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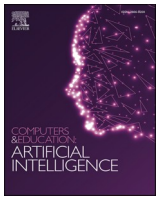

AI-assisted audio-learning improves academic achievement through motivation and reading engagement

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ABSTRACT

Artificial intelligence (AI) is transforming education by enabling the creation of innovative learning resources that may cater to diverse learning needs. Students with common forms of neurodiversity, such as ADHD, often face unique challenges in higher education that are not adequately addressed by current educational resources. One potentially helpful resource is audio content, which provides a flexible and accessible supplement to traditional educational materials. While audio content, such as podcasts, is widely popular, its effect on academic achievement remains underexplored. This pre-registered randomized controlled trial investigated the impact of AI-assisted audio-learning modules on academic achievement, with a particular focus on the mediating roles of motivation and reading engagement. Results showed that the audio-learning modules increased student motivation and reading engagement. Importantly, audio-learning driven increases in motivation and reading engagement boosted academic achievement. Furthermore, students with greater ADHD symptom severity particularly benefited from the audio-learning modules, as they played a crucial role in determining course success. Together, this study highlights the potential of AI-assisted audio-learning modules as a valuable tool in digital education environments, catering to diverse learning needs and improving educational outcomes.

1. Introduction

In recent years, generative artificial intelligence (AI) has transformed various aspects of education, enabling new forms of engagement and interaction with learning materials (Lo, 2023; Yan et al., 2024; Munir et al., 2022). While post-pandemic shifts have emphasized video-based learning, the benefits of audio-learning have been overlooked. Audio-learning, characterized by its "anytime-anywhere" accessibility, allows students to engage with educational content in flexible, non-traditional learning environments, such as while commuting or doing chores. With the popularity of podcasts growing globally, with over 500 million listeners worldwide and a significant proportion of younger generations regularly listening (Podcast Index, 2024), audio-learning presents a powerful, yet underutilized, medium for enhancing student learning.

Despite the clear advantages of audio-learning, educators are often faced with the challenge of creating additional learning materials to integrate new teaching methods. This is where generative AI systems, such as OpenAI's ChatGPT (Generative Pre-Trained Transformer), can play a pivotal role by automating the creation of such AI-assisted audio-learning modules. Recent developments in large language models (LLMs) have expanded the potential to generate human-like, natural audio content, enabling the production of high-quality, audio-based learning materials. The current study explores how generative AI can be leveraged to develop audio-learning modules—short audio summaries of textbook content—designed to enhance students' motivation, engagement, and academic outcomes.

2. Background

2.1. AI-assisted audio-learning and motivation

Previous studies on audio-learning have shown promising results, with university students using audio-based resources often outperforming their peers in terms of exam performance (Abdous et al., 2012; Avila & Lavadia, 2019; Chin et al., 2017; Furtado et al., 2023; Kalludi et al., 2013; Morris, 2010). However, much of this research has been limited by small sample sizes and methodological constraints, such as a lack of randomized controlled trials. Consequently, the specific mechanisms through which audio-learning improves academic

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outcomes remain unclear. Here, we hypothesize that AI-assisted audio-learning enhances academic outcomes by fostering motivation and engagement.

Motivation is widely regarded as one of the most critical predictors of academic achievement (Eccles & Wigfield, 2002; Schunk & DiBenedetto, 2020). According to self-determination theory (Ryan & Deci, 2000, 2020), satisfying the fundamental needs for autonomy, competence, and relatedness promotes motivated behavior. Audio-learning, with its inherent flexibility, may foster a greater sense of autonomy by giving learners control over when and where they engage with content. Additionally, because audio-based learning is often perceived as less cognitively demanding than reading dense texts (Bolliger et al., 2010; Castro-Alonso & Sweller, 2020; de Oliveira Neto et al., 2015), it can boost students' feelings of competence. Finally, listening to a voice – even if it is AI-generated – may create a sense of social relatedness, further enhancing motivation. Therefore, the first objective of the current study is to assess whether AI-assisted audio-learning modules improve academic achievement by enhancing student motivation (as measured through both self-report and via engagement with study materials).

