., Doz, D., Jenko, M., & Žakelj, A. (2024). Mathematics education: What was it, what is it, and what will it be?. *International Electronic Journal of Mathematics Education*, *19*(3), em0783. https://doi.org/10.29333/iejme/14663

Crompton, H., Burke, D., Jordan, K., & Wilson, S. W. G. (2021). Learning with technology during emergencies: A systematic review of K-12 education since 2010. *British Journal of Educational Technology*, 52(4), 1554–1575. https://doi.org/10.1111/bjet.13114

Dowker, A., Sarkar, A., & Looi, C. Y. (2016). Mathematics anxiety: What have we learned in 60 years? *Frontiers in Psychology*, 7, 508. https://doi.org/10.3389/fpsyg.2016.00508

Drijvers, P. (2019). Embodied instrumentation: different perspectives on using digital technology in mathematics education. *International Journal of STEM Education*, 6(1), 1–14. https://doi.org/10.1186/s40594-019-0167-y

Goodyear, P. (2020). Design and co-configuration for hybrid learning: Eco-social systems and practical resilience. *British Journal of Educational Technology*, 51(4), 1045–1060. https://doi.org/10.1111/bjet.13010

Handal, B., et al. (2023). Canvas and beyond: Holistic digital ecosystems in mathematics teacher training. *Journal of Digital Learning in Teacher Education*, 39(1), 44–59. https://doi.org/10.1080/21532974.2022.2132333

Hohenwarter, M., et al. (2016). Teaching and learning geometry with GeoGebra. *International Journal for Technology in Mathematics Education*, 23(2), 73–82. https://doi.org/10.1564/tme_v23_i2_a01

Hoyles, C. (2018). Transforming the mathematical knowledge network with digital technologies. *Educational Studies in Mathematics*, 99(3), 263–277. https://doi.org/10.1007/s10649-018-9844-7

Ilhan, A., Aslaner, R., & Yaşaroğlu, C. (2025). Development of digital literacy skills of 21st century mathematics teachers and prospective teachers through technology assisted education. *Education and Information Technologies*, *30*(8), 10837-10862. https://doi.org/10.1007/s10639-024-13283-w

Jonassen, D. H., et al. (2005). Everyday problem solving in the workplace: A framework for research and practice. *Educational Technology Research and Development*, 53(1), 41–56. https://doi.org/10.1007/BF02504857

Köhler, T., et al. (2022). The digital transformation of teacher education: Structural and pedagogical challenges. *Computers & Education*, 182, 104473. https://doi.org/10.1016/j.compedu.2022.104473

Loewus, L. (2021). Adapting to the digital shift: How variable learning modalities affect preservice teacher performance. *Journal of Teacher Education*, 72(4), 412–425. https://doi.org/10.1177/0022487120974421

Mayer, R. E. (2014). *The Cambridge Handbook of Multimedia Learning* (2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369

Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist*, 38(1), 43–52. https://doi.org/10.1207/S15326985EP3801_6

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record*, 108(6), 1017–1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Mishra, N. R. (2023). Constructivist approach to learning: An analysis of pedagogical models of social constructivist learning theory. *Journal of research and development*, *6*(01), 22-29. https://nepjol.info/index.php/jrdn/article/view/55227

Mukhlis, H., Haenilah, E. Y., Maulina, D., & Nursafitri, L. (2024). Connectivism and digital age education: Insights, challenges, and future directions. *Kasetsart Journal of Social Sciences*, *45*(3), 803-814. https://so04.tci-thaijo.org/index.php/kjss/article/view/274837

Ng, W. (2015). *New digital technology in education: Conceptualizing professional learning for educators*. Springer. https://doi.org/10.1007/978-3-319-17461-7

Nguyen, L. T., & Tuamsuk, K. (2022). Digital learning ecosystem at educational institutions: A content analysis of scholarly discourse. *Cogent Education*, *9*(1), 2111033. https://doi.org/10.1080/2331186X.2022.2111033

Niess, M. L. (2018). Scaffolding mathematics teachers' technological pedagogical content knowledge (TPACK) development. *Journal of Research on Technology in Education*, 50(2), 111–127. https://doi.org/10.1080/15391523.2017.1411516

O'Keeffe, L., et al. (2020). Online learning in mathematics education: Shared perspectives on the transition to remote instruction. *Mathematics Education Research Journal*, 32(4), 573–591. https://doi.org/10.1007/s13394-020-00345-8

Paivio, A. (2014). *Mind and its evolution: A dual-coding theoretical approach*. Psychology Press. https://doi.org/10.4324/9781410612144

Redecker, C. (2017). *European Framework for the Digital Competence of Educators: DigCompEdu*. Joint Research Centre, European Commission. https://doi.org/10.2760/159770

Ríordáin, M. N., et al. (2021). Exploring the intersection of mathematics anxiety, technology integration, and online learning in initial teacher education. *Mathematics Teacher Education and Development*, 23(2), 89–111.

Rose, D. H. (2018). *Universal Design for Learning: Theory and Practice*. CAST Professional Publishing.

Ruthven, K. (2018). Instructional technology and mathematical practices: Core themes, Research trends, and future directions. *Educational Studies in Mathematics*, 99(3), 245–261. https://doi.org/10.1007/s10649-018-9828-7

Sáiz-Manzanares, M. C., et al. (2020). Effectiveness of self-regulated learning in architecture and engineering students in digital environments. *International Journal of Engineering Education*, 36(2), 654–666.

Sankey, M., et al. (2010). Engaging students through multimodal learning environments: The journey of a causal map. *Australasian Journal of Educational Technology*, 26(6), 852–870. https://doi.org/10.14742/ajet.1045

Sweller, J. (2021). Operational definitions of cognitive load theory constructs. *Educational Psychology Review*, 33(2), 465–475. https://doi.org/10.1007/s10648-020-09572-7

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory* (Vol. 1). Springer Science & Business Media. https://doi.org/10.1007/978-1-4419-8126-4

Tall, D. (2020). *Advanced Mathematical Thinking*. Routledge. https://doi.org/10.4324/9780429341496

Wang, C., Chen, X., Yu, T., Liu, Y., & Jing, Y. (2024). Education reform and change driven by digital technology: A bibliometric study from a global perspective. *Humanities and Social Sciences Communications*, *11*(1), 1-17. https://doi.org/10.1057/s41599-024-02717-y

Zimmerman, B. J. (2015). Self-regulated learning: Theories, measures, and outcomes. *International Encyclopedia of the Social & Behavioral Sciences*, 21, 541–546. https://doi.org/10.1016/B978-0-08-097086-8.26060-1

Zou, D., Xie, H., & Kohnke, L. (2025). Navigating the future: establishing a framework for educators' pedagogic artificial intelligence competence. *European Journal of Education*, *60*(2), e70117. https://doi.org/10.1111/ejed.70117