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Adaptive learning in bionics: transforming science education

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Introduction: Adaptive learning platforms offer innovative teaching approaches by tailoring educational content to individual learner's needs, abilities, and paces.

Methods: This study investigates the effects of an adaptive digital learning platform on user experience, motivation, and learning outcomes among 56 sixth-grade students from two German grammar schools. Students completed three bionics-focused modules— "polar bear", "heat transfer", and "temperature and heat"—integrated into science lessons. Data from questionnaires and performance tests assessed prior knowledge, learning success, cognitive activation, and situational interest.

Results: The findings indicate that 98% of students found digital media motivating, with 81% favoring a hybrid mix of traditional and digital teaching methods. Positive emotional responses were reported by 62% of participants, though 38% experienced uncertainty. The "polar bear" module achieved the highest learning gain (+41%), followed by "heat transfer" (+23%) and "temperature and heat" (+13%) module.

Discussion: These results suggest that adaptive digital learning platforms can enhance learning outcomes and cognitive engagement, particularly when the content aligns with student interests and needs.

KEYWORDS

adaptive learning, intelligent tutoring systems, science education, bionics, situational interest, motivation, cognitive activation

1 Introduction

The development of adaptive learning systems and intelligent tutoring systems (ITS) has brought transformative changes to the education sector, enabling highly personalized learning environments (Contrino et al., 2024; Christodoulou and Angeli, 2022; Akyuz, 2020). Personalized learning refers to an educational approach that tailors teaching methods, content, and pacing to the individual needs, preferences, and goals of each learner. This approach allows for flexibility and engagement, empowering students to take ownership of their learning process (Van der Kleij et al., 2015; Pane et al., 2017). Within personalized learning, adaptive learning systems dynamically adjust educational content in real time using technology. These systems analyze data on a learner's behavior, performance, and preferences to optimize the learning path, ensuring that content delivery is tailored to each individual (Jose et al., 2024). Adaptive learning emphasizes continuous responsiveness to learner progress, helping to maintain an appropriate level of challenge and engagement throughout the educational process. Intelligent tutoring systems (ITS) extend adaptive learning by incorporating artificial intelligence to simulate human tutoring. ITS engage learners in interactive dialogs, provide real-time feedback, and guide problem-solving processes based on detailed analysis of student performance (VanLehn, 2011; Graesser et al., 2001). Unlike general adaptive platforms, ITS focus on step-by-step support and feedback tailored to the learner's specific needs, often

excelling in teaching complex problem-solving and critical thinking skills. The primary differences between these approaches lie in their technological sophistication and scope: Personalized Learning: Serves as the overarching framework, focusing on customizing the learning experience to align with student needs and preferences without necessarily using technology (Pane et al., 2017). Adaptive Learning: Adds a dynamic, data-driven layer to personalization, using real-time adjustments to tailor content based on learner performance and behavior (Capuano and Caballé, 2020; Walkington, 2013; Wan et al., 2023). ITS: Builds upon adaptive learning with AI-driven tutoring, providing individualized, interactive guidance and feedback similar to one-on-one human tutoring (VanLehn, 2011; Graesser et al., 2001). These interconnected concepts work synergistically to create highly engaging and effective educational environments tailored to the unique needs of each learner. Despite their considerable potential, the adoption of adaptive learning systems in Germany remains limited. Platforms such as Area9 Lyceum (Area9 Lyceum, 2024) and Bettermarks (2024) are beginning to gain attention in schools. While Area9 Lyceum is still in the pilot phase, Bettermarks has been extensively implemented in public and private schools across the country (Spitzer and Musslick, 2021; Spitzer et al., 2023). These platforms utilize AI-based algorithms to personalize learning by analyzing learners' behavior and performance in real time. This enables dynamic adjustments to difficulty levels, information presentation, and pacing, creating a supportive environment that fosters engagement and accelerates progress in areas where learners are already proficient. A critical factor in the success of adaptive learning systems is their ability to stimulate situational interest, a temporary form of interest that arises spontaneously in response to specific contexts (Schraw et al., 2001; Hidi and Renninger, 2006). Situational interest is driven by three primary factors: novelty and unexpected interactions (epistemic), emotional engagement (emotional), and the perceived relevance of tasks to learners' goals (value-based). It occurs when learning content is novel, engaging, or particularly pertinent. Research has shown that situational interest increases learners' attention (Harackiewicz et al., 2016) and motivation (Chen et al., 2001), leading to deeper understanding and improved learning outcomes. Unlike personal interest, which develops gradually into a stable and enduring interest, situational interest is transient but plays a crucial role in fostering engagement and motivation (Hidi and Renninger, 2006). In addition to situational interest, motivation and cognitive activation are pivotal elements of effective teaching and learning environments. Motivation is influenced by intrinsic factors, such as enjoyment and personal goals, and extrinsic factors, such as rewards or recognition (Legault, 2016). Intrinsic motivation has been shown to complement extrinsic motivation in specific contexts, making it essential to foster both for optimal learning. Cognitive activation, on the other hand, involves mentally stimulating learners by tailoring material to their specific level of difficulty, promoting critical thinking and the application of knowledge (Groß-Mlynek et al., 2022; Sweller, 1994). Together, these factors ensure that adaptive learning platforms engage learners effectively and promote deep, meaningful learning experiences. Platforms like Area9 Lyceum Rhapsode operationalize these principles through advanced AI-driven personalization. For example, this platform integrates cognitive activation principles by maintaining an optimal challenge level for learners and fostering critical thinking through adaptive engagement (Nye, 2015). It uses dual assessment models that combine objective evaluations of accuracy with subjective self-assessments of confidence, encouraging reflection and supporting deeper cognitive processes (Kang et al., 2017). These features make adaptive learning systems powerful tools for addressing situational interest, motivation, and cognitive activation, thus enhancing educational outcomes.

To evaluate how adaptive platforms like Area9 Lyceum Rhapsode achieve these objectives, this study investigates their implementation in secondary science education, focusing specifically on their application in bionics, a novel and interdisciplinary subject area. Adaptive platforms have demonstrated significant potential in STEM education; however, much of the existing research has been conducted in controlled laboratory settings. This leaves a critical gap in understanding their effectiveness in real-world classroom contexts. Addressing this gap, the study explores how the Area9 Lyceum Rhapsode platform fosters situational interest, cognitive activation, and learning gains within authentic educational environments.

The study builds on key gaps identified in the literature:

1 The limited transferability of findings from controlled environments to everyday school settings.
2 The lack of systematic analyses of adaptive platforms in interdisciplinary topics like bionics, which represent complex and innovative STEM challenges.
3 The absence of empirical investigations into situational interest and cognitive activation, despite their critical roles in successful learning.
4 The need for practical insights into addressing technical and organizational challenges in adaptive system implementation.

By addressing these gaps, this research aims to bridge the divide between theoretical advancements and practical applications of adaptive learning platforms. Specifically, the study evaluates whether the integration of the Area9 Lyceum Rhapsode platform can enhance students' learning outcomes, providing both theoretical insights and pragmatic solutions for modern education. This study not only extends the applicability of adaptive platforms to real-world settings but also pioneers their use in innovative STEM areas such as bionics, highlighting their potential for interdisciplinary learning.

The following research questions guide this inquiry:

1 RQ1: What are students' attitudes toward the use of digital media in the classroom and their experiences with digital media in their leisure time?
2 RQ2: What are students' emotions and attitudes toward the usability of the digital learning environment?
3 RQ3: Is the digital learning environment cognitively stimulating, and can it arouse situational interest in students?
4 RQ4: Does the digital learning environment facilitate enhanced learning gains?

RQ1 pertains to the students' use of digital media in their leisure time as well as their general attitude toward digital media. The objective is to gain an understanding of their habits and attitudes toward digital media within the context of the educational institution prior to their engagement with the digital learning platform.

RQ2–4 pertain to direct engagement with the digital adaptive learning environment and examine students' emotional responses, cognitive activation, situational interest, and learning gains. The

objective is to ascertain the implementation of a digital learning platform in educational institutions can enhance students' learning outcomes.

Through this analysis, the study contributes to bridging the gap between theoretical advancements and practical implementation of adaptive platforms but also offers novel insights into their application in underexplored STEM areas such as bionics. These findings provide a foundation for further exploration of adaptive learning platforms across diverse educational contexts and curricula, ensuring their scalability and sustainability in modern classrooms. The results are expected to guide educators, policymakers, and developers in effectively integrating adaptive systems into varied learning environments, thereby enhancing their educational impact.

2 Materials and methods

2.1 Participants

The study involved 56 sixth-grade students from two grammar schools located in the state of North Rhine-Westphalia, Germany. Of the participants 28 were male, 21 were female, and 7 did not specify their gender. The majority (43 students) of the group was 11 years old, while the remaining individuals (13 students) were 12 years old. 56 students participated in the pre-test while 50 students participated in the post2-test. This discrepancy in student participation between the different tests are due to the fact that the project was conducted over multiple school lessons, during which some students were unable to attend all sessions, because of absences or scheduling conflicts. The assessment of learning gains from the three learning modules was based on data from students who completed all three tests (pre-, post1-and post2-test). As part of the study, participants completed questionnaires using eighth-generation iPads at various points during the completion of the modules on the adaptive learning platform Area9 Lyceum Rhapsode.

2.2 Study design

This study employed a quantitative experimental design to assess the effectiveness of the Area9 Lyceum Rhapsode digital learning platform on students' learning outcomes in secondary education. Students were randomly assigned to different groups, each of which worked through various expert modules on the platform. The study was conducted between January 2023 and March 2023. Data collection occurred over a two-week period at multiple time points, including pre-and post-performance tests, as well as pre-, UE-, and post-questionnaires. Participants were allocated 10–15 min to complete the questionnaires. These instruments enabled the collection of both performance data and user experience feedback, encompassing variables such as motivation, emotional responses, system usability, and other measured variables (see Table 1). A detailed overview of the study procedure is provided in Figure 1. The data were analyzed using *t*-tests and ANOVA to assess differences between groups and evaluate the effectiveness of the intervention. Effect sizes were calculated to measure the magnitude of the observed differences. The choice of a quantitative methodology was driven by the need to gather controlled, measurable data to assess learning outcomes and the platform's impact on students' academic progress.

2.3 Questionnaires and performance tests

To evaluate the effectiveness of the adaptive learning platform and its impact on students, three surveys were administered at different stages of the study. The surveys targeted key dimensions of interest, including motivation, cognitive activation, situational interest, emotions, and system usability. All surveys utilized a seven-point Likert scale ranging from "strongly disagree" to "strongly agree." A "neither category" is provided to prevent students with neutral attitudes from shifting to other categories and a non-content option "I cannot say anything about that" to ensure comprehensive and unbiased data.

2.3.1 Pre-questionnaire

The pre-questionnaire was conducted prior to student's engagement with the digital learning platform. It assessed motivation in the classroom, learning success, using digital media in lessons, how much time was spent with digital media, and different types of digital media used (see Table 1).