2.2. AI-assisted audio-learning and neurodiversity

A second objective of the current study is to investigate the potential benefits of AI-assisted audio-learning for students with Attention Deficit Hyperactivity Disorder (ADHD), a neurodevelopmental disorder affecting both cognitive and motivational processes (Abdelnour et al., 2022; Sonuga-Barke et al., 2008; Henning et al., 2021). According to the dual pathway model of ADHD, students with ADHD often face challenges with working memory and maintaining motivation, leading to lower academic achievement and higher dropout rates compared to typically developing students (Sonuga-Barke, 2003). We hypothesize that AI-assisted audio-learning may mitigate these challenges by reducing cognitive load. According to Cognitive Load Theory (CLT) (Sweller, 2011, 2015, 2020), audio learning helps reduce extraneous cognitive load, which often arises when reading lengthy or visually complex texts (Evans et al., 2024; Evans & Martin, 2023). Since audio materials do not include visual elements, they may allow for clearer processing of information. Additionally, dense information can be more easily segmented and understood through voice modulation (Sweller, 2020; Castro-Alonso & Sweller, 2020). This hypothesized decrease in extraneous cognitive load, paired with the hypothesized increase in motivation, may be particularly beneficial for students with ADHD.

3. Research questions

In summary, this study aims to evaluate the efficacy of AI-assisted audio-learning on academic achievement, explore how AI-assisted audio-learning affects academic achievement, focusing on motivation and reading engagement as underlying mechanisms, and assess the specific benefits of AI-generated audio-learning for students with ADHD, leading to the following research questions.

1. Is AI-assisted audio-learning effective in improving academic achievement?
2. Do motivation and/or reading engagement mediate the relationship between AI-assisted audio-learning and academic achievement?
3. Does AI-generated audio-learning provide specific benefits for students with greater ADHD symptom severity?

4. Method

This study was pre-registered on the Open Science Framework (OSF) (see pre-registration: OSF link). All procedures adhere to the pre-registration unless stated otherwise. Our code is publicly available, and data will be shared upon request.

4.1. Participants

A total of 410 first-year Psychology students ($M = 20.10$ years, $SD = 3.11$ years, 75.2% female) participated in this study. Ethical approval was obtained from the ethical review board of the Psychology Department at the University of Amsterdam.

4.2. Design and procedure

We employed a randomized controlled weekly diary design, with participants assigned to either the audio-learning condition (60%) or a control condition (40%). The larger allocation to the audio-learning condition was to anticipate potential attrition in this group, as the use of audio-learning materials was voluntary.

Participants were tracked over a two-month period while enrolled in a course titled *Brain & Cognition* - an undergraduate module offered as part of a broader Psychology degree program. The module included approximately 420 students and carried a weight of 6 credits, with students typically completing 60 credits per year. This corresponds to an expected workload of 21 hours per week, amounting to 168 hours in total. The teaching structure consisted of weekly lectures supplemented by small-group compulsory tutorials. During these tutorials, students worked on assignments directly related to the study materials. In addition, students were required to complete weekly assignments in a digital learning environment, contributing 20% to the overall grade. In addition, assessment included two exams at the end of weeks 4 and 8, each contributing 40% to the overall grade.

Before the study commenced, students provided informed consent and completed baseline questionnaires covering demographics, academic motivation, study strategies, and diagnoses and symptomatology of ADHD or dyslexia. Each week, participants reported on their study motivation, engagement, study methods, and use of learning materials.

4.3. Materials and measures

4.3.1. Audio-learning modules developed with the help of generative AI

Students were assigned by their teacher to read two chapters weekly from *Cognitive Neuroscience: The Biology of the Mind* (Gazzaniga et al., 2018). With support of the *Anywyse* tool – a didactic audio-lesson scriptwriter enhanced by generative AI, each chapter was divided into two to three audio modules lasting between 7 and 15 min, depending on the content density.

More specifically, audio modules were generated using an AI-driven pipeline powered by OpenAI's GPT-4-1106-preview model, configured with a temperature of 0.7 to balance creativity and coherence. No training was involved. Textbook chapters were divided into passages of 3000–6000 words, with each audio module covering 1–3 passages from the same chapter. For each passage, the model identified 2–3 take-home messages, which, along with the original text, were used to generate scripts emphasizing these key points. The scripts included explanatory content, concise summary sentences to clarify complex ideas, and recaps of the take-home messages. For modules that spanned multiple passages, the tool incorporated previously generated scripts to ensure continuity. After completing each passage's script, the model generated a recap and two comprehension questions focused on the take-home messages, followed by a 10-second pause before providing the answers. Each module also began with an introductory segment to activate prior knowledge and provide an overview of key points to be discussed. The finalized scripts were then voiced using the ElevenLabs AI text to speech service.

