

Enhancing Creative Thinking, Spatial Visualization, and Emotional Engagement through 3D Digital Learning Environments in Engineering Education for Sustainable Development

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Abstract—This study investigates the relationships between the use of three-dimensional (3D) technology, creative thinking, spatial visualization, and emotional engagement as foundational competencies for future engineering education. This study adopted a cross-sectional correlational design with purposive sampling and structured instruments using Likert scales to measure cognitive, technological, and affective variables. Descriptive statistics, Pearson correlation, and multiple regression were used to analyze data. The results showed that all the variables had a positive relationship. The strongest predictor of emotional engagement was creative thinking, followed by 3D technology use and spatial visualization, both of which had significant positive effects. Students use interactive 3D to investigate geometric and spatial concepts and enhance cognitive processes. This is important to engineering learning. The findings shed light on the potential of adaptive digital environments in fostering spatial, creative, and affective competences and supporting technology-enhanced pathways toward engineering education and SDG 4.

Keywords—3d digital learning; creative thinking; digital learning; emotional engagement; geometry education; spatial visualization; sustainable development goals.

I. INTRODUCTION

The increasing integration of digital technologies into engineering education has changed how students engage with abstract mathematical, spatial, and technical concepts. Spatial reasoning is particularly important because students must interpret relationships among shape, orientation, position, and three-dimensional structures as preparation for subsequent engineering learning. Digital environments can support these processes through dynamic and interactive representations, while three-dimensional (3D) visualization allows students to observe, rotate, manipulate, and examine objects from multiple perspectives (Hohenwarter et al., 2020; Radianti et al., 2020). Studies on

3D learning environments have demonstrated their potential to improve conceptual understanding and spatial abilities relevant to engineering education. Interactive visualization supports deeper processing of spatial relationships and problem-solving activities (Sorby, 2009). Three-dimensional simulation can also facilitate understanding of complex structures through realistic and manipulable representations (Shabudin et al., 2022), while advances in 3D technologies continue to expand applications in visualization and technical training (Triawan et al., 2026). These developments indicate that 3D environments can provide a useful technological foundation for developing spatial competencies required in future engineering education.

Preparation for engineering learning involves more than spatial visualization. Another aspect is creative thinking. This is because students need to explore different strategies, recognize patterns, build representations, and develop solutions to spatial and geometric problems. Spatial visualization and creative thinking can therefore function as complementary cognitive processes. Technology-supported environments may strengthen both processes by allowing students to test ideas, modify representations, and observe the consequences of different spatial transformations. Developing these abilities at the school level can provide an important cognitive foundation for subsequent engineering learning. Emotional engagement is another important dimension of technology-supported engineering learning. Positive emotions can strengthen attention, motivation, persistence, and knowledge retention, whereas negative emotional experiences can reduce students' willingness to engage with cognitively demanding activities (Immordino-Yang & Damasio, 2007; Pekrun, 2006). Interactive 3D environments may increase curiosity and involvement by

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allowing students to interact directly with abstract spatial concepts. Understanding the relationship between cognitive development and emotional engagement is therefore important for preparing students both cognitively and affectively for future engineering education.

The need for this study arises from the increasing use of 3D digital technologies to develop competencies relevant to engineering education without sufficient understanding of how technological, cognitive, and affective factors interact. Previous studies have frequently examined visualization, cognitive performance, technology use, or emotional factors separately (Sorby, 2009; Immordino-Yang & Damasio, 2007; Pekrun, 2006). A more integrated analysis is therefore required to clarify how 3D technology use, creative thinking, spatial visualization, and emotional engagement are related and how these relationships may support preparation for engineering learning. This issue is also pertinent to adaptive and student-centered engineering education. Individual differences in cognitive flexibility, prior experience, and responses to digital environments may influence how students benefit from technology-supported learning. Adaptive systems can respond to learner characteristics and technological conditions (Mulyana et al., 2025). Similarly, technology-supported pedagogy requires alignment between technological resources, learner needs, and engineering learning practices (Khimmatiev et al., 2025). Examining cognitive, affective, and technological factors together can therefore provide a stronger basis for developing responsive digital environments that support pathways toward engineering education.