2.3.2 Usability-emotion questionnaire (UE)

The UE- [Usability, Emotion] questionnaire was administered following completion of the learning modules (expert modules) in the digital learning platform. It assesses system usability and emotions during the learning experience (see Table 1).

2.3.3 Post-questionnaire

Once the digital learning environment had been completed, the post-questionnaire was administered.

This questionnaire assessed learning success, cognitive activation (encouragement to work) and situational interest (see Table 1). This involves active, mental engagement with the learning object.

All surveys were administered online via LimeSurvey, enabling efficient and standardized data collection across participants (see Table 1 and Figure 1).

2.3.4 Performance tests (learning success tests)

In addition to the affective variables (see Table 1), the learning gain that may have been achieved by students through the use of the learning platform was assessed using a performance test. A 14-question test was designed for this purpose, consisting of four questions from the "temperature and heat" module, and five questions each from the "polar bear" and "heat transfer" modules.

The first set of questions in each module was classified as Level I. Level I questions are closed-ended questions that assess factual knowledge, focusing on memorization and understanding of basic concepts. These were multiple-choice questions, each with four answer options, one of which was correct, and the others serving as distractors. Additionally, students were asked to indicate their confidence level for each answer. For the statement "For the answer I marked…," they selected one of the following options: (1) I was absolutely sure, (2) I was almost sure, (3) I was unsure, and (4) I guessed.

Example for Level I Question:

Level I Question:

A polar bear is surrounded by a layer of:

- Hollow guard hairs, dense underfur, white skin, and a layer of fat

TABLE 1 Overview of the variables analyzed, the sources of the test instruments used and their implementation in the pre-, UE, and post-tests.

	Variables	Sources test instruments	Implementation	Items	Reliability
Pre-questionnaire The pre-questionnaire is conducted before working with the digital learning environment	Motivation in the classroom	- Monitor of digital education from the Bertelsmann foundation (Bertelsmann Foundation, 2017) e.g., item: "I am motivated when… … learning programs, such as learning apps, learning games or simulations are used in lessons"	Online via Lime-Survey	3	Cronbach's alpha: 0.49
	Learning success	designed by our project team, e.g., item: "With learning programs, I learn content better than when it is explained to me by teachers"		1	–
	Digital media in lessons	- Monitor of digital education from the Bertelsmann foundation (Bertelsmann Foundation, 2017) e.g., item: "I prefer performance feedback from a learning program than to get personal feedback from a teacher"		5	–
	Time with digital media	Designed by our project team, e.g., item: "In total, I spend this much time per day… …using digital devices such as tablets, laptops or smartphones"		6	Cronbach's alpha: 0.84
	Used digital devices	Designed by our project team, e.g., item: "I prefer to learn with books than with digital devices"		5	–
UE-questionnaire The UE-questionnaire took place immediately after processing the digital learning environment.	Emotions (pleasure, satisfaction, frustration, stress, uncertainty)	-Emotions: Two-dimensional classification of achievement emotions is based on the publication of Pekrun (2014). Four items are taken from the Achievement Emotions questionnaire [AEQ] developed and validated by Pekrun et al. (2011, 2002) and Becker et al. (2020) Emotional stress was additionally analyzed for negative emotions. e.g., item: "I was frustrated while learning with the digital learning platform"	Online via Lime-Survey	5	Cronbach's alpha: 0.77
	System usability	System usability scale: from (Brooke, 1996) The 10 items were translated into German for the questionnaire and adapted to the intervention. e.g., item: "I found the learning platform easy to use"		10	Cronbach's alpha: 0.83
Post-questionnaire The post-questionnaire was at the end of the work with the digital learning environment.	Learning success	Designed by our project team, e.g., item: "I intend to continue utilizing the digital platform in the classroom"	Online via Lime-Survey	2	Cronbach's alpha: 0.75
	Cognitive activation	Cognitive activation: the questionnaire by (Burge et al., 2015) was translated into German and adapted to the intervention, e.g., item: "During lessons with the digital learning platform… …I was encouraged to develop my own solutions"		8	Cronbach's alpha: 0.6
	Situational interest	Situational interest: The test instrument by short-scale from (Potvin et al., 2023) was translated into German and adapted to the intervention. In addition, item 1 was recoded as we did not want to have negatively worded items. Item 1 has been changed to "I am interested in what I have learned using the digital learning platform. e.g., item: "While using the digital learning platform… …learning was more interesting than traditional lessons"		7	Cronbach's alpha: 0.83 (item 3: "While using the digital learning platform ... ...it was useless to me" was recoded due to negative wording).

10.3389/feduc.2025.1427083

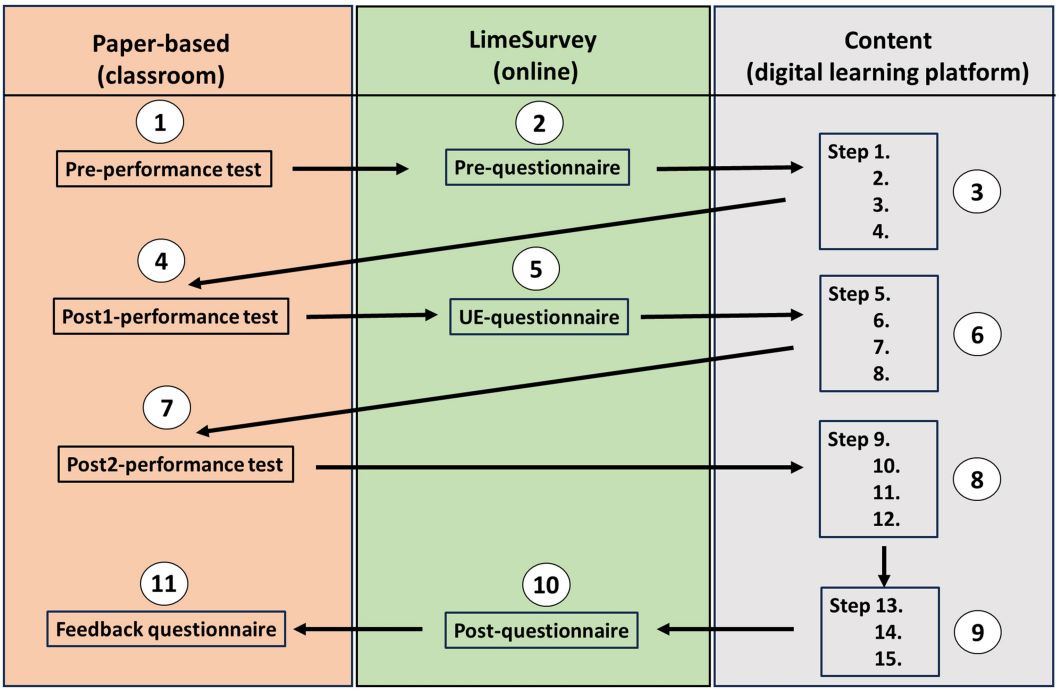

FIGURE 1
Overview of the study procedure. The study process on the digital learning platform consisted of 15 steps: (1) an introduction to fundamental concepts and methodologies, followed by (2) in-depth learning through expert modules. Next, participants created (3) a summary of the learned content. In step (4), a "What do you already know?" Post-1 performance test and a UE questionnaire were conducted. (5) Optional additional modules were available to participants. In step (6), participants worked in expert groups to create an expert summary, which was then (7) evaluated by the teacher. This was followed by (8) an exchange in core groups. Step (9) included another "What do you already know?" Post-2 and performance test. In step (10), participants created posters about the thermal insulation of a house. (11) Teacher feedback was provided, followed by (12) a presentation in a gallery walk, where students also gave a feedback. Finally, step (13) involved a digital selection task on thermal insulation, where participants chose from three proposed options and engaged in a discussion. Additionally, the study concluded with two final steps: (14) a final group discussion and evaluation, and (15) a final evaluation and recognition of achievements. Performance tests were conducted on paper in the classroom (orange), questionnaires were administered online using LimeSurvey (green), and steps 1-15 were carried out on the digital learning platform (gray). The numbers 1-11 indicate the order of the study.

- Lined guard hairs, thin underfur, black skin, and a layer of fat
- Hollow guard hairs, dense underfur, black skin, and a layer of fat
- Hollow guard hairs, thin underfur, white skin, and a layer of fat

Regarding the answer I selected:

- I was absolutely sure.
- …I was almost sure.
- …I was unsure.
- …I guessed.

The final question in each module was a Level II question, requiring students to apply a known fact to a novel situation. These open-ended questions tested higher cognitive skills, including application, analysis, synthesis, and evaluation. Level II questions were designed to encourage students to think critically, make connections, and reflect on the material beyond basic knowledge.

Example for Level II Question:

Level II question:

Galapagos penguins live on the Galapagos Islands, where the average annual temperature is 24°C. Emperor penguins live in Antarctica, where it can get as cold as −30°C. What statement can you make about penguins?

- Galapagos penguins are larger and heavier than emperor penguins.
- Emperor penguins are larger and heavier than Galapagos penguins.
- Galapagos penguins and emperor penguins are the same size and weight.
- More information is needed to make a statement.

Regarding the answer I selected:

- …I was absolutely sure.
- …I was almost sure.
- …I was unsure.
- …I guessed.

The performance test was administered on three occasions: before the modules to assess prior knowledge (pre-performance test), and at two time points during the use of the digital learning platform (post1-and post2-performance tests) to measure knowledge acquisition.

2.4 Learning modules from the adaptive platform Area9 Lyceum Rhapsode

Each randomly assigned group worked on one of the three expert modules, which covered the following topics: "polar bear", "temperature and heat" and "heat transfer".

The "polar bear" module ($N = 18$) examined the principle of thermal insulation, the structure of the polar bear fur hide and the outer layer of the body, the light conduction hypothesis and Bergmann's rule.

The "temperature and heat" module ($N = 17$) covered thermodynamic systems, different temperature scales, the distinction between temperature and heat quantity, and heat capacity.

The "heat transfer" module ($N = 15$) was concerned with the various forms of heat transfer (conduction, convection and radiation), thermal conductivity and light conduction. In the digital learning environment, an avatar, designated as a coach, guided students through the digital learning environment. The coach conveyed the learning content in the form of explanatory texts and provides students with feedback. Additionally, students had the option of having the content of the coach text played back to them.

2.5 Testing the usability of the adaptive learning platform

The usability of the Area9 Lyceum Rhapsode adaptive learning platform was tested with 52 students. The System Usability Scale (SUS) questionnaire based on Brooke (1996) was used to evaluate the platform. The SUS consists of 10 statements and students answered on a 7-point Likert scale from "strongly disagree" (0) to "strongly agree" (6). Our eighth item "I cannot say anything about that' was excluded from the analysis. The SUS score was calculated by adding the scores of each item and multiplying the sum by 1.66666667 to give an overall rating of the system's usability on a scale of 0 to 100.

2.6 Data analysis

The primary research activities entailed an empirical analysis of quantitative data. Descriptive and inferential statistics were performed using Prism 8 (GraphPad Software, La Jolla, California, USA). The statistical significance of differences between two paired sample groups was assessed using a two-tailed paired *t*-test. For comparisons involving more than two groups, one-way ANOVA with repeated measures (within-group) or two-way ANOVA with repeated measures (within-between group) was conducted, followed by the Tukey *post-hoc* test for multiple comparisons.

