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Exploration of an adaptive e-learning environment's effectiveness for teaching specialized topics in number theory

Theses of doctoral (PhD) dissertation

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Topic and structure of the dissertation

This dissertation centers on an educational science research project situated at the intersection of digital pedagogy and mathematics education. The global transformation of educational systems underscores the topical relevance of this study, highlighting the impact of digitalization and the growing demand for adaptive technological solutions that cater to learner diversity. The primary objective of the research is to develop and evaluate the effectiveness of an Adaptive Electronic Learning Environment (AES), with a particular focus on teaching number theory at the secondary and higher education levels—an area of mathematics that is often underrepresented in curricula yet holds significant importance.

The selection of this topic is justified by several factors. On the one hand, pedagogical experience indicates that number theory is scarcely addressed in secondary school curricula. On the other hand, the learning habits and motivational characteristics of digital natives differ markedly from those of previous generations. The mere proliferation of technological tools does not guarantee educational effectiveness; instead, adaptive systems are needed—ones that can take into account learners' backgrounds, prior knowledge, and individual learning styles. This dissertation aims to design, implement, and evaluate such a system in terms of its pedagogical impact and practical usability.

The structure of the dissertation follows the generally accepted framework of educational science research. The first chapter provides a detailed discussion of the study's relevance and significance, outlining the research problem within the context of academic theory. The research objectives, questions, and hypotheses are clearly formulated, providing a solid foundation for the design and execution of the empirical investigations.

The second chapter is dedicated to exploring the theoretical background, aiming to establish meaningful connections between the fields of pedagogy and information technology. The novelty of this chapter lies not only in the systematic review of the literature but also in its role in grounding both the theoretical and practical aspects of the system's development.

The third chapter provides a detailed description of the methods and tools used. In this section, the author presents the structure, functions, and didactic design of the self-developed Adaptive Electronic Learning Environment. A particular strength of this chapter is its dual focus: it not only describes the applied procedures but also reflects on their validity and limitations, thereby offering a reliable basis for interpreting the empirical findings presented in the following chapter.

The fourth chapter presents the research findings. In addition to statistical analyses, qualitative insights are also included to support a deeper interpretation of the results.

The fifth and sixth chapters offer the concluding reflections of the dissertation, addressing the validation of the hypotheses and the educational significance of the newly developed learning tool. The seventh chapter serves as a critical self-reflection, acknowledging the limitations of the research and proposing directions for the further development of adaptive learning systems.

Theoretical background of the research

In addition to traditional professional skills, there is a growing emphasis on the skills that allow technology and human thinking to work together. In the education system, this means that curricula must increasingly focus on developing 21st-century skills by introducing new methodologies and approaches.

Educating children in the digital age requires teachers to be able to adapt to technological advances while focusing on developing students' digital competencies. This means not only using tools, but also rethinking pedagogical methods and content (Lénárd, 2015). ICT tools are not merely tools for teaching, but can also serve as drivers for transforming the learning process when properly integrated into the educational system (Falus et al., 2012).

Bertalan Komenczi pointed out the importance of e-learning two decades ago, but stressed that it would remain an option unless pedagogical practice adapted to it (Komenczi, 2004).

In addition to general knowledge acquisition, one of the primary goals of e-learning is to develop professional skills and understanding that enable learners to achieve their learning objectives (Clark & Mayer, 2016).

The pedagogy of e-learning involves a deeper exploration of educational strategies that incorporate the adaptability of real-time, personalized learning content to the individual learner (Négyesi & Csernai, 2022).

Traditional e-learning systems, however, tend to ignore the diversity of learners, their abilities, knowledge and skills, as well as the learning context (Négyesi, 2023; Négyesi, 2021).

Adaptation has so far received very little attention in e-learning platforms, even though an e-learning course should not be designed in a vacuum, but should best meet the

needs and wishes of learners and adapt as the course progresses (Négyesi, 2023; Négyesi, 2021).

Adaptive systems aim to adapt traditional approaches to learning to the needs of learners (Essalmi et al, 2010).

In mathematics teaching, maintaining students' motivation is a key factor that significantly determines their engagement in the subject and their learning outcomes. Motivation not only influences attention and activity during lessons but also has a long-term impact on the development of learners' mathematical competences and attitudes towards the subject. Therefore, teachers need to adopt methodological approaches that help to maintain students' interest while taking into account individual differences and needs.

Csányi et al. (2014) note that for students abstraction is not only a barrier to comprehension, but can also reduce their interest in the subject. This is particularly noticeable in the case of concepts such as prime numbers, divisibility or the Euclidean algorithm, which require an abstract way of thinking.