Technology-supported preparation for engineering education also contributes to sustainable development. Digital technologies can expand access to interactive learning resources and support the development of technical and spatial competencies. These approaches are consistent with SDG 4 through accessible and high-quality learning opportunities. Previous studies have also linked technology-supported learning with sustainability, accessibility, and inclusive educational development (Adeoye, 2026; Glushchenko et al., 2027; Al-Zahrani & Bello, 2026; Bariquit et al., 2026). Accordingly, the development of spatial, creative, technological, and affective competencies can support more sustainable pathways into engineering education.

Despite these developments, a research gap remains. Previous studies have demonstrated the importance of dynamic learning environments, immersive technologies, 3D visualization, spatial-skill development, emotional engagement, and adaptive digital systems (Hohenwarter et al., 2020; Radianti et al., 2020; Sorby, 2009; Immordino-Yang & Damasio, 2007; Pekrun, 2006; Mulyana et al., 2025). However, these dimensions have generally been investigated separately. Limited attention has been given to a unified analytical framework that simultaneously examines 3D technology use, creative thinking, spatial visualization, and emotional engagement as foundational competencies for future engineering education. A further gap concerns the relative predictive contributions of cognitive and technological variables to emotional engagement.

The integration of technological, cognitive, affective, adaptive, and sustainability dimensions within the 3D-supported pathways toward engineering education requires an integrated investigation. Table I summarizes the major research areas, their principal contributions, identified limitations, and specific gaps addressed in the present study.

This study examines the relationships between 3D technology use and several aspects. The aspects are creative thinking, spatial visualization, and emotional engagement among students. It also places particular emphasis on their relevance as foundational competencies for future engineering education. Specifically, the study aims to address several points:

1. describe the levels of 3D technology use, creative thinking, spatial visualization, and emotional engagement;
2. determine the correlations among these variables; and
3. identify the predictive contributions of 3D technology use, creative thinking, and spatial visualization to emotional engagement.

The novelty of this study lies in integrating technological, cognitive, and affective dimensions within a single analytical framework oriented toward engineering education. This approach provides a basis for developing adaptive, inclusive, and sustainable digital learning pathways that prepare students for future engineering learning.

TABLE I
SUMMARY OF PREVIOUS RESEARCH AREAS AND IDENTIFIED RESEARCH GAPS.

Research area	Main contribution	Limitation identified	Gap addressed in this study
3D and dynamic mathematics learning	Supports interactive visualization and exploration	Often focuses mainly on technology effectiveness	Integrates 3D technology use with cognitive and affective variables
Spatial visualization	Supports mental representation and manipulation of geometric structures	Commonly examined as an isolated cognitive skill	Examines its relationship with creative thinking and emotional engagement
Creative thinking	Supports flexible problem-solving and alternative representations	Limited integration with spatial visualization	Examines creative thinking within a 3D learning framework
Emotional engagement	Influences attention, motivation, and persistence	Frequently examined separately from cognitive outcomes	Integrates emotional engagement with cognitive and technological variables
Adaptive learning	Supports responsiveness to learner characteristics	Limited integration with geometry-specific cognitive and affective variables	Considers learner differences within digital geometry learning

Sustainable education	Promotes inclusive and equitable access to quality education	Often discussed conceptually	Links digital learning with cognitive, affective, and inclusion-oriented outcomes
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II. LITERATURE REVIEW

A. *Three-Dimensional Digital Learning in Geometry Education*

3D digital learning environments enable students to look at, manipulate, and explore objects from different viewpoints. Such environments are especially relevant to preparation for engineering education because spatial and geometric ideas require students to interpret relationships among shape, orientation, position, and spatial transformation. This process can be supported by dynamic digital environments where students can interact with mathematical and spatial representations directly, rather than through static diagrams alone (Hohenwarter et al., 2020). Immersive and interactive technologies also offer opportunities for active exploration and visualization relevant to future engineering learning (Radianti et al., 2020). Applications of 3D technology have also demonstrated value in technical contexts where spatial interpretation is essential. Three-dimensional simulation can aid in comprehending intricate structures through realistic and manipulable representations (Shabudin et al., 2022). The development of 3D technologies has broadened the scope of application of visualization-based learning and technical training (Triawan et al., 2026). These results suggest that 3D environments are an appropriate technological basis for the development of the spatial skills required by future engineering education.