To test the assumptions for parametric tests, the normality of the data was assessed using the D'Agostino and Pearson test, while homogeneity of variances was examined using the Brown-Forsythe test and Bartlett's test. For repeated-measures designs, sphericity was tested using Mauchly's test. If the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied. Effect sizes were calculated using Cohen's d for paired comparisons and Cohen's f for ANOVA, to quantify the magnitude of observed effects, with interpretations based on standard thresholds: small ($d = 0.2$, $f = 0.1$), medium ($d = 0.5$, $f = 0.25$), and large ($d = 0.8$, $f = 0.4$) (Cohen, 1992).

A chi-square test for independence was used to examine whether gender distribution differed significantly between the learning modules. This test assessed the relationship between gender and module type under the null hypothesis of independence.

Sample sizes were calculated *a priori* using G*Power to ensure sufficient statistical power and justify the number of participants. The calculations were based on a significance level of $\alpha = 0.05$, power ($1 - \beta = 0.80$), and effect sizes corresponding to large effects. The required sample sizes were 15 participants for a paired t-test ($d = 0.8$), 12 participants for a one-way repeated-measures ANOVA ($f = 0.4$), and 18 participants for a two-way repeated-measures ANOVA ($f = 0.4$). These calculations confirmed that the sample sizes were sufficient to detect large effects, ensuring the robustness of the analyses.

Data are presented as means ± SEM, and statistical significance was set at the following levels: *n.s.* (not significant), $p^* < 0.05$, $p^{**} < 0.01$, $p^{***} < 0.001$, and $p^{****} < 0.0001$. Charts and tables were generated based on the results of the statistical tests.

3 Results

This section presents the results of the data analysis with regard to the previously defined research questions.

> RQ1: What are students' attitudes toward the use of digital media in the classroom and their experiences with digital media in their leisure time?

3.1 Students' motivation is enhanced through the integration of digital media, particularly learning software, into lessons

The advent of digital media, including learning software, has transformed the teaching and learning processes in educational institutions. This has enabled teachers and learners alike to adopt innovative methodological approaches. In order to assess the impact of digital media and learning applications on students' motivation to learn, a performance evaluation was conducted in this study, specifically measuring students' motivation to learn with digital media.

The evaluation indicated that approximately 75% of the students reported an increase in motivation when they were given the opportunity to utilize digital technologies to create a major project or presentations, or when lessons were enhanced by the integration of digitally supported learning stations (88%) (Figure 2A). Furthermore, a considerable proportion of the participants, approximately 98%, demonstrated an increased willingness to acquire knowledge when lessons were complemented by the use of learning software, such as apps, games or simulations (Figure 2A). With regard to the general preference for the use of digital media in teaching, it was found that majority of students favored this approach (88%). However, 40% of the students were against digital-only teaching, while 81% preferred a hybrid approach, combining traditional learning methods with digital media (Figure 2B). With regard to teachers'use of new digital technologies, 82% of students expressed a wish for teachers to be more willing to experiment with digital media (Figure 2C). In terms of feedback on learning performance, specifically referring to students' individual progress in understanding, applying, and developing skills based on the lesson content, 59% of students indicated a preference for personal feedback from a teacher, while 30% favored feedback provided

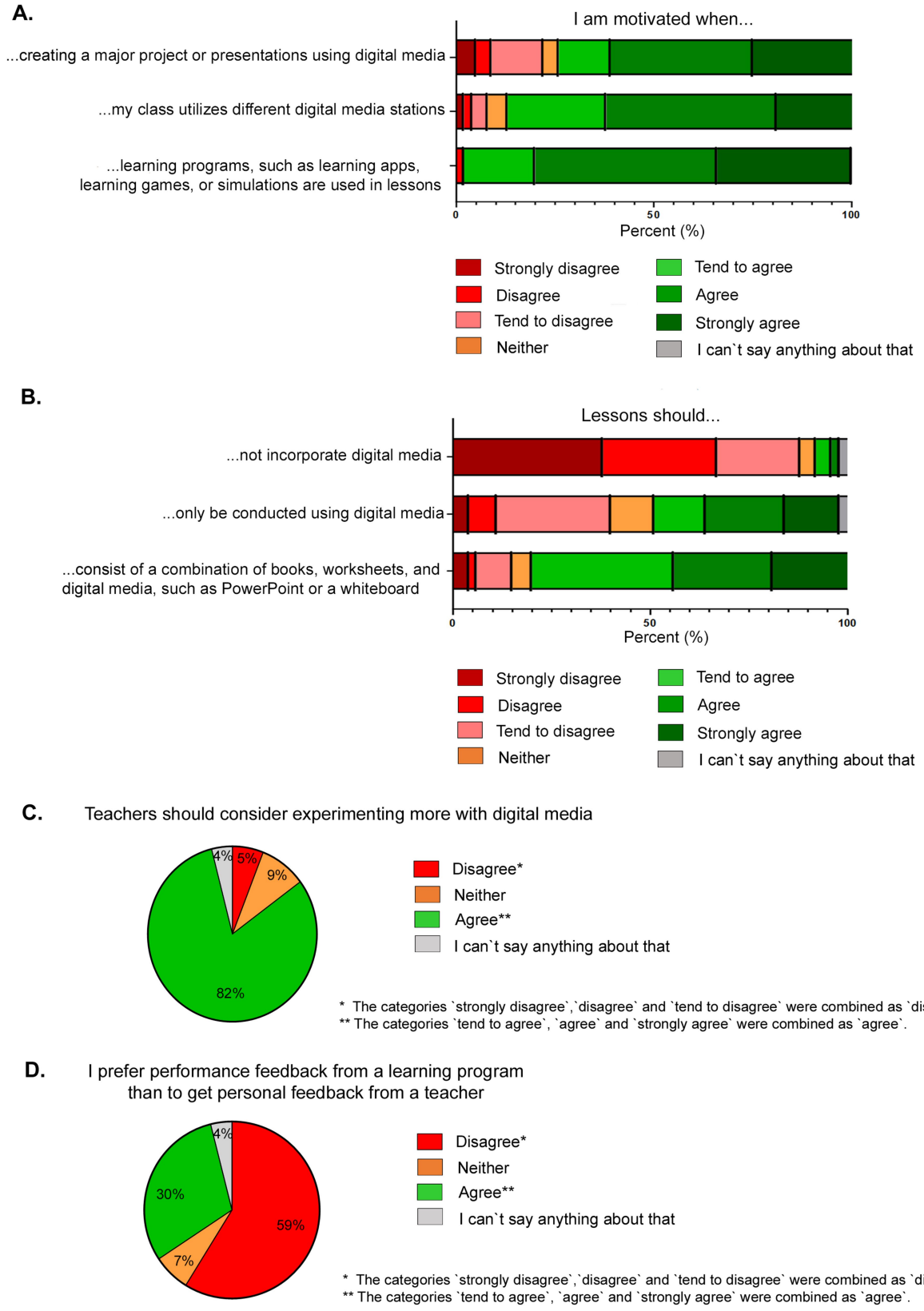

FIGURE 2
Students' motivation is enhanced through the integration of digital media, particularly learning software, into lessons. **(A)** Motivation to learn, **(B)** Use of digital media in the classroom, **(C)** Use of new digital media by teachers, **(D)** Feedback on learning performance.

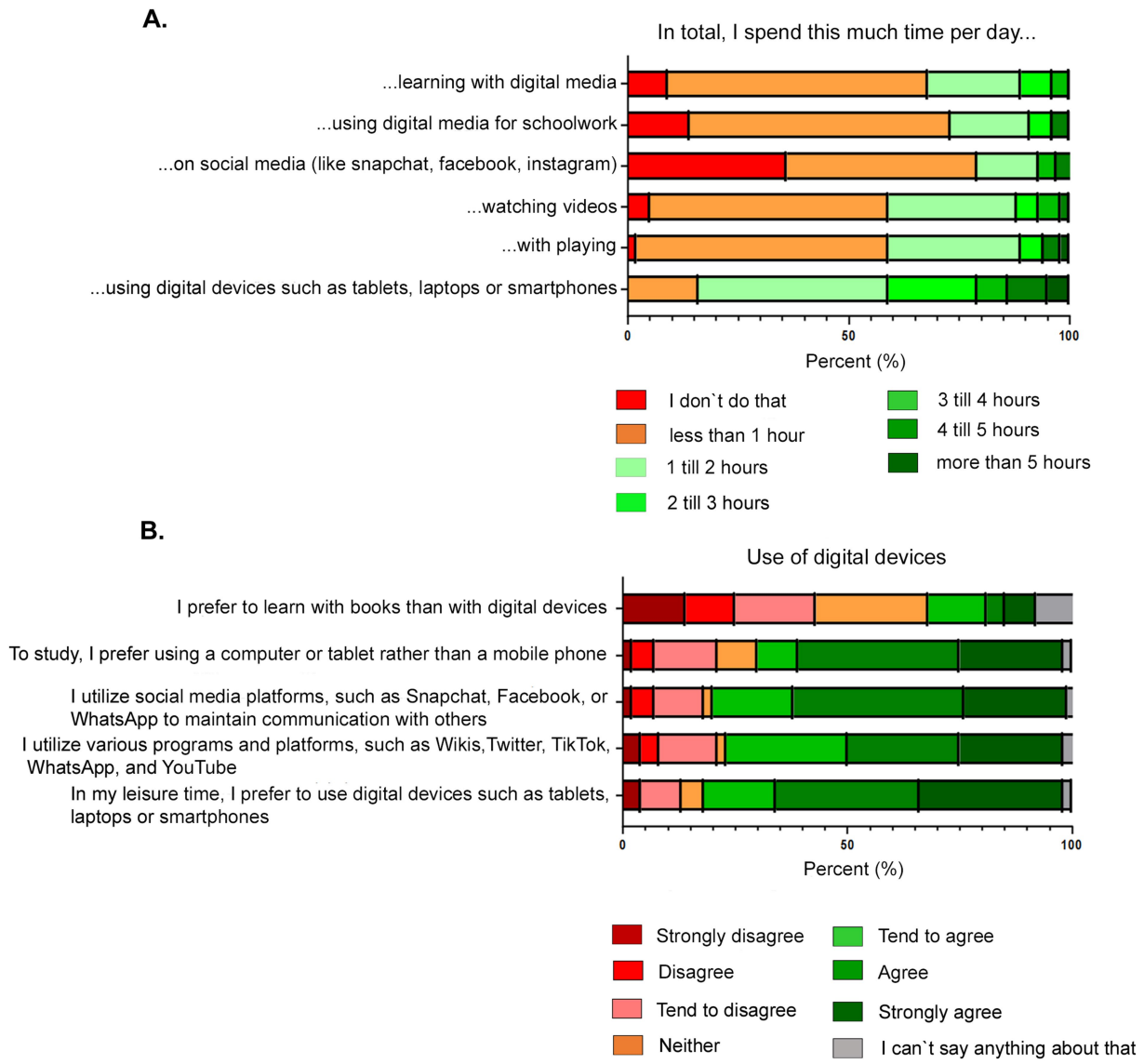

FIGURE 3
Students demonstrate a diverse utilization of digital media during their leisure time. **(A)** Time spent with digital media, **(B)** Use of digital devices.

by a learning program (Figure 2D). In conclusion, the results indicate that a balanced integration of digital media into the educational process is important for increasing motivation to learn, while recognizing the value of face-to-face interaction and individual feedback from teachers.