The difficulties in teaching number theory in secondary schools stem not only from the content of the curriculum but also from shortcomings in pedagogical methodology and teacher training. Effective teaching requires the development of a methodological toolkit that maintains both student interest and motivation while providing opportunities for understanding and applying abstract concepts (Négyesi et al., 2023; Négyesi, 2021).

M. Nádasi Mária (2010) stresses that adaptivity is not only a technological approach, but also a pedagogical and methodological one. The basic principles of adaptive education include the use of differentiated learning strategies, continuous monitoring of learners' individual needs and the development of curricula to meet these needs. It also emphasizes that adaptivity is not solely focused on children's performance, but also involves a transformation of the teacher's role. The teacher is seen more as a facilitator, a mentor who helps the learner achieve their own learning goals.

Nóra Rapos et al (2011) focus on the relationship between adaptivity and inclusion. They point out that adaptive education is not only about personalising the curriculum, but also about embracing the diversity of learners and transforming the educational environment to enable all learners to learn successfully.

In adaptive e-learning, the concept of adaptation refers to the platform's ability to respond dynamically to learner performance and modify the learning experience accordingly (Négyesi et al., 2023).

Adaptive e-learning systems are significantly transforming educational environments, but they cannot replace the value and role of educators. Teachers have unique competencies that are irreplaceable in supporting the functioning of adaptive systems. Maintaining a balance between educators and technology is essential for achieving optimal educational outcomes. Only by integrating pedagogical and technological aspects can learning processes be truly optimised.

Research objectives, questions and hypotheses

The research objectives are articulated on multiple levels. At the theoretical level, the author explores elements of 21st-century learning theories and digital pedagogy that underpin the legitimacy and applicability of adaptive learning environments. Particular attention is given to the issues of personalized learning, self-regulation, and motivation, as well as to the interrelation between the pedagogical and technological dimensions of adaptivity.

At the empirical level, the research aims to present and evaluate the impact of a self-developed, responsive adaptive e-learning system (https://aes.negyesipeter.hu), designed according to didactic design principles, on student attitudes, performance, and motivation. To this end, the author employed a range of research methods, including questionnaires, log file analysis, eye tracking, usability testing, and attitude scales, which enabled a comprehensive evaluation of the system's effectiveness.

The practical goal of the research was to develop a digital learning tool tailored to the Hungarian secondary and higher education context, effectively supporting the understanding, practice, and application of number theory problems. Special emphasis was placed on the development of features that assist teachers, ensuring accessibility and mobile-friendly design, and the system's suitability for both in-class and out-of-class learning, supporting frontal, individual, pair, and cooperative learning formats alike.

In line with the research objectives outlined above, the author seeks to answer the following questions:

- Q1: Does the new adaptive learning environment, which is not yet widespread in our country, significantly improve students' attitudes towards numeracy topics?
- Q2: Does the new learning tool, through its content and methodological innovations, significantly improve students' understanding of number theory problems and the effectiveness of problem solving?

- Q3: How satisfied are students and teachers with the adaptive learning system?

Hypotheses related to research question Q1:

- H1: The use of a new teaching tool will significantly increase students' motivation to learn mathematics.
- H2: The use of the new learning tool will significantly improve students' confidence in solving number theory problems.
- H3: The use of the new learning tool significantly increases students' activity in the learning process.
- H7: The use of the new learning tool significantly increases students' independent learning skills.

Hypotheses related to research question Q2:

- H4: The use of the new learning tool significantly improves students' problem-solving skills.
- H5: The use of the new learning tool significantly reduces the error rate of students when solving problems in calculus.
- H6: The use of the new learning tool significantly improves students' time management skills during the learning process.

Hypotheses related to research question Q3:

- H8: According to Jakob Nielsen's assessment of the five usability factors, the created adaptive e-learning system achieves an average score of at least 4 for each of the measured factors, from both the learner and student perspectives.
- H9: The created adaptive e-learning system scores at least a four average on the Jakob Nielsen 5 usability factors for teachers and trainers for each of the measured factors.
- H10: Feedback from teacher colleagues demonstrates the necessity of using an adaptive e-learning environment in the teaching process.
- H11: The adaptive e-learning system will have significantly higher levels of student activity indicators after the study, indicating the effectiveness of the system.