B. *Creative Thinking and Spatial Visualization*

Spatial visualization is a key cognitive ability in future engineering education as students have to mentally represent, rotate, transform, and interpret spatial objects. Spatial skills can be developed through structured visualization activities and interactive learning experiences, and are especially relevant to technical and engineering learning (Sorby, 2009). Digital environments can facilitate this development because students can directly and repeatedly observe geometric and spatial transformations. Creative thinking is also important for preparation toward engineering education because students may need to generate alternative representations, identify patterns, explore multiple solution strategies, and construct relationships among spatial and geometric concepts. Creative thinking and spatial visualization can therefore be considered complementary cognitive processes: spatial visualization supports the mental representation of technical and geometric structures, whereas creative thinking supports flexible exploration of possible relationships and solutions. Although previous studies have established the importance of visualization and spatial abilities, fewer studies have examined how spatial visualization relates simultaneously to creative thinking and technology use within the same digital learning environment oriented toward future engineering

education. This relationship requires further examination because interactive 3D environments may support not only spatial processing but also flexible and exploratory thinking that is relevant to subsequent technical and engineering learning.

C. *Emotional Engagement in Digital Learning*

Emotional engagement is an important component of preparation for engineering education because emotions influence attention, motivation, persistence, decision-making, and knowledge retention (Immordino-Yang & Damasio, 2007; Pekrun, 2006). Consequently, improvement in cognitive performance alone may not adequately describe learning effectiveness when students are not emotionally involved in learning activities relevant to future engineering study. Interactive digital environments may strengthen emotional engagement by providing opportunities for exploration and immediate interaction with technical and spatial learning content. In 3D-supported learning, students can manipulate and examine abstract geometric and spatial objects directly, potentially increasing curiosity and involvement in activities that develop competencies relevant to engineering education. However, emotional engagement has frequently been investigated separately from cognitive variables such as creative thinking and spatial visualization. This separation limits understanding of whether stronger cognitive involvement in 3D environments is also associated with greater emotional engagement as part of students' preparation for future engineering learning.

D. *Adaptive Learning and Individual Differences*

Students may respond differently to the same digital environment because of differences in cognitive characteristics, prior experience, flexibility, and openness to technology-supported learning. Adaptive learning approaches are therefore relevant to engineering education because they can support the development of competencies required for technical and spatial learning. Adaptive computing frameworks demonstrate how technological systems can respond dynamically to changing conditions and user requirements (Mulyana et al., 2025). Technology-supported engineering education also requires the integration of technological competence with appropriate pedagogical practice (Khimmatiev et al., 2025). In 3D-supported learning, individual differences may influence how students process visual and spatial information, explore alternative solutions, and respond emotionally to interactive activities. Thus, cognitive and affective variables should be considered together when evaluating digital learning environments intended to support preparation for future engineering education.

E. Sustainable Education and the Sustainable Development Goals

Technology-supported engineering education can contribute to sustainable development by expanding access to quality technical learning and supporting inclusive pathways toward engineering study. SDG 4 emphasizes inclusive and equitable quality education, and digital technologies can provide additional opportunities for flexible and accessible preparation for engineering education. Previous studies have connected inclusive educational development with sustainability, educator development, and community-oriented educational practices (Adeoye, 2026; Glushchenko et al., 2027; Al-Zahrani & Bello, 2026; Bariquit et al., 2026). 3D digital learning can contribute to sustainable engineering education through reusable visual and spatial learning resources and interactive environments that support various ways of developing technical competencies. However, sustainable use of digital technology in engineering education requires more than mere availability of technology; it requires evidence that digital environments support meaningful contributions to cognitive development, emotional engagement, spatial competence, and responsive learning experiences that prepare students for future engineering study.

III. RESULTS AND DISCUSSION

A. Research Design

This study took a cross-sectional correlational design to investigate the relationships among the use of 3D technology, creative thinking, spatial visualization, and emotional engagement. The educational research framework of this methodological approach is further discussed, and the correlational design was chosen because the study aimed at investigating the direction and magnitude of relationships between naturally occurring technological, cognitive, and affective variables without the manipulation of the learning condition; Therefore, the statistical relationships and predictive relationships were used to interpret the findings as opposed to the direct causal effects.