The generative AI tool followed principles of a constructivist learning framework (Bada & Olusegun, 2015) to generate the text content which was subsequently voiced into audio. That is, the script of the tool followed key instructional strategies: (a) activating prior knowledge, (b) providing an overview of key points, (c) explaining key points with relatable examples, and (d) including self-test questions. After generation, both authors reviewed the modules for accuracy and made

necessary revisions ensuring ethical use of generative AI. Specifically, we implemented a checklist to ensure that the AI-generated content was free of false or incomplete information and aligned with the educational goals (see Supplemental Text II for the checklist). Students were also informed that the audio-content was (partly) generated with AI and could therefore contain incomplete information. In total, 32 audio-learning modules were created, amounting to 384 min of content (average duration: 12 min per module). One minute of audio covered approximately 1000 words of the textbook. It was emphasized that the audio-learning materials were intended as supplementary summaries, not as replacements for other course materials, and students were advised to refer to the book for comprehensive understanding. Access to the audio-learning modules was available through any internet-enabled device, including smartphones, tablets, and laptops, ensuring flexibility and accessibility for all participants. Figs. S1 and S2 provide usage data, illustrating where participants accessed the audio content. All audio-learning modules can be accessed here: https://listen.anywyse.audio/series/331/.

4.3.2. Motivation

Each week, participants responded to the question, *"How motivated did you feel to study for this course this week?"*, using a 5-point Likert scale (1 = "Not at all" to 5 = "Very much").

4.3.3. Reading engagement with textbooks

Students self-reported the number of hours spent studying with textbooks each week.

4.3.4. Engagement with audio-learning materials

Listening times were tracked through the *Anywyse* listening platform.

4.3.5. Academic achievement measures

Primary academic achievement was measured through students' self-reported exam grades, which included both open-ended and multiple-choice questions based on textbook and lecture content. We used the average of both exam grades. Weekly assignment grades, consisting of multiple-choice quizzes based on textbook material, were used as a secondary measure of academic achievement.

4.3.6. ADHD symptoms

We measured ADHD symptom severity using the Adult ADHD Self-Report Scale (ASRS-18) (Kessler et al., 2005). An example question is "How often do you have difficulty getting things in order when you have to do a task that requires organization?". This self-report instrument consists of 18 items, and participants were asked to choose the response that best described their behavior in the past six months on a 5-point Likert scale (1 = never, 5 = very often). A higher total score reflects greater ADHD symptom severity. In the sample of the current study, the ASRS-18 showed good internal consistency (Cronbach's $\alpha = .89$).

4.3.7. ADHD status and dyslexia status

We also asked whether students were diagnosed with ADHD and Dyslexia (see also supplementary materials Fig. S3). Specifically, we asked 'Do you have AD(H)D' and 'Do you have Dyslexia'? Answer options included: 'Yes, I have been diagnosed with AD(H)D/Dyslexia', 'No, I have not been diagnosed with AD(H)D/Dyslexia, but I suspect I may have it', 'No, I do not have AD(H)D', and 'I prefer not to answer'. Only those who indicated to have a diagnosis were classified as having AD(H)D/Dyslexia.

4.4. Data analysis plan

As pre-registered, we excluded participants in the audio-learning group who listened to less than 76.8 min (20%) of the total 384 min of audio materials. Descriptive analyses of motivation, textbook reading time, and assignment grades were conducted using multilevel regression analyses with the lme4 package in R (Bates et al., 2014), incorporating condition (audio = 1, control = −1) as a predictor and including random intercepts and slopes for participants across weeks. Independent t-tests were used to compare cumulative motivation scores and reading times between conditions.

To examine whether 1) audio-learning impacted academic achievement, through 2) motivation and reading engagement, we performed mediation analyses using Hayes' PROCESS macro (Hayes, 2015) in R. Additionally, we conducted an exploratory (i.e., non-pre-registered) serial mediation analysis, examining both motivation and reading time as mediators between condition and exam grades. Next, for a deeper exploration, Bayesian multilevel mediation analyses were carried out using the brms package (Bürkner, 2017) (not pre-registered), modeling weekly motivation and reading engagement as mediators between condition and weekly assignment grades, with random intercepts and slopes for week within participants.

Finally, to evaluate 3) whether audio-learning benefits were particularly pronounced for students with greater ADHD symptom severity, linear regression analyses were conducted within subgroups based on median splits of ADHD severity and audio-learning engagement (i.e., students with high versus low listening times). We modeled exam grades as a function of condition, ADHD severity, and their interaction.

5. Results

5.1. Data preprocessing

From the 257 participants in the audio-learning condition, 137 participants were excluded from the analyses as they listened to less than 20% of the audio-learning materials. All analyses were performed on the remaining 273 participants. For descriptive statistics of the two groups, see Table 1. Comparing the groups on individual difference variables, t-tests found no significant differences in age ($p = .17$) or ASRS18 scores ($p = .89$). Further, chi-squared tests found no significant differences in gender distribution ($p = .61$), ADHD status ($p = .10$) or dyslexia status ($p = .17$) between participants in the audio- versus control condition.