Research phases, methods and tools

The research was structured into three main phases. The first phase was the preliminary study, aimed at mapping the needs of students and teachers, as well as conducting a literature review. In this phase, the author utilized online questionnaires and

conducted a systematic literature review focused on adaptive mathematics education. This phase served as the foundation for identifying what is genuinely needed in educational practice. In the second phase, the author employed action research to investigate both the needs of students and teachers, as well as the effectiveness of the developed adaptive e-learning system in real educational settings. The system was tested and refined over multiple cycles to ensure its optimal alignment with user expectations. The third phase involved a comprehensive set of research methods to evaluate the system's effectiveness. Students and teachers completed custom-designed online questionnaires; eye-tracking studies were conducted to explore learning styles; and logfile analysis was used to examine usage patterns. Additionally, web ergonomics and usability tests were performed based on Jakob Nielsen's usability heuristics. The entire research process was characterized by methodological triangulation: a combination of diverse methods was applied to gain a more comprehensive understanding of the system's impact and functioning.

The development of the system was based on the steps of the PADDIE+M model. The platform is fully accessible, thanks to the built-in tools provided by the UserWay plugin. It is accompanied by a task bank covering both intermediate and advanced levels, which can be continuously expanded. The learning materials and tasks are editable by teachers, ensuring that the platform remains adaptable and customizable in the long term.

The learning materials of the adaptive e-learning system cover six carefully selected topics in number theory. Students join the system via registration, after which they can enroll in specific courses. During the development of the content, didactic design principles were consciously applied. Access to the learning materials is sequential, ensuring the presence of prerequisite knowledge and supporting the principle of gradual progression. Each course includes theoretical explanations, formative check questions, and concludes with a final test. The final test is automatically evaluated, and the results determine the initial difficulty level of the tasks assigned to the learner in the next stage. Each set of tasks is available in five difficulty levels. The system monitors which sub-tasks the student struggles with and adjusts subsequent learning steps accordingly.

Theses

Based on the hypotheses validated through statistical methods during the research, the following new scientific findings can be formulated. These results not only support the effectiveness of adaptive e-learning systems but also guide the development of mathematics

education, particularly the teaching of number theory, the application of digital learning materials, and the implementation of pedagogical innovations. The theses presented below contain empirically grounded conclusions that may contribute to the further development of adaptive learning environments and their broader integration into educational practice.

1. **Thesis 1: There is a high demand for adaptive learning environments among students, especially regarding personalized feedback and visual explanations (Négyesi, 2025; Négyesi et al., 2023; Négyesi, 2021).**
    - Statistical verification: according to the results of the input questionnaire, 75.4% of respondents considered the importance of personalised feedback critical (4 or 5 on a Likert scale) and 84.7% considered visual explanations to be helpful.
    - Significance of the thesis: From a technological perspective, the formulated thesis supports the rationale for developing adaptive e-learning systems, with particular emphasis on those quality features that influence user experience and learning effectiveness. Adaptivity becomes pedagogically meaningful not in isolation, but through the personalization of feedback and the clarity of explanations. This is especially important in scientific and mathematical disciplines, where the complexity of content demands learning-supportive approaches that are also visually accessible. Students' positive attitudes toward such systems further reinforce the relevance of this development direction, as the features they favor—such as personalized feedback and visual explanations—directly contribute to the system's usability and acceptance.
2. **Thesis 2: A significant relationship exists between the use of digital learning materials and the perceived importance of personalized content (Négyesi, 2025; Négyesi et al., 2023).**
    - Statistical verification: chi-square test result: $\chi^2(4, N=118) = 12.56$; $p = .028$. The p-value is less than 0.05, indicating a statistically significant relationship between the two variables.
    - The significance of the thesis lies in the significant relationship between the use of digital learning materials and the perceived importance of personalized content, indicating that experiences in digital learning environments influence students' pedagogical preferences. Students who regularly use digital materials are more likely to recognize the added value of personalized content, particularly in terms of meeting individual learning needs. This correlation supports the

notion that technology use not only enhances technical skills but also contributes to the pedagogical acceptance of differentiated learning processes.