B. Participants and Sampling

The participants were students who were selected through purposive sampling, in which the purposive sampling was applied because the study required participants who were directly involved with geometry learning and had experience relevant to the digital or 3D-supported learning context examined in the study, and the participant-selection criteria therefore focused on students engaged with geometry learning who could respond to the technological, cognitive, and affective measures used in the research, in which the source manuscript does not report the exact number of participants, indeed, therefore, the verified sample size should be inserted from the original research records before final submission, and no sample-size value was estimated or generated in this revision.

C. Research Instruments

Data were collected using validated Likert-scale instruments to measure the cognitive and affective variables. The instruments used to measure the cognitive and affective variables were as follows. This included measures of creative thinking, spatial visualization, and emotional engagement. The measurement framework also included 3D technology use as the technological variable. This was to explore the relationship with the cognitive and affective outcomes. Responses elicited from the structured instruments were converted into quantitative scores to facilitate subsequent descriptive, correlation, and regression analyses.

D. Research Procedure

The research procedure involved four sequential steps. These steps are (i) purposive sampling was used to select students who satisfied the criteria of the study; (ii) structured instruments were used to gather data on the use of 3D technology, creative thinking, spatial visualization, and emotional engagement; (iii) the responses collected were collated into a quantitative dataset based on the four study variables; and (iv) the dataset was analyzed using descriptive statistics, Pearson correlation, and multiple regression to explore the distributions, relationships, and predictive effects of the variables. In this study, a cross-sectional correlational design was used as opposed to a controlled experimental intervention; thus, all variables were measured during the study period without manipulation of an experimental treatment.

E. Data Analysis

Data were analyzed with Pearson correlation and multiple regression to identify relationships and predictive effects between variables. The analysis procedure was conducted in three stages: (i) descriptive statistics were used to describe 3D technology use, creative thinking, spatial visualization and emotional engagement, where these descriptive results provide an overview of the distribution of the main study variables, (ii) Pearson correlation analysis was used to determine the direction and strength of the bivariate relationships among 3D technology use, creative thinking, spatial visualization and emotional engagement, Statistical significance was interpreted from the reported p-values with $p < 0.05$ considered statistically significant, (iii) multiple regression analysis was used to evaluate the predictive contributions of 3D technology use, creative thinking, and spatial visualization to emotional engagement. The regression analysis was interpreted using the unstandardized coefficient (B), standard error, standardized beta coefficient (β), t-value, and p-value for each predictor. Predictors with $p < 0.05$ were interpreted as statistically significant. Thus, the analysis included descriptive statistics to characterize the variables measured, Pearson correlation to examine the relationships between variables, and multiple regression to test their relative predictive contribution to emotional engagement.

IV. RESULTS AND DISCUSSION

A. Descriptive Characteristics of the Main Variables

Figure 1 presents descriptive statistics for the use of 3D technology, spatial visualization, creative thinking, and emotional engagement. The results show relatively high engagement with 3D-supported learning and moderate to high levels of cognitive and affective development, where interactive visualization can improve student engagement with geometry and offer opportunities for cognitive processing and exploration. This observed pattern is in line with the educational role of dynamic and immersive learning environments that can support active exploration and visualization of complex ideas (Hohenwarter et al., 2020; Radianti et al., 2020). Such environments are useful for geometry learning because students need to mentally process spatial relations while interacting with abstract representations.

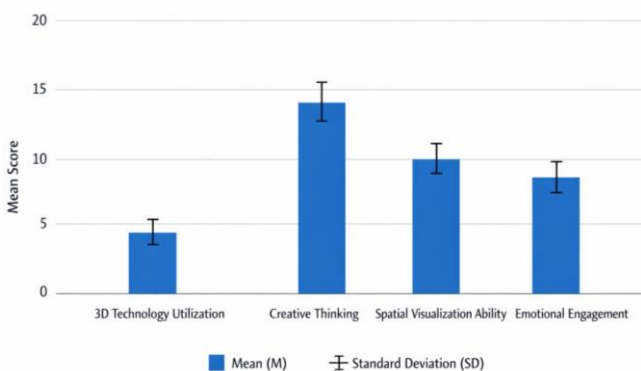


Fig. 1. Descriptive statistics for the primary variables.