3.2 Students demonstrate a diverse utilization of digital media during their leisure time

The role of digital media in the education of students has become increasingly important in recent years. It offers numerous opportunities to enhance and enrich the teaching and learning process. However, it also presents potential risks, particularly in relation of the amount of time students spend with digital media at school and in their leisure time. The surveys sought to quantify the amount of time students spend using digital media on a daily basis outside of regular school lessons. This encompasses time spent on educational activities, undertaking schoolwork, utilizing social networks, viewing videos, and engaging in digital gaming. The daily usage time was analyzed at different time intervals (Figure 3A).

The analysis of digital media use for educational purposes indicates that a considerable proportion of students (59%) utilize digital technologies for learning purposes for <1 h per day. However, a smaller number of students invest 1–2 h (21%), 2–3 h (7%), or even 3–4 h (4%) of time per day in digital learning activities. It is important to note that 9% of students do not integrate digital media into their learning at all (Figure 3A). When examining the use of digital media for schoolwork, a similar pattern emerges: the majority of students (59%) prefer to use digital media for <1 h per day. Furthermore, 18% of respondents indicated that they use digital media for 1–2 h, 5% for 2–3 h, and a further 4% for 4–5 h a day for their homework. The proportion of non-users for this specific application was slightly

higher than for general learning at 14% (Figure 3A). The survey on social media usage revealed a 36% increase in non-users among the student population. In addition, only 43% of students reported spending <1 h per day on social networking sites. The proportion of active users declines precipitously with increasing time spent on social media, with 14% reporting spending 1–2 h, and 4% spending 3–4 or 4–5 h per day on social media (Figure 3A). Video consumption is a prevalent pastime among students, with only 5% of non-users. The majority of students (54%) dedicate <1 h a day to video viewing, while a notable proportion (29%) allocate 1–2 h a day to this activity. However, a minority of students engage in this activity for more than two hours per day: 2–3 h (5%), 3–4 h (5%) and 4–5 h (2%) (Figure 3A). With regard to digital gaming, only 2% of students reported no engagement with gaming activities whatsoever. Conversely, the majority (57%) of respondents indicated that their daily gaming time did not exceed 1 h. Furthermore, 30% of the learners engaged in gaming for between 1–2 h, while a smaller contingent of the students (5%) spent 2–3 h gaming. Notably, 4% of students devoted 4–5 h a day to gaming, and a minimal fraction (2%) even invested more than 5 h a day in gaming. The distribution of gaming habits among the study's participants demonstrates a diverse engagement with digital games, encompassing a range of minimal to extensive daily time use (Figure 3A). Looking at the overall use of digital devices, a significant proportion of students (43%) spend 1–2 h per day using digital technologies, with a further 20% of respondents spending 2–3 h per day. In addition, there is a smaller segment of users who interact with digital devices for even longer periods, including 3–4 h (7%), 4–5 h (9%), and more than 5 h (5%) per day. This distribution highlights the diverse integration of digital technologies into students' daily lives, reflecting a wide range of engagement levels (Figure 3A). The analysis reflects a heterogeneous use of digital media among students, with educational purposes often pursued to a moderate extent, while entertainment (such as watching videos and playing games) is used and more widely and intensively. Notably, a small subset of students reported not using digital media at all. Overall, the data indicate a nuanced integration of digital technologies into the educational routine, presenting both opportunities for tailored learning experiences and challenges for balanced media use.

In addition to measuring the time spent using digital media, the study also analyzed the specific types of digital technologies used by students (Figure 3B) in order to provide a complete picture of their digital media practices outside of school. The survey aimed to identify preferences for traditional books versus digital devices, and to assess the preferred use of computers or tablets versus mobile phones. It also explored the extent to which learners work with specific programs and learning platforms and whether there is a general affinity for working with digital technologies. These aspects were investigated in order to gain a more comprehensive understanding of the target group's skills and habits in using digital media. The survey of students revealed a clear preference for digital media over traditional books. Only 24% of respondents tended to favor books over digital alternatives, while 68% expressed either a dislike or a neutral attitude toward books, indicating a lower affinity for traditional forms of reading. These data suggest a predominant preference for digital media (Figure 3B). When asked about their preferred digital activities computers/tablets and mobile phones, 68% of respondents indicated a clear preference for computers or tablets. This suggests a strong preference for larger screen devices when engaging with digital media (Figure 3B). An overwhelming majority of students (79%) approve of the use of social media platforms such as Snapchat, Facebook, and WhatsApp, which highlights the significant role that social media plays in their lives. A mere 20% of pupils exhibit a critical or indifferent attitude toward the use of digital devices (Figure 3B). Similarly, digital programs and platforms such as Wikis, Twitter, TikTok, WhatsApp and YouTube are widely accepted, with 75% of respondents expressing a positive attitude. Only a minority of 23% have a neutral or negative view, indicating a high level of reliance on digital tools for various purposes (Figure 3B). The survey results indicate that 80% of respondents enjoy using digital devices, reflecting a generally positive attitude toward technology. In contrast, only 18% express no enjoyment or indifference toward digital devices (Figure 3B). The survey findings demonstrate a clear preference among students for digital media and technology, both as learning tools and for entertainment and social networking. Traditional books and reading methods are less popular, suggesting a shift in preferences and habits. The pervasive preference for computers or tablets over mobile phones, coupled with the high use of social media and digital platforms, underscores the pivotal role that digital technologies play in students' daily lives. The generally positive attitude toward digital devices suggests a seamless and somewhat reliant integration of digital technologies into their personal and educational environments.

> RQ2: What are students' emotions and attitudes toward the usability of the digital learning environment?

3.3 Positive emotions predominate in the use of the digital learning environment

The utilization of digital learning platforms and software is a fundamental aspect of the learning experience. Emotions can exert both positive and negative influences on the process. Research in this field has demonstrated that affective states (positive emotions), can enhance learner engagement and performance (Rodríguez-Muñoz et al., 2021; Rand et al., 2020; Pekrun et al., 2017), whereas negative emotions, have the opposite effect (Pentaraki and Burkholder, 2017). These positive and negative emotions experienced by students were investigated in the UE test to ascertain whether the adaptive learning platform had a positive effect on their learning behavior. As illustrated in Figure 4A, the majority of students indicated that they enjoyed learning with the digital learning environment and were successful without feeling frustrated or stressed. However, 38% of the students reported that they felt uncertain when learning with the digital learning environment. When all positive (pleasure and satisfaction) and negative (frustration, stress, and uncertainty) emotions are considered together (Figure 4B), it can be seen that the positive emotions (62%) significantly outweigh negative ones (35%). In addition to the survey of emotions, Brooke's System Usability Scale (SUS) (Brooke, 1996) employed to assess the usability of the learning platform. The SUS is based

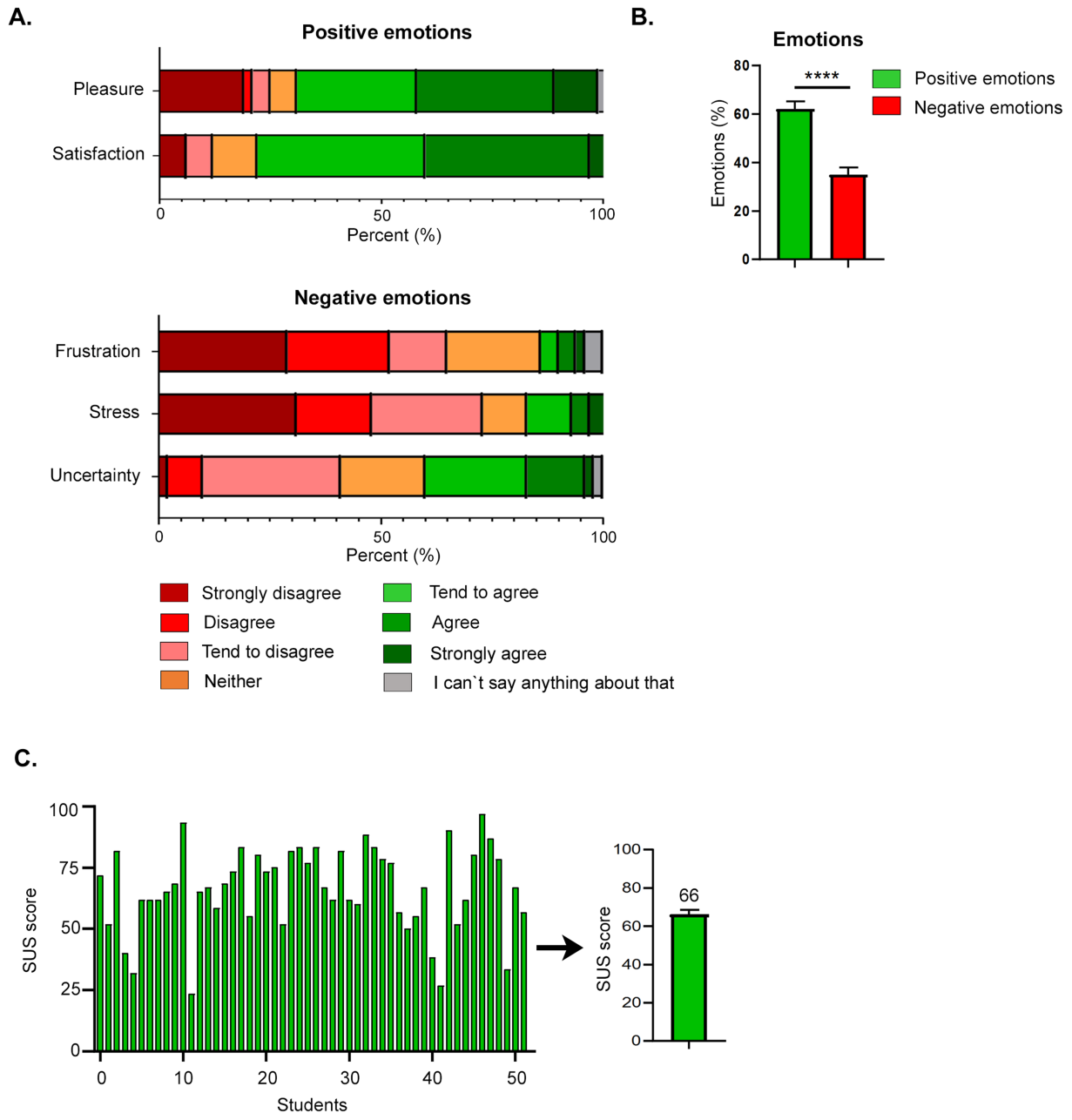

FIGURE 4
Positive emotions predominate in the use of the digital learning environment. **(A)** Positive (pleasure, satisfaction) and negative (frustration, stress, uncertainty) emotions, **(B)** Total positive and negative emotions compared, **(C)** System usability score of each student (left image) and overall score (right image).

on a 5- (or 7-) item Likert scale and plays a pivotal role in the evaluation of digital learning environments. The SUS values of the individual students and the overall SUS value were calculated (Figure 4C). The overall SUS score obtained was 66 (Figure 4C), which is lower than the average score of 68 (Sauro, 2011) and indicates a need for improvement in usability of this platform. In conclusion, the analysis of students' emotional experiences in digital learning environments shows that positive emotions such as pleasure and satisfaction predominate. Furthermore, the usability of digital learning platforms, as measured by SUS, is a decisive factor for their acceptance and effectiveness.