3. **Thesis 3: The use of individual learning strategies and digital learning materials varies significantly across grade levels. University students face greater difficulties in learning number theory (Négyesi, 2025).**
    - Statistical verification: ANOVA: $F(2, 115) = 8.34$; $p = .0004$. Tukey's post hoc test showed that university students experience significantly more challenges than high school students.
    - The significance of the thesis lies in highlighting grade-level differences in learning strategies and the use of digital learning materials, particularly within the context of higher education. For university students, learning number theory presents increased challenges, which can be attributed to both the abstract nature of the content and to the self-directed structure of the learning process. In the development of educational technologies, it is essential to consider the differing needs that arise at various academic levels, as well as the degree of learner autonomy. The effectiveness of digital learning materials depends not only on their availability but also on their ability to align with the learners' prior knowledge, learning styles, and cognitive characteristics.
4. **Thesis 4: Based on the results of the eye-tracking study, students with visual and verbal learning styles can be clearly identified (Négyesi, 2024).**
    - Statistical verification: the meta-heatmaps produced during the study revealed that students with a verbal learning style primarily focused on the textual parts. In contrast, those with a visual learning style tend to concentrate on graphical elements and diagrams.
    - Significance of the thesis: It enables the objective and empirically measurable identification of learning styles. Through the statistical analysis of observable gaze patterns and visual focal points, it is possible to reliably distinguish between students who primarily rely on visual information and those who prefer textual content in their learning process. This provides a foundation for the development of adaptive learning materials tailored to learners' dominant information-processing preferences. Furthermore, it contributes to the optimization of cognitive load and enhances learning efficiency, particularly when the

educational environment is capable of adapting to individual learner profiles in a personalized manner.

5. **Thesis 5: The adaptive e-learning environment significantly increases learner activity (Négyesi, 2025).**
    - Statistical verification: the number of daily check-ins increased significantly after the study (before study = 120.5; after study = 145.3; $t = -2.45$; $p = .015$).
    - The significance of the thesis lies in providing empirical evidence for the pedagogical effectiveness of adaptive systems, particularly in terms of student engagement and motivation. The increase in student activity reflects not only greater intensity in the learning process but also enhanced quality, as active participation is associated with a deeper understanding and the construction of long-term knowledge. The personalized learning pathways, feedback mechanisms, and pace optimization offered by adaptive systems directly support self-regulated learning, an especially critical factor in digital learning environments.
6. **Thesis 6: The use of the adaptive e-learning environment significantly increases students' motivation toward number theory topics (Négyesi, 2025).**
    - Statistical verification: the mean score for the question measuring change in motivation was 4.15 (Likert scale: 1-5), which was significantly higher than the neutral mean ($t(264) = 16.23$; $p < .001$).
    - The significance of the thesis lies in the fact that number theory typically comprises abstract and formal content that many students find difficult to comprehend, often resulting in low levels of motivation and learner engagement. However, an adaptive learning environment can support the learning process through personalized feedback, visual explanations, and learning pathways tailored to each student's pace. This approach reduces the cognitive load and anxiety associated with the subject. Empirical evidence confirms that the adaptive system not only improves learning outcomes but also increases interest and intrinsic motivation in a topic area, such as number theory, that is traditionally considered difficult to teach and learn.

7. **Thesis 7: The use of the adaptive learning tool improves students' time management skills during the learning process (Négyesi, 2025).**
    - Statistical verification: the mean of the question measuring improvement in time management skills was 4.12, significantly higher than the neutral value ($t(264) = 16.34$; $p < .001$).
    - The significance of the thesis lies in the fact that adaptive technology supports not only content acquisition but also has a positive impact on the metacognitive skills required for an effective learning organization. The structured learning pathways, progress-tracking feedback, and visual indicators related to time investment provided by adaptive systems promote the development of learners' self-regulation skills, particularly in terms of conscious time management and prioritizing learning activities. The use of adaptive learning tools is valuable not only from a content-related perspective but also in terms of learning organization, especially in digital learning environments where independent time management plays a critical role in successful learning.
8. **Thesis 8: From both student and learner perspectives, the adaptive e-learning system achieved an average score of at least 4 in all evaluated dimensions based on Jakob Nielsen's usability factors (Négyesi, 2025).**
    - Statistical verification: the results of the one-sample t-test showed that the mean score for all usability factors was significantly higher than the neutral score of 3 ($p < .001$), indicating that learners positively evaluated the usability of the system:
        - learnability: 4.32 ($t(264) = 18.45$; $p < .001$),
        - efficiency: 4.18 ($t(264) = 16.78$; $p < .001$),
        - memorability: 4.25 ($t(264) = 17.89$; $p < .001$),
        - error handling: 4.10 ($t(264) = 15.67$; $p < .001$),
        - satisfaction: 4.30 ($t(264) = 18.12$; $p < .001$).
    - The significance of the thesis is that the system's high level of usability from the end-users' perspective is empirically confirmed. Nielsen's usability heuristics provide a comprehensive framework for assessing user experience, and the fact that all dimensions received an average rating of at least 4 indicates that the adaptive system is not only functionally effective but also well-aligned with learners' expectations and needs. The technological solution does not impose an

additional burden on users; rather, it facilitates the learning process. This substantiates the pedagogical legitimacy of the broader implementation and long-term use of adaptive systems in education.