B. Relationships among 3D Technology Use, Creative Thinking, Spatial Visualization, and Emotional Engagement

Table II shows the Pearson correlation coefficients for the four variables studied and Pearson correlation was used to test the direction and strength of the bivariate relationships, and the statistical significance was determined by the p-values reported. All observed associations were positive, and the correlation between 3D technology use and creative thinking was 0.342, while the correlation between 3D technology use and spatial visualization was 0.298. The

association between creative thinking and spatial visualization was stronger ($r = 0.468$), Emotional engagement also showed a positive correlation with 3D technology use ($r = 0.210$), creative thinking ($r = 0.301$), and spatial visualization ($r = 0.287$).

TABLE II
CORRELATION MATRIX

Variable	1	2	3	4
3D Technology Use	—			
Creative Thinking	0.342***	—		
Spatial Visualization	0.298**	0.468***	—	
Emotional Engagement	0.210*	0.301***	0.287**	—

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Students who report more frequent use of 3D learning technologies also report slightly higher creative thinking and spatial visualization scores. The positive relation between creative thinking and spatial visualization is particularly important for geometry education, because spatial representation and flexible problem solving may serve as complementary cognitive processes. This interpretation is consistent with research highlighting the significance of the development of spatial skills in technically and visually demanding learning contexts (Sorby, 2009). Furthermore, the positive correlations with emotional engagement suggest that cognitive and technology variables are related to students' affective involvement in learning. However, the cross-sectional correlational nature of the study implies that these relationships should be viewed as associations, not direct causal effects.

C. Predictive Contribution to Emotional Engagement

The multiple regression results for testing the predictive effects of 3D technology use, creative thinking, and spatial visualization on emotional engagement are shown in Table 3. The analysis results were interpreted using the unstandardized coefficient (B), standard error, standardized beta coefficient (β), t-value, and p-value. Then, all three predictors had statistically significant positive coefficients. Creative thinking has the largest standardized coefficient ($\beta = 0.35$, $p < 0.001$), followed by 3D technology use ($\beta = 0.23$, $p = 0.007$) and spatial visualization ($\beta = 0.21$, $p = 0.016$). Within the fitted regression model, creative thinking is classified as the strongest relative predictive association with emotional engagement among the three predictors.

TABLE III
MULTIPLE REGRESSION ANALYSIS RESULTS.

Predictor	Unstandardized B	Std. Error	Beta (β)	t-value	p-value
Constant	3.21	1.12	—	2.86	0.005
3D Technology Use	0.41	0.15	0.23	2.73	0.007
Creative Thinking	0.32	0.09	0.35	3.56	<0.001
Spatial Visualization	0.27	0.11	0.21	2.45	0.016

The positive involvement of 3D technology use supports the need for interactive digital environments in learning. The contribution of spatial visualization further indicates that cognitive processing remains closely connected with engagement. Emotional and cognitive processes are known to interact during learning, and positive affective involvement can support attention, motivation, and persistence. The regression findings should not be interpreted as proof of causality. Rather, they show that 3D technology use, creative thinking, and spatial visualization are statistically associated with emotional engagement when considered together in the regression model.

D. Adaptive Cognitive-Affective Integration

Figure 2 is the conceptual model of adaptive cognitive-affective integration for geometry education. The presented model emphasizes the relationship between cognitive variables and emotional engagement, taking into account individual differences in cognitive flexibility and openness. This model exhibits a wider perspective of technology-supported geometry learning as consisting of more than a single isolated learning outcome.

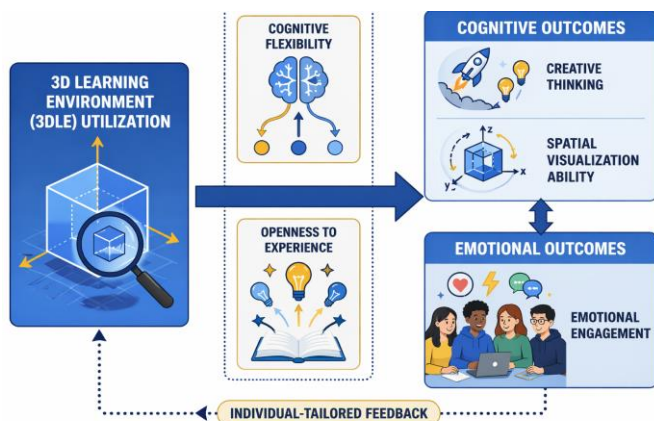


Fig. 2. Conceptual model of adaptive cognitive-affective integration in geometry education.