> RQ3: Is the digital learning environment cognitively stimulating and can arouse situational interest in students?

3.4 The utilization of the digital learning platform enhance student learning, situational interest and cognitive activation

Digital learning platforms have the potential to transform student learning by providing interactive, personalized learning experiences. This study explored the extent to which these

FIGURE 5
The utilization of the digital learning platform enhance student learning, situational interest and cognitive activation. **(A)** Reuse of learning environment, **(B)** Cognitive activation during the lesson, **(C)** Situational interest during the lessons with the digital learning environment.

technologies, analyzed using the Area 9 Lyceum Rhapsode digital learning platform, contribute to deeper cognitive activation in students and can engage learners" situational interest. The analysis revealed that the majority of students would like to continue using the Area9 Lyceum Rhapsode platform in class (84%), while 8% of the respondents expressed disagreement and another 8% chose neither option (Figure 5A). In order to gather information about the students' cognitive activation, which has been shown to enhance

classroom learning, they were asked about their experiences with the digital learning platform (Figure 5B). The analysis of the digital learning environment suggests that tasks requiring extensive thinking are central, as confirmed by the high rate of student agreement. The data also indicates that learners were encouraged to develop their own solutions, suggesting an environment that favors active and independent learning. While opinions on the variety of the tasks may vary, the majority were in favor. This suggests that the learning tasks cover a wide spectrum. Furthermore, the encouragement to learn from mistakes and the invitation to reflect on their own solutions were also well received by the students. These aspects can be seen as supporting the development of critical thinking. In addition, a significant proportion of respondents indicated that they were encouraged to apply their newly acquired knowledge in different contexts, thereby reinforcing its relevance and applicability. Another noteworthy observation is that students frequently approached tasks with multiple potential solutions, indicating that flexibility and creativity were encouraged as part of the problem-solving process. Although opinions varied, the majority of respondents rated this type of task positively (Figure 5B). In addition to cognitive activation, the learners were also asked about their situational interest while working with the digital learning platform (Figure 5C). Overall, the feedback on the digital learning platform was mostly positive. The platform is generally regarded as a valuable tool in the learning process, as evidenced by the fact that users rarely found it useless. The high level of interest shown by students in the content of the platform confirms its ability to capture and hold their attention. While opinions on the importance of the material vary, there is a general agreement on its relevance. In addition, most learners (69%) find digital learning more interesting than traditional teaching, suggesting that digital platforms can create a stimulating learning environment. Specific feedback from students suggests that they perceive the platform as effective in helping them understand complex topics, such as thermal insulation in polar bears. Furthermore, a substantial proportion of learners (46%) reported increased concentration when using the digital learning platform, suggesting that it may provide an environment conducive to learning. The perception that time passes more quickly when working with the platform can be seen as an indicator of deeper engagement and interest in the learning material. The responses of learners show that the digital learning platform is a stimulating and effective resource for learning (Figure 5C). In summary, the digital learning environment was generally well-received by students and appears to foster the development of critical thinking, problem-solving skills, and the application of learned knowledge in new contexts, as reflected in the students' statements. Furthermore, the digital learning platform is perceived as a stimulating tool that is effective in stimulating learners' interest and concentration, and is crucial for a deeper understanding of the learning material. Learners perceive the digital learning environment as a valuable resource for enhancing their understanding and consolidation of the learning material.

> RQ4: Does the digital learning environment facilitate enhanced learning gains?

3.5 The learning modules on the Area 9 Lyceum Rhapsode platform lead to topic-related learning gain for the students

To determine whether the use of digital learning modules leads to learning gains for students, students completed one of three distinct modules on "polar bear", "heat transfer", and "temperature and heat". A total learning gain of 21% was achieved in the post2-test compared to the pre-test ($p^{****} < 0.0001$) (Figure 6A). To ascertain whether all three modules resulted in a similar learning gain for the students, the different modules were investigated in detail in the pre-, post1-and post2-tests (Figure 6B). Following the completion of the expert module "polar bear" on the learning platform, students demonstrated a significant improvement in their ability to answer questions correctly in comparison to the pre-test ($p^{****} < 0.0001$). The "polar bear" module resulted in an increase in learning of over 40% (Figure 6B). The majority of students demonstrated an understanding of the subject matter, answering at least three questions correctly and scoring a minimum of 60% on the post1-test. A third of the students achieved the maximum score of 100%. However, the module on "heat transfer" showed an increase in learning of just over 20% from the pre-test to post1-test ($p^{**} < 0.0094$). Only three students scored 100% on the post1-test. Similarly, the module on "temperature and heat" resulted in a 13% increase in learning between the pre-test and post1-test ($p > 0.05$, *n.s.*). Only one student achieved a perfect score on the post1-test, while three students were unable to answer any questions correctly. Nevertheless, in all completed learning modules there was either no discernible increase in learning between post1-and post2-tests (e.g., "temperature and heat" module), or the score on the post2-test was actually lower than on the post1-test (e.g., "polar bear" by 1% or "heat transfer" by 2%). The module on "polar bear" showed the most increase in learning with 41% improvement. This was followed by the "heat transfer" module (23%) and the "temperature and heat" module (13%). The results indicate that the "polar bear" module produced the best results for the post1-and post2-tests, while the "heat transfer" module performed better in the pre-test. The pre-test result was actually 2% better than the post1-and post2-test results for the "temperature and heat" module (Figure 6B). A comparison between the different learning modules revealed that the "polar bear" and "heat transfer" modules exhibited a significant increase in learning compared to the "temperature and heat" module ("polar bear" vs. "temperature and heat": $p^{****} < 0.0001$, "heat transfer" vs. "temperature and heat": $p^{****} = 0.0001$), whereas the difference in learning between the "polar bear" and "heat transfer" modules was not found to be significantly different ($p = 0.588$, *n.s.*) (Figure 6C). In conclusion, the learning modules from the Area9 Lyceum Rhapsode learning platform resulted in topic-related learning gains for the students.

3.5.1 Results summary

The results of this study provide valuable insights into the effectiveness of the adaptive learning platform and learners' responses. The key findings are summarized below.