9. **Thesis 9: The adaptive e-learning system significantly increases students' activity and participation in the learning process (Négyesi, 2025).**
    - Statistical verification: logfile analysis revealed an increase in the number of daily logins (from 120.5 to 145.3; $t = -2.45$; $p = .015$) and a corresponding increase in the number of daily tasks solved (from 85.7 to 102.4; $t = -2.12$; $p = .034$).
    - Significance of the thesis: The positive impact of the adaptive e-learning environment on student participation is empirically confirmed. Activity and engagement represent two fundamental dimensions of the learning process, as they significantly influence academic performance, the development of self-regulated learning, and long-term knowledge retention. The significant increase in these indicators suggests that the adaptive system supports learning not only at the content or organizational level but also by creating a structured and dynamic learning environment that fosters active participation and enhances both the cognitive and affective engagement of learners.
10. **Thesis 10: Teachers clearly recognize the necessity of implementing adaptive e-learning systems; however, the deeper integration of adaptive mechanisms, the development of automated feedback systems, and the strengthening of teachers' digital competencies are essential for the full educational integration of such systems (Négyesi, 2025).**
    - Statistical verification:
        - The importance of adaptive systems was rated by teachers with a mean of 4.3 (on a Likert scale of 1-5), which is significantly higher than neutral.
        - 87.5% of teachers would recommend the system to other teachers, which strongly confirms its necessity in the educational process.
        - For the Jakob Nielsen usability factors, the mean scores given by educators ranged from 4.07 to 4.37 on a 5-point Likert scale, confirming the ease of use and effectiveness of the system.
        - The relationship between the usability factors and satisfaction showed a strong correlation, with a Pearson correlation coefficient of 0.78 between

the "Ease of use" factor and "Satisfaction" ($p < .01$), indicating that the ease of use of the system has a significant impact on overall satisfaction.

  - Based on linear regression analysis, the usability factors together explained 72% of the teachers' satisfaction ($R^2 = .72$), indicating a strong correlation between system usability and teachers' experience.

- Significance of the thesis: It presents a comprehensive approach to understanding the conditions necessary for the successful educational integration of adaptive e-learning systems. While there is an apparent openness among teachers to the necessity of implementing such systems, their actual success depends on multiple interrelated factors. The level of teachers' digital competence, the technological maturity of the adaptive mechanisms, and the degree to which these systems are deeply integrated into pedagogical practice all determine the extent to which adaptive systems can evolve into truly effective learning environments.

Summary

Based on the research findings, the practical applicability of adaptive learning environments has been confirmed across multiple dimensions. The investigations highlighted that such systems can meaningfully enhance students' motivation, engagement, and participation in the learning process — aspects that are particularly important when teaching more abstract subjects that require higher-order thinking, such as number theory. Students' positive attitudes and the high usability ratings of the system indicate that personalized feedback and visual explanations genuinely support individual learning processes, reduce cognitive load, and promote the development of active learning strategies.

From the perspective of school practice, it is especially relevant that the use of the system improves students' problem-solving and time management skills, thereby fostering autonomous and reflective learning. This skill-development potential not only supports classroom activities but also contributes to the long-term development of students' learning strategies.

Based on teachers' feedback, the key conditions for implementing the system have also been identified: the development of teachers' digital competencies, the further improvement of automated feedback mechanisms, and the deeper integration of adaptive features into education. This knowledge can be directly applied in teacher training and can also inform strategies for the development and implementation of digital learning tools.

Overall, the practical value of the research lies in the fact that the adaptive e-learning system represents a pedagogical innovation capable of effectively supporting individual learning pathways, enhancing student engagement, and being integrated into classroom practice in a practical and applicable way. The research findings are helpful and contribute to the development of strategies that personalize learning and digitally support pedagogical work.

Further Research Directions

The research findings lay the groundwork for several future lines of investigation. Primarily, there is a need to expand the sample to include various regions, school types, and learner populations to enhance representativeness and the generalizability of the results. Additionally, longitudinal studies are necessary to evaluate the long-term effects of the adaptive system, particularly regarding the sustainability of student motivation, self-regulation, and academic achievement.

Further research potential lies in adapting the system to other subject areas. During disciplinary adaptation, it is advisable to examine how the content-related and functional components of the system can be applied in different learning contexts (e.g., natural sciences, history). It is also highly relevant to involve special learner groups, such as students with special educational needs or highly gifted learners, in future studies, as this may necessitate fine-tuning of the adaptive mechanisms and a deeper level of personalization.

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