5.2. Descriptive statistics and direct effects on academic achievement

Multilevel regression analyses revealed that students in the AI-assisted audio-learning condition reported significantly higher outcomes across key measures compared to the control group. Fig. 1 illustrates these results. Specifically, students in the audio-learning condition demonstrated higher motivation scores throughout the course ($b = 0.26$, $p = .005$), greater reading engagement ($b = 4.35$, $p < .001$), and higher weekly assignment grades ($b = 6.49$, $p = .022$) compared to students in the control condition.

Cumulatively, across all weeks, students in the audio-learning condition exhibited an average increase in motivation of 9.79% compared

Table 1
Descriptive statistics for participants in each condition. Mean scores are displayed with standard deviations between brackets.

	Audio	Control
Number of participants	120	153
Female/Male/Other	92/27/1	111/39/3
Mean age	20.49 (3.44)	19.94 (3.11)
ASRS18 Score	47.89 (4.17)	47.81 (4.09)
Total listening time	238.62 min (157.52)	–
Weekly listening time	34.09 min (22.50)	–
Motivation/week	3.14 (0.75)	2.86 (0.78)
Reading hours text-books/week	12.21 h (8.75)	7.67 h (6.40)
Weekly assignment grade	63.32 (29.37)	53.16 (23.90)
Exam grade	6.33 (1.65)	6.22 (1.73)
ADHD cases	10	13
Dyslexia cases	1	6