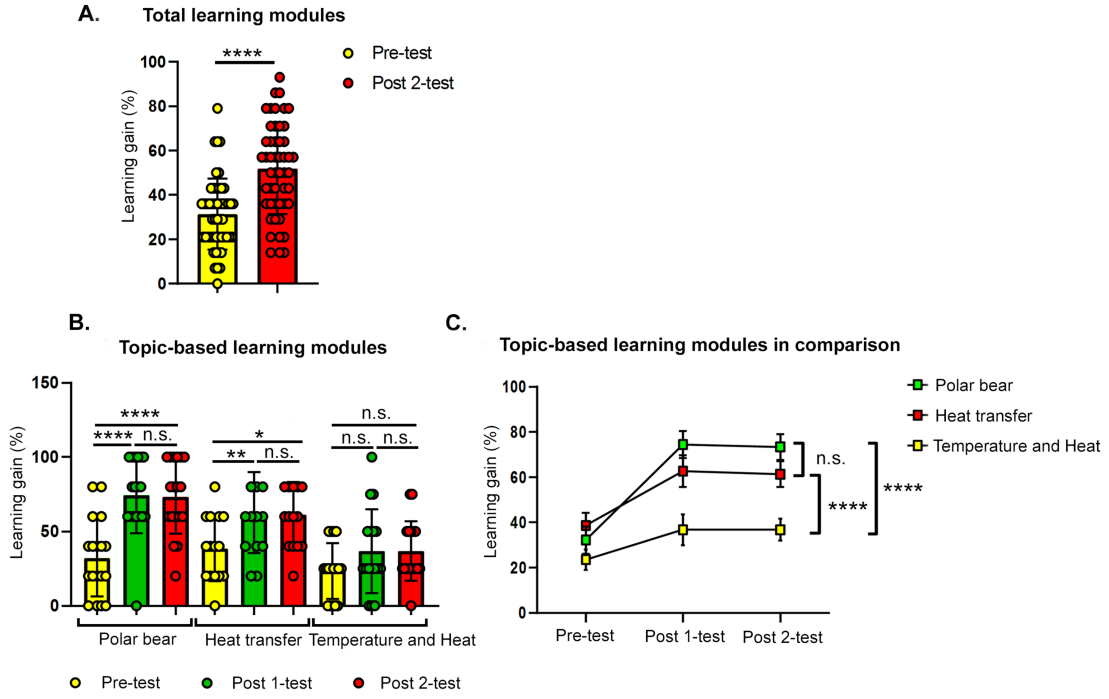

FIGURE 6
The learning modules on the Area 9 Lyceum Rhapsode platform lead to topic-related learning gain for the students. **(A)** Learning gains (%) of all learning modules (total) after pre-and post2-test. Pre-test: M = 31.42 (95% CI: [26.87, 35.97], SD = 16.00; post2-test: M = 51.86 [95% CI: 46.01, 57.71], SD = 20.59; t = 6.821, df = 49, critical t = 2.009 (α = 0.05). **(B)** Learning gains (%) from pre-, post1-and post 2-test of the topic-based modules "polar bear", "heat transfer" and "temperature and heat" modules. *Polar bear*: pre-test: M = 32.22 [95% CI: 19.39, 45.05], SD = 25.79; post1-test: M = 74.44 [95% CI: 61.77, 87.12], SD = 25.49; post2-test: M = 73.33 [95% CI: 61.03, 85.63], SD = 24.73, effect size Cohen's d = 1.65 (pre-and post1-test), effect size Cohen's f = 0.775. Large effects according to Cohen (1992). Repeated measures one-way-ANOVA: $F_{(2, 34)}$ = 29.64, critical F = 3.28 (α = 0.05), p**** < 0.0001; Tukey multiple comparison *post-hoc*-test: pre-test vs. post1-test: p**** < 0.0001; pre-test vs. post2-test: p**** < 0.0001; post1-test vs. post2-test: p = 0.74, *n.s. Heat transfer*: pre-test: M = 38.67 [95% CI: 26.49, 50.85], SD = 22.00; post-1 test: M = 62.67 [95% CI: 47.65, 77.68], SD = 27.12; post-2 test: M = 61.33 [95% CI: 49.15, 73.51], SD = 22.00, effect size Cohen's d = 0.97, effect size Cohen's f = 0.462. Large effects according to Cohen (1992). Repeated measures one-way ANOVA: $F_{(2, 28)}$ = 6.434, critical F: 3.34 (α = 0.05), p** = 0.005, Tukey multiple comparison *post-hoc*-test: pre-test vs. post-1 test: p** = 0.0094, pre-test vs. post2-test: p* = 0.0145, post1-test vs. post 2-test: p = 0.9825, *n.s.*). *Temperature and heat*: pre-test: M = 23.53 [95% CI: 13.92, 33.14], SD = 18.69; post-1 test: M = 36.76 [95% CI: 22.31, 51.22], SD = 28.11; post2-test: M = 36.76 [95% CI: 20.48, 47.05] SD = 20.00, effect size Cohen's d = 0.55, effect size Cohen's f = 0.275. Moderate effect according to Cohen (1992). Repeated measures-one-way ANOVA: F(2, 32) = 2.37, critical F: 3.284, p > 0.11, *n.s.*, Tukey-multiple comparison *post-hoc*-test: pre-test, post1-test, post2-test: p > 0.05, *n.s.* **(C)** A comparison of learning gains (%) of topic-based learning modules. Two-way repeated measures ANOVA: Mauchly's test indicated a violation of the sphericity assumption (p < 0.05). A Greenhouse–Geisser correction was applied to adjust the degrees of freedom. Main Effect of Time (pre-test, post1-test, post-2 test): F (1.983, 91.10) = 28.45, p**** < 0.0001, Main effect of group (learning module): $F_{(2, 47)}$ = 11.70, p**** < 0.0001, Interaction effect (Time × Group): $F_{(4, 94)}$ = 3.067, p* = 0.0201, variance between subjects: $F_{(47, 94)}$ = 2.360, p*** = 0.0002, accounting for 33.46% of the total variance. Tukey's multiple comparison *post-hoc*-test: "polar bear" vs. "temperature and heat": Mean difference: 27.65 [95% CI: 14.79, 40.50], p**** < 0.0001; "heat transfer" vs. "temperature and heat": Mean difference: 21.78 [95% CI: 9.896, 33.84], p**** = 0.0001; "polar bear vs. heat transfer": Mean difference: 5.778 [95% CI: −8.004, 19.56], p = 0.580, *n.s.*

The analysis revealed that digital media, particularly learning software, significantly increased student motivation (RQ1). For example, 75% of students reported greater motivation when using digital technologies, and 98% showed a heightened willingness to acquire knowledge when lessons were complemented by apps, games, or simulations (Figure 2A). The majority of participants (81%) preferred a hybrid approach that combines traditional and digital teaching methods, while 40% opposed digital-only teaching (Figure 2B). Additionally, 82% expressed a desire for teachers to make greater use of digital technologies (Figure 2C), and 59% of students preferred personal feedback from teachers over feedback provided by learning programs (30%, Figure 2D).

Beyond the classroom, students demonstrated diverse patterns of digital media use in their leisure time (Figure 3A). A significant proportion (59%) used digital media for educational purposes for <1 h per day, while smaller numbers allocated 1–2 h (21%) or more. Conversely, entertainment activities such as video consumption and gaming showed higher engagement. For example, 54% of students watched videos for <1 h daily, but 29% spent 1–2 h and 12% spent over 2 h. Gaming followed a similar trend, with 57% playing for under an hour daily and 30% engaging for 1–2 h. The overall data reflect a nuanced integration of digital media into students' daily lives, with educational use being moderate compared to entertainment.

Regarding emotions (RQ2), the digital learning platform received predominantly positive feedback: 62% of students reported feelings of pleasure and satisfaction during use, though 38% experienced some uncertainty (Figure 4A). The analysis of positive and negative emotions showed that positive emotions (62%) significantly outweighed negative ones (35%, Figure 4B). The platform's usability was rated with a SUS score of 66, slightly below the average benchmark of 68 (Figure 4C).

Furthermore, the platform fostered cognitive activation and situational interest (RQ3) by promoting independent problem-solving, critical thinking, and the application of new knowledge in various contexts. Tasks that required reflection and creativity were particularly well-received (Figure 5B). The platform was also effective in capturing students' attention, helping them understand complex topics, such as thermal insulation in polar bears, and increasing concentration levels (Figure 5C). A significant portion of learners found digital learning more engaging than traditional teaching methods.

Finally, performance data showed a significant learning gain (RQ4). Across all modules, the total learning gain as measured by pre-and post-tests was 21% (Figure 6A). Among the individual modules, the "polar bear" module achieved the highest improvement (+41%), followed by "heat transfer" (+23%) and "temperature and heat" (+13%) modules (Figure 6B). Comparisons of learning gains across modules (Figure 6C) revealed that both the "polar bear" and "heat transfer" modules resulted in significantly greater improvements than the "temperature and heat" module ($p < 0.0001$ for both comparisons). The difference in learning outcomes between "polar bear" and "heat transfer" modules was not statistically significant.

4 Discussion

This study aimed to evaluate the implementation of the adaptive learning platform Area9 Lyceum Rhapsode in secondary science education, focusing specifically on its application in bionics, a novel and interdisciplinary subject area. By addressing the gap between theoretical advancements in adaptive learning and their practical application in real-world classroom settings, the research investigated how the platform fosters situational interest, cognitive activation, and learning gains. The study also explored students' attitudes toward digital media (RQ1), their emotional responses and the usability of the platform (RQ2), the platform's capacity to stimulate cognitive engagement and situational interest (RQ3), and its impact on learning outcomes (RQ4). These insights provide a basis for understanding the potential of adaptive learning systems in STEM education.

> RQ1: What are students' attitudes toward the use of digital media in the classroom and their experiences with digital media in their leisure time?

The results of the pre-test show that the majority of students have a positive attitude toward the use of digital media in the classroom. Furthermore, they perceive it to be not only beneficial but also motivating. An analysis of digital media use in educational institutions reveals an increase in use in schools even before the coronavirus pandemic (Lorenz et al., 2022). Despite recent developments, the 2018 ICILS study indicates that Germany still has some catching up to do internationally (Eickelmann et al., 2019; Drossel et al., 2019). Nevertheless, there is reason for optimism as the 2021 country indicator demonstrates that an encouraging 38.9% of teachers in Germany utilize computers in class on a daily basis, representing a significant increase from the 2017 indicator (Lorenz et al., 2022). The early years of the coronavirus pandemic saw a surge in digitalization, characterized by an increased use of digital media, particularly in distance learning and dual training (Eickelmann and Gerick, 2020; Eickelmann et al., 2020). Recent studies have demonstrated that, even following the resumption of face-to-face teaching, the use of digital media has continued to increase in comparison to pre-pandemic levels. This is corroborated by the study by Mußmann (Mußmann, 2021), which revealed that 89.5% of the teachers surveyed ($N = 2,671$) utilize digital media in the classroom at least once a week. Nevertheless, it is crucial to highlight that the frequency of media use alone cannot be employed to infer the quality of media use in an educational context (Backfisch et al., 2021). To understand the role of motivation in students' attitudes toward digital media, we chose the Bertelsmann Foundation Model (Bertelsmann Foundation, 2017) as the theoretical framework for our study. This model conceptualizes motivation as a multifactorial construct influenced by intrinsic and extrinsic factors, as well as environmental and structural elements. Its specific emphasis on external factors such as task design, feedback, and system adaptability makes it particularly suitable for investigating intelligent virtual tutoring systems. For example, adaptive systems that provide immediate feedback and adjust task difficulty can directly address motivational needs by enhancing students' perceived competence and engagement (Hillmayr et al., 2017). While the Bertelsmann Foundation Model was prioritized in this study, the Self-Determination Theory (SDT) provides a complementary perspective on motivation. SDT emphasizes intrinsic and extrinsic motivation, focusing on autonomy, competence, and relatedness as core psychological needs (Ryan and Deci, 2000). However, its central focus on autonomy and social relatedness is less directly applicable to adaptive learning systems, which primarily aim to enhance competence through personalized feedback and difficulty adjustments. For this reason, the Bertelsmann Foundation Model offers a more comprehensive framework for analyzing the specific motivational mechanisms relevant to intelligent digital systems (Bertelsmann Foundation, 2017). The findings of our study support this theoretical approach. Students reported feeling more motivated when digital media were used in ways that aligned with the Bertelsmann Foundation Model's principles, such as by integrating interactive elements, multimedia content, and personalized feedback. This aligns with previous research demonstrating the motivational benefits of well-designed digital learning environments (Nooriafshar, 2007; Hillmayr et al., 2017). Our findings indicate that while digital media can be an effective tool in the classroom, it should not be the sole means of instruction. Instead, a combination of digital and conventional learning methods is recommended to enhance the effectiveness of teaching and learning (Nooriafshar, 2007). A meta-study conducted by Hillmayr et al. (2017) demonstrated a positive impact of digital teaching materials, particularly when used in conjunction with traditional materials. This resulted in increased motivation across all STEM subjects. Students in our study reported daily use of digital media, expressing a strong preference for its integration into the classroom. Digital media were found to enhance student engagement, facilitate personalized learning, and improve access to a diverse range of resources. Moreover, the incorporation of interactive and multimedia content was shown to illustrate complex issues and improve understanding. Digital media also promote collaboration and communication between students and teachers, overcoming temporal and spatial constraints. However, the study also revealed

potential risks. Excessive screen time was reported by a small proportion of students, raising concerns about its negative impacts on physical and mental health. Research links prolonged screen use to neck and back pain (Azevedo et al., 2023), obesity (Fang et al., 2019; Khajeheian et al., 2018; Zhang et al., 2016), sleep disturbances (Parent et al., 2016), and depressive symptoms (Hoare et al., 2016; Suchert et al., 2015). Additionally, the distraction posed by social media can affect learning outcomes.

Based on the findings, RQ1—What are students' attitudes toward the use of digital media in the classroom and their experiences with digital media in their leisure time?—can be confidently answered. Students exhibit a predominantly positive attitude toward the use of digital media in the classroom, citing its benefits for engagement, motivation, and personalized learning. They also frequently use digital media in their leisure time, which aligns with their preference for its integration into educational contexts.

However, the study also highlights critical challenges, including the potential negative health effects of excessive screen use and the risk of distraction. These findings underscore the importance of balanced digital media usage, integrating both digital and traditional learning methods to maximize benefits while mitigating risks. While digital media have transformative potential, their effectiveness ultimately depends on thoughtful implementation and an emphasis on media literacy to prepare students for responsible use.

> RQ2: What are student's emotions and attitudes toward the usability of the digital learning environment?