Spatial visualization supports mental manipulation of geometric structures, and creative thinking supports free exploration of potential relationships and solutions. Affective involvement may influence student motivation to continue with these activities, and students' responses to digital learning environments may be influenced by personal characteristics. From a technological perspective, 3D digital environments are interactive systems that enable learners to explore abstract ideas in a dynamic way. Adaptive technologies may further support responsiveness to differences in learner characteristics and technological requirements (Mulyana et al., 2025). This reinforces the

importance of considering learner variation when designing technology-supported learning environments.

E. Implications for Geometry Education

The use of technology in 3D-supported geometry learning should not be the sole criterion for evaluation. The positive correlations between 3D technology use, creative thinking, spatial visualization, and emotional engagement indicate that the technological, cognitive, and affective aspects are interconnected in the learning process.

In particular, creative thinking seems to be of great importance, as it has the strongest standardized regression coefficient in Table III. Greater flexibility in generating and exploring ideas is also tied to greater emotional involvement of students. Spatial visualization is also important since learning geometry requires students to interpret and manipulate abstract spatial relationships.

This study adds to the existing body of research in the area of mathematics learning and technology-supported education. In mathematics education, studies have pointed to the importance of confidence, student interest, digital learning tools, and artificial intelligence (Bendol & Dalayap, 2025; Jose, 2022; Dermawan et al., 2022; Davidson et al., 2026). The present results extend this discussion by including technology use, creative thinking, spatial visualization, and emotional engagement within the same analysis.

F. Implications for Sustainable Development

The potential of 3D technologies for geometry education could also be a driver for sustainable educational development by promoting accessible, technology-enhanced, and learner-oriented learning. Digital resources can be reused and adapted across learning contexts, and interactive visualization can provide additional support for visual and exploratory learners.

The results are relevant to SDG 4 as inclusive and quality education requires learning environments that support cognitive development and student engagement. Prior research has identified the need for inclusive educational design, educator development, and sustainable educational practices (Adeoye, 2026; Glushchenko et al., 2027; Al-Zahrani & Bello, 2026; Bariquit et al., 2026).

Sustainable digital education should not be defined only by access to technology. It should also consider whether technological environments support meaningful cognitive development, emotional engagement, and responsiveness to learner differences. In this context, the integration of 3D visualization, creative thinking, spatial development, and affective engagement provides a broader perspective for

designing adaptive and sustainable geometry-learning environments.

Beyond its immediate influence on geometry learning, the proposed 3D-supported educational approach has broader relevance to the Sustainable Development Goals (SDGs). It affects SDG 4 on inclusive and equitable quality education, interactive digital environments can facilitate access to visual learning resources, cater to a range of learning styles, and provide flexible ways for students to investigate abstract mathematical ideas, these features are consistent with sustainable educational practices that promote accessibility, inclusion, learner engagement, and sustainable educational quality (Adeoye, 2026; Glushchenko et al., 2027; Al-Zahrani & Bello, 2026; Bariquit et al., 2026), the current framework demonstrates that educational technology can create not only cognitive achievement but also more inclusive and responsive learning experiences by integrating 3D visualization with creative thinking, spatial development, and emotional involvement. Therefore, the use of 3D digital environments for education based on geometry can contribute to a sustainable educational transformation through the link between technological innovation and student engagement, accessibility, and quality learning in line with the SDGs.

CONCLUSION

Learning geometry with 3D support is associated with students' creative thinking, spatial visualization and emotional involvement. Correlation analysis revealed that all major study variables were positively related to each other. Multiple regression analysis demonstrated that creative thinking had the strongest relative predictive association with emotional engagement, followed by 3D technology use and spatial visualization. These results underscore the need to simultaneously consider technological, cognitive and affective dimensions when evaluating digital environments for geometry learning. The study adopted a cross-sectional correlational design, thus the results should be understood as statistical associations rather than direct causal effects. The convergence of interactive visualization, cognitive development, learner engagement and adaptive learning presents an opportunity to build more responsive and inclusive digital learning environments. This approach also contributes to sustainable education and SDG 4 by promoting technology-enhanced, accessible, and quality learning in the education of geometry.

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