The results of this study indicate that positive emotions, such as pleasure and satisfaction, outweigh negative emotions, such as frustration, stress, and uncertainty when using the digital learning environment. According to Pekrun and Stephens (2010), emotions play an essential role in the development of key competencies, performance-enhancing cognitions, and motivation, making them central to the teaching and learning process. Positive emotions are associated with enhanced learning efficiency and improved cognitive processing (Hinton et al., 2008), whereas negative emotions have been shown to reduce learning efficiency and impair memory performance (McLeod and Fettes, 2007). The findings highlight a predominantly positive emotional response among students, with many expressing satisfaction and pleasure while using the platform. These emotions likely stem from the interactivity and adaptive features of the learning environment, which align with research suggesting that personalized feedback and engaging design can promote intrinsic motivation and satisfaction (Ryan and Deci, 2000). However, a significant proportion of learners reported experiencing uncertainty during their interaction with the digital platform. This uncertainty warrants closer examination, as it can hinder the formation of positive emotions and may reduce the effectiveness of the learning experience. Feedback from the System Usability Scale (SUS) and open-ended responses from feedback questionnaires suggest that the structure and navigation of the digital learning platform may contribute to these feelings. Poorly designed interfaces or unclear navigation can create cognitive overload, which is a common barrier to effective learning in digital environments (Hattie and Donoghue, 2016). Moreover, research on emotional design in multimedia learning shows that factors such as color, shape, and layout can influence emotional responses and subsequent learning outcomes (Plass et al., 2014). Future research should aim to disentangle the specific factors driving uncertainty, such as unclear instructions, overly complex navigation, or insufficient scaffolding for less confident users. The usability of the digital learning environment was assessed using the System Usability Scale (SUS), a validated metric for evaluating system usability (Brooke, 1996). The SUS score of 66 falls slightly below the established average score of 68, as reported by Sauro (2011). While Bangor et al. (2009) classify a score of 66 as being in the "upper critical range," this result still highlights areas for improvement, particularly when considering the specific needs of a younger user group. The feedback identified several usability issues, including poor display quality on iPads, which is a critical limitation given their widespread use in schools in North Rhine-Westphalia, Germany. Device compatibility significantly influences user satisfaction and learning outcomes in digital environments (Virtanen et al., 2017). Optimizing the platform for iPads and other commonly used devices in schools could help alleviate some of the uncertainty reported by students and improve the overall usability of the platform. Additionally, research shows that poor usability can negatively impact emotional engagement, further emphasizing the need for structural improvements to foster a seamless learning experience (Plass et al., 2014). The interplay between emotional responses and usability underscores the importance of a well-structured digital learning environment. Positive emotions, such as satisfaction and pleasure, are closely linked to ease of use and effective task completion. Conversely, uncertainty and frustration often stem from usability challenges, as seen in the suboptimal SUS score and specific feedback regarding navigation and compatibility issues. These findings align with research showing that usability is a critical determinant of emotional engagement in digital learning environments (Pekrun and Stephens, 2010; Hattie and Donoghue, 2016).

The results of this study partially answer RQ2—What are student's emotions and attitudes toward the usability of the digital learning environment?—. Students' emotions toward the digital learning environment were predominantly positive, with pleasure and satisfaction outweighing frustration, stress and uncertainty. However, the observed usability challenges, particularly the suboptimal SUS score and device compatibility issues, indicate areas requiring improvement. These findings suggest that while the digital platform effectively supports positive emotional engagement for many students, targeted enhancements in usability and structural clarity are essential to fully address student needs. By improving the design and functionality of the digital learning environment, it is possible to foster both emotional engagement and usability, thereby maximizing its effectiveness as a teaching and learning tool.

> RQ3: Is the digital learning environment cognitively stimulating and can it arouse situational interest in students?

Cognitive activation is a fundamental component of high-quality teaching that encourages students to engage deeply with the content at a level appropriate to their individual needs (Minnameier et al., 2015; Kunter et al., 2005; Groß-Mlynek et al., 2022). Such activating learning opportunities are shown to positively influence learning outcomes (Fauth and Leuders, 2018).

In this study, 66% of the participating students reported that cognitive activation strategies were an integral part of the bionics

TABLE 2 Cognitive activation.

During my lessons with the digital learning platform...		
	Bionic-project*	PISA in practice**
1 …I was encouraged to consider problems.	58%	69%
2 …I was assigned tasks that required extended time of thinking.	62%	72%
3 …I was encouraged to develop my own solutions.	65%	46%
4 …various tasks were presented in different contexts.	65%	67%
5 …I received assistance in learning from mistakes I have made.	69%	78%
6 …I was prompted to explain how I solved a problem.	52%	83%
7 …I was encouraged to apply what I have learned to new contexts.	81%	73%
8 …I was assigned tasks that can be solved in several different ways.	72%	66%
Total	66%	69%

*Results for "tend to agree", "agree" and "strongly agree". **Results for "often", "almost always" and "always".

lessons delivered through the Area9 Lyceum Rhapsode digital learning environment. This rate is slightly below the 69% reported in the *PISA-in-Practice* study (Burge et al., 2015), indicating that the Area9 Lyceum Rhapsode system provides cognitive activation opportunities comparable to those observed in other educational settings (Table 2). However, notable differences were observed between the bionics study and the *PISA-in-Practice* study in specific dimensions of cognitive activation. For instance, in the bionics study, the proportion of students who agreed with the statements "to be considered about problems" (statement 1) and "explain the solution" (statement 6) was only 58 and 52%, respectively. These results contrast with the agreement rates of 69 and 83% reported in the *PISA-in-Practice* study (Burge et al., 2015). Conversely, higher approval rates were observed for "developing one's own solutions" (statement 3) and "applying newly acquired knowledge in other contexts" (statement 7), with agreement rates of 65 and 81%, compared to 46 and 73% in the *PISA-in-Practice* study. These findings suggest that while the digital learning environment excels in fostering the application of knowledge, it could benefit from improvements in tasks requiring extended reflection and solution explanation.

Interest has been consistently recognized as a critical intrinsic factor driving student motivation and learning (Potvin et al., 2023). Research demonstrates that interest influences numerous cognitive processes, including reading comprehension, attention, information processing, and problem-solving (Hidi and Renninger, 2006; Schraw and Lehman, 2001). Situational interest, a short-term motivational state arising from engaging and stimulating contexts, can evolve into personal interest with sustained exposure and relevance, thereby exerting a long-term influence on learning outcomes (Renninger and Hidi, 2016).

In this study, 73% of students agreed that the digital learning environment fostered situational interest, aligning with previous research showing that well-designed digital platforms can enhance cognitive and emotional engagement (Moon et al., 2020). Sensors and adaptive algorithms in such environments can play a key role in tracking and supporting emotional engagement, which is crucial for maintaining motivation and curiosity (Apostolidis and Tsiatsos, 2011). Furthermore, personalized adaptation has been shown to increase not only cognitive flexibility but also sustained interest by tailoring tasks to individual learning profiles (Zhang and Goh, 2021). However, future studies should validate these findings using instruments such as those developed by Potvin et al. (2023) to ensure their generalizability across diverse digital platforms.

Emotional factors played a pivotal role in our study: 62% of students reported experiencing positive emotions such as pleasure and satisfaction while using the adaptive learning platform (Figure 4A). Such emotions are critical for fostering situational interest by triggering spontaneous curiosity and intrinsic motivation. Research highlights the importance of emotional experiences in creating positive valences that enhance engagement and deepen learning (Schiefele, 1991; Krapp, 2005). Adaptive systems further enhance this effect by personalizing content delivery, which strengthens the emotional connection to the material. For instance, personalized and emotionally engaging contexts have been shown to support intrinsic motivation and sustained interest, particularly when learners can relate the material to their goals and needs (Renninger, 2000).

Value-based factors also contributed to sustaining student interest. By presenting content in meaningful and relevant contexts, the platform allowed learners to recognize the utility and applicability of the material to their academic and personal goals. This alignment with learner values has been shown to play a crucial role in maintaining long-term engagement (Eccles and Wigfield, 2002).

Epistemic factors, such as novelty and the balance between challenge and achievability, are also significant. While novelty sparks curiosity and situational interest, dynamically tailoring content to the learner's cognitive level often helps sustain this interest by creating "flow experiences," characterized by heightened motivation and immersion (Csikszentmihalyi, 1990). However, research indicates that situational interest triggered by epistemic factors is less sustainable compared to interest supported by emotional or value-based influences (Schmidt and Rotgans, 2021). Studies show that situational triggers, such as novelty or utility-focused tasks, are effective in generating short-term interest but often insufficient to maintain long-term engagement (Hulleman et al., 2010; Bergin, 1999).

The results of this study indicate that the digital learning environment is cognitively stimulating and effectively arouses situational interest in students. With 73% of students acknowledging increased situational interest and 66% reporting cognitive activation strategies, the platform demonstrated its capacity to engage students cognitively and emotionally. While there is room for improvement in fostering deeper reflective thinking and providing explanation-based tasks, the overall findings

affirm that the digital learning environment addresses the requirements posed by RQ3—Is the digital learning environment cognitively stimulating, and can it arouse situational interest in students?—. Emotional factors emerged as the most influential, followed by value-based factors, with epistemic factors providing complementary support. These results emphasize the importance of designing adaptive digital platforms that balance cognitive, emotional, and motivational elements to maximize student engagement and learning outcomes.

> RQ4: Does the digital learning environment facilitate enhanced learning gains?

The results unequivocally confirm that the digital learning environment significantly facilitated learning gains across the three modules.

A Chi-square test was conducted to determine whether the random assignment resulted in an even distribution of genders across the modules. The test revealed no statistically significant difference in gender distribution [$\chi^2(2) = 1.45$, $p = 0.484$], indicating that the assignment process successfully created balanced groups. Although the gender distribution was statistically even, potential gender-based differences in prior knowledge, engagement, or confidence in science-related topics could still influence learning outcomes. Previous studies suggest that such differences are more likely to arise from cultural and educational factors rather than intrinsic ability differences (Stoet and Geary, 2018; Hyde, 2005). For example

- *Polar bear module*: The high learning gain of 41% suggests that the content was equally engaging and accessible to all genders.
- *Heat transfer module*: The lower learning gain of 23% might reflect differences in familiarity with physics-related topics, which may stem from prior educational exposure.
- *Temperature and heat module*: The learning gain of 13% could be attributed to the challenges posed by abstract thermodynamic concepts, which may require tailored pedagogical strategies to support diverse learning styles.

Future research should examine gender-specific preferences and strategies to better understand their influence on learning outcomes.

The "polar bear" module exhibited the highest learning gain (41%) and a post-2 test score of 73% [$F_{(2, 34)} = 29.64$, $p^{****} < 0.0001$]. These results, supported by a very large effect size ($d = 1.65$) and a sufficient sample size ($N = 18$), indicate robust learning outcomes. The success of this module aligns with theories of multimedia learning, which emphasize the importance of clearly structured content aligned with prior knowledge (Mayer, 2009; Clark and Mayer, 2016). However, challenges with Bergmann's Rule highlight gaps between theoretical knowledge and practical applications. Scaffolding strategies, such as breaking down complex concepts into manageable steps, could help bridge these gaps (Hattie and Donoghue, 2016). Similarly, the limited understanding of the light conduction hypothesis underscores the need to align content more closely with curriculum goals and relevance.

The "heat transfer" module achieved a learning gain of 23% and a post-2 test score of 61% [$F_{(2, 28)} = 6.434$, $p^{**} = 0.005$]. The observed large effect size ($d = 0.97$) and sufficient sample size ($N = 15$) confirm the robustness of these findings. The success in understanding thermal radiation (82% correct responses) demonstrates the effectiveness of targeted content design, as highlighted in previous research on task-specific learning (Hattie and Donoghue, 2016). However, the absence of questions on thermal conductivity limits the comprehensiveness of the assessment. Future studies should ensure that all key concepts are adequately covered to avoid potential gaps in understanding (Perkins and Salomon, 1992).

The "temperature and heat" module posed the greatest challenge, with a learning gain of 13% and a post-2 test score of 37% [$F_{(2, 32)} = 2.365$, $p = 0.1102$, *n.s.*]. While the medium effect size ($d = 0.55$) suggests some progress, the sample size ($N = 17$) was below the recommended threshold for medium effects ($N = 34$). The limited progress in this module highlights the difficulties students faced with abstract thermodynamic concepts. Transfer tasks, with only 22% correct responses, further illustrate the need for clearer task framing and more scaffolding (Perkins and Salomon, 1992). Although the Chi-square test indicated an even gender distribution, future research should investigate whether gender-based preferences or cognitive strategies influence performance on abstract scientific topics (Hyde, 2005).

The absence of additional learning gains between post-1 and post-2 tests, combined with slight decreases (1–2%), suggests declining attention or engagement over time. This emphasizes the importance of incorporating strategic breaks to maintain motivation and focus (Fredricks et al., 2004; Deci and Ryan, 1985).

The significant interaction between time and module [$F_{(4, 94)} = 3.067$, $p^* = 0.0201$] highlights the need for module-specific instructional strategies. For example, while the "polar bear" module benefited from alignment with prior knowledge, the "temperature and heat" module faced challenges due to content complexity and insufficient scaffolding.

The evidence supports RQ4—Does the digital learning environment facilitate enhanced learning gains?—, confirming that the digital learning environment facilitated enhanced learning gains overall. However, variability across modules underscores the importance of thoughtful content design, sufficient sample sizes, and attention to potential gender-specific dynamics. While random assignment ensured an even gender distribution, nuanced differences in engagement or comprehension may still influence outcomes in specific modules.

4.1 Limitations and future directions

Adaptive digital learning environments are of significant importance in modern education as they have been demonstrated to enhance the learning process. However, it is important to note that the present study is subject to certain limitations that must be taken into account for a comprehensive evaluation of the results. While this study provides valuable insights into the effectiveness of the Area9 Lyceum Rhapsode platform in secondary science education, several limitations must be acknowledged, particularly regarding the generalizability of the findings. Firstly, the sample size, comprising 56 students from two grammar schools in Germany, limits the ability to generalize the results to broader populations. This relatively small and localized sample could restrict the applicability of the findings to students in other educational institutions or regions with different socioeconomic, cultural, or educational contexts. For example, students from schools in rural or less

technologically advanced regions might have less positive experiences with the platform due to potentially lower digital competencies or limited access to digital devices (Mertens, 2010). Consequently, the conclusions drawn from this study may not fully account for variations in student experiences across diverse learning environments. Future studies should aim to include larger and more diverse samples to validate and extend the findings across varied educational settings. Moreover, the demographic composition of the sample—including a majority of students aged 11 years and a smaller group aged 12—further constrains the scope of the findings. It remains unclear how the platform's effectiveness might vary among older or younger students, particularly those with different learning needs or varying levels of familiarity with digital tools. For instance, older students might benefit more from the platform as they may possess more advanced cognitive abilities required to utilize adaptive learning platforms effectively (Hattie and Donoghue, 2016; Schiff and Vakil, 2015). Motivational differences between age groups could also significantly affect the use and outcomes of the platform (Ryan and Deci, 2000). Expanding research to include diverse age groups, socioeconomic backgrounds and cultural contexts would provide a more comprehensive understanding of the platform's adaptability and impact. Additionally, this study focused exclusively on the subject of bionics in science education. While this allowed for a detailed exploration of a novel and interdisciplinary topic, the findings may not directly translate to other subjects or disciplines. Future research should investigate the applicability and effectiveness of the platform across a wider range of subjects to establish its broader educational success. A major limitation arises from technical issues that affected both user interaction with the platform and the overall progress of the project. Specifically, technical errors prevented learners from completing required steps, thereby hindering progression to subsequent tasks. These technical issues disrupted the learning process and potentially affected the effectiveness of the digital learning environment and the learning outcomes achieved. For instance, the iPads used during the project experienced challenges related to technical and compatibility issues, including difficulties in completing tasks due to control elements not being fully optimized for smaller screens. Additionally, text input on iPads occasionally proved problematic, with the keyboard moving unexpectedly or text being inadvertently deleted. These experiences highlight the challenges of using digital educational technologies and emphasize the need for robust and intuitive systems. Future research could address these limitations by employing a larger and more diverse sample size to enhance the representativeness of the findings. Additionally, cross-cultural studies could explore how adaptive learning platforms perform in various educational systems and cultural contexts. For example, studies comparing students from different countries could provide insights into whether cultural differences affect the platform's acceptance and effectiveness (Arenas-Gaitán et al., 2011; Shadiev et al., 2021). Future research should also investigate how adaptive platforms can be tailored to meet the needs of students in resource-limited settings with varying levels of digital infrastructure. Expanding the demographic range of participants, including students from different age groups and educational levels, could provide deeper insights into the platform's adaptability and scalability. Longitudinal studies could further investigate the long-term impacts of adaptive learning by tracking whether the platform achieves sustainable learning outcomes and how its use evolves over multiple years. Incorporating more objective measures, such as classroom observations or automated analyses, could provide richer insights into student engagement and learning outcomes. By focusing on an interdisciplinary subject like bionics, this study uniquely demonstrates the potential of adaptive learning platforms to foster cognitive activation and situational interest in underexplored STEM domains. These findings emphasize the need for future research to investigate the transferability of these results across a variety of subjects and diverse educational contexts. Furthermore, a targeted investigation into the scalability of adaptive platforms in resource-limited environments could provide practical pathways for broader application. Addressing these limitations presents a clear opportunity for improvement. Optimizing compatibility between desktop and iPad versions, ensuring control elements are easily accessible, and refining the text input experience would significantly improve usability and efficiency. These adjustments would facilitate smoother workflows and create a more seamless learning experience for students. Necessary adjustments to the project plan and the use of alternative equipment were made due to delays caused by extended processing times and technical shortcomings. This underscores the importance of flexible planning and reliable technology. It should be noted that the small sample size of our pilot study limits the statistical significance of our results. To gain a more comprehensive understanding of students' preferences and learning outcomes, future studies should aim for larger sample sizes and specifically adapt the survey instruments to replicate results with higher statistical power. Additionally, the proposed longitudinal studies and cross-cultural comparisons should specifically aim to examine the transferability of the results to various educational contexts. This could help develop a more robust understanding of how such platforms can address diverse demographic and cultural needs. A clear description of potential pathways for adapting the platform to scale to broader applications would also contribute to improved generalizability of the results.

4.2 Addressing gaps in the literature

The introduction identified several gaps in the existing literature on adaptive learning platforms and their application in real classroom contexts. This study contributes to bridging these gaps and generating new insights in educational research. Previous studies on adaptive learning systems have predominantly focused on controlled laboratory settings, limiting the transferability of findings to everyday school environments. Our findings uniquely demonstrate that the Area9 Lyceum Rhapsode platform can be successfully integrated into students' daily routines, promoting both cognitive activation and situational interest. This bridges the gap between controlled laboratory research and practical, everyday classroom applications, providing evidence of adaptive platforms' effectiveness in authentic educational settings (Rzepka et al., 2023). Another contribution of this study lies in applying the platform to a novel and interdisciplinary topic: bionics. Bionics represents a complex, innovative STEM topic that challenges traditional learning approaches, making it an ideal context for testing adaptive platforms. While adaptive systems have been examined in traditional subjects such as mathematics (Sjaastad and Tømte, 2018) or language learning (Ahmed and Ibrahim, 2023; Kaur et al., 2023) a systematic analysis of their potential in complex interdisciplinary contexts has been lacking. Our findings show that adaptive learning platforms can enhance students' situational interest in an innovative topic like bionics while simultaneously fostering cognitive processes. This provides valuable insights for

integrating such systems into modern curricula and demonstrates their adaptability to underexplored STEM areas. The literature highlights that situational interest and cognitive activation are key factors for successful learning. However, there is a lack of empirical studies investigating these factors in connection with adaptive platforms. Our results address this critical research gap by demonstrating that the platform significantly enhances situational interest through personalized content and cognitive activation through adaptive feedback. These findings advance the understanding of how adaptive learning systems can positively influence key learning outcomes, providing a foundation for further studies in this area. Another gap pertains to the investigation of technical and organizational challenges in the implementation of adaptive systems. Our study documents specific obstacles, such as device compatibility and technical errors, and offers practical suggestions for optimization. For example, ensuring compatibility across devices and refining text input mechanisms could enhance usability and efficiency. This not only delivers theoretical insights but also pragmatic solutions for the implementation of such systems in practice. These recommendations highlight how addressing technical limitations can improve the scalability and generalizability of adaptive learning platform. Through these contributions, this study not only fills critical gaps in the literature but also provides a framework for future research. These findings provide a foundation for future studies to explore the adaptability of such platforms in varied educational systems and cultural contexts. Investigating adaptive systems in more diverse educational contexts, exploring additional interdisciplinary topics, and addressing technical challenges will further enhance the understanding and application of these platforms in modern education.

5 Conclusion

The Area9 Lyceum Rhapsode adaptive learning platform was successfully integrated into students' everyday school life, receiving overwhelmingly positive feedback despite some implementation challenges. A 21% increase in learning success from pre-test to post2-test, along with favorable emotional responses and a preference for the digital environment, demonstrates the platform's potential to promote cognitive activation and situational interest in real-world classroom settings. Most students expressed interest in using such systems more frequently and recommended the platform to others. These findings underscore the importance of adaptive learning environments in modern education but also highlight areas for improvement. Notably, the study's small and localized sample limits the generalizability of the results. Technical challenges, including device compatibility and usability issues, further emphasize the need for robust, intuitive designs to ensure a seamless user experience. Addressing these limitations through larger and more diverse sample sizes, cross-cultural research, and technical refinements will enhance the evidence base and applicability of such platforms. This study also makes significant contributions to the literature by bridging the gap between theoretical advancements and practical implementation of adaptive platforms. By focusing on a novel, interdisciplinary topic-bionics-this research highlights the potential of adaptive learning platforms to foster situational interest and cognitive activation in underexplored STEM areas. These findings build on existing research into adaptive learning environments (Wu et al., 2023) and provide unique insights into their real-world application in interdisciplinary topics such as bionics. These findings lay the groundwork for further research into adaptive learning platforms across diverse educational contexts and curricula, ensuring their scalability and sustainability in modern classrooms.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was obtained from the participant's legal guardians or next of kin.

Author contributions

NH: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. SB-G: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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