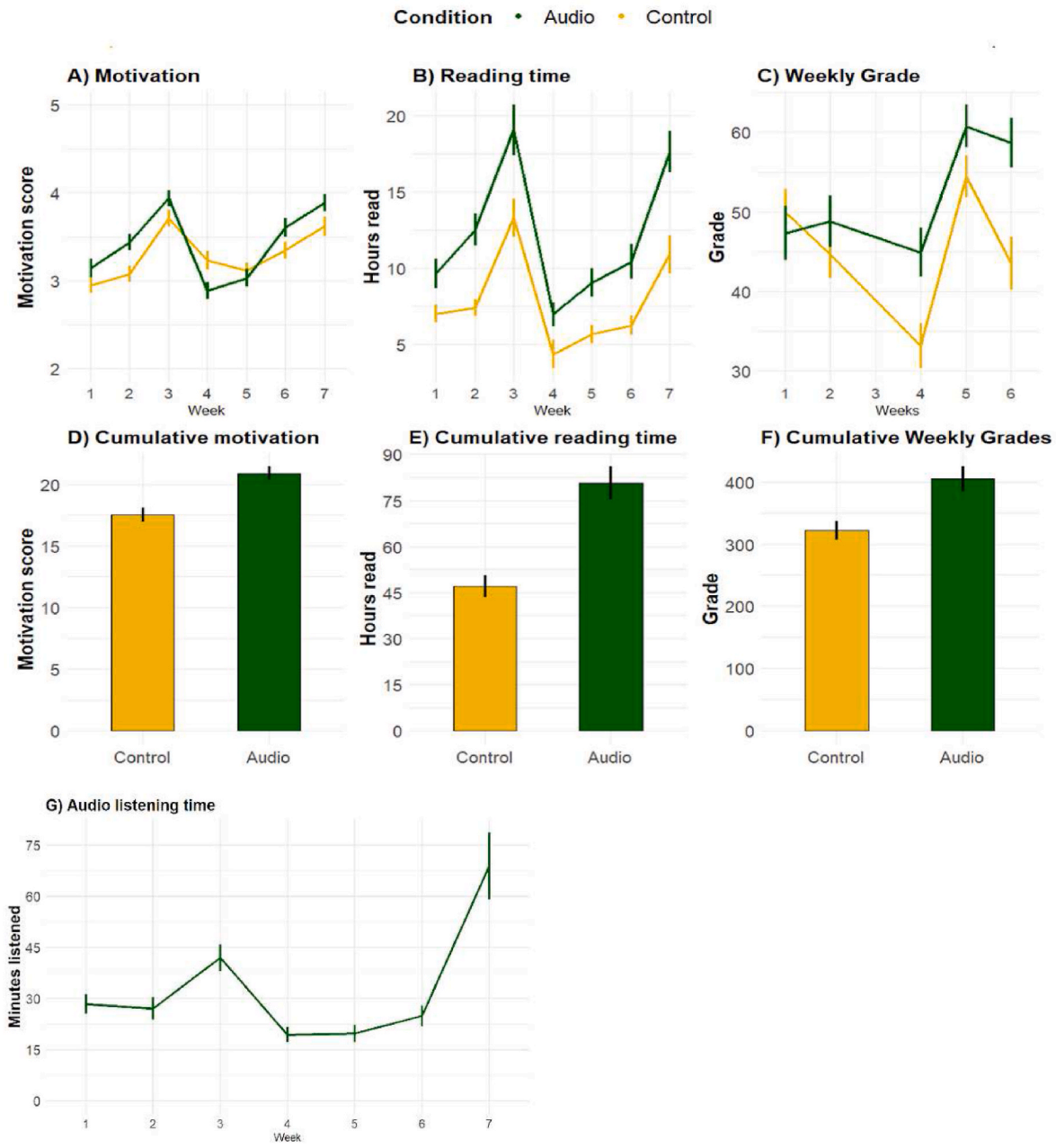

Fig. 1. Displaying for each condition A) Motivation scores across weeks, B) Reading time across weeks, C) Weekly grades across weeks (in percentages), D) Cumulative motivation, E) Cumulative reading time, and F) cumulative weekly grades. G) shows listening time in minutes for the audio-learning group. In all figures, bars denote ± SEM.

Note: The peaks and troughs observed in A, B, C, and G align with exam assessments in weeks 4 and 8, as students likely increased study efforts before the exams and reduced engagement immediately afterward.

to the control group (t (260) = 3.00, p = .003). Reading time was, on average, 59.26% higher in the audio-learning group than in the control condition (t (260) = 4.77, $p < .001$), suggesting that AI-generated audio content encouraged deeper engagement with course materials.

With respect to our first research question regarding the effectiveness of AI-assisted audio learning in improving academic achievement, no direct effect was observed on exam grades, t (260) = −0.48, p = .629. However, the audio-learning group outperformed the control condition in average weekly assignment grades, achieving a 19% higher score on average (t (260) = 2.83, p = .005).

5.3. Audio-learning does not mediate changes in exam grades through motivation

Next, we examined the first part of our second research question: whether motivation mediated the link between AI-assisted audio learning and academic achievement. Results of a mediation analysis indicated that the use of AI-generated audio-learning modules significantly increased motivation (β = 0.20, p = .004). However, the effect of motivation on exam grades was not significant (β = −0.01, p = .87), nor was the direct effect of audio-learning on exam grades (β = 0.06, p = .63). The indirect effect of audio-learning on exam grades via motivation was also not significant (β = −0.00, 95% CI [−0.05, 0.05]). These findings suggest that, while AI-assisted audio-learning modules

effectively boost student motivation, this alone does not directly translate into higher exam grades.

5.4. Textbook reading time mediates changes in exam grades

We next examined the second part of our second research question: whether engagement with textbooks (measured as reading time) mediated the relationship between AI-assisted audio-learning and exam grades. The results showed that audio-learning significantly increased reading time ($\beta = 0.27$, $p < .001$), and reading time positively impacted exam grades ($\beta = 0.21$, $p = .004$). The indirect effect of audio-learning on exam grades through reading time was also significant ($\beta = 0.09$, 95% CI [0.03, 0.19]). Fig. 2 provides an illustration of this mediation effect.

5.5. Serial mediation: motivation and reading time together

To explore whether both motivation and reading time contributed sequentially to exam performance, we conducted a serial mediation analysis. Results, again, showed that audio-learning had a significant effect on motivation ($\beta = 0.20$, $p = .004$), and motivation significantly predicted increased reading time ($\beta = 0.27$, $p < .001$). Reading time, in turn, positively predicted exam grades ($\beta = 0.23$, $p = .003$). The indirect effect of audio-learning on exam grades through the combined mediators of motivation and reading time was also significant ($\beta = 0.01$, 95% CI [0.01, 0.03]). This suggests that AI-assisted audio-learning improves academic outcomes by first boosting motivation, which then leads to greater engagement with reading materials, ultimately enhancing exam performance (Fig. 3).

5.6. Exploratory mediation analyses: weekly assignment grades

An exploratory Bayesian multilevel serial mediation analysis was conducted to assess the effects of AI-assisted audio-learning on weekly assignment grades, mediated through both motivation and reading time. Fig. 4 displays the results (see also Table S1). The analysis revealed that audio-learning had a significant positive effect on motivation ($\beta = 0.17$, 95% CI [0.02, 0.32]) and reading time ($\beta = 0.27$, 95% CI [0.12, 0.41]). Motivation significantly predicted reading time ($\beta = 0.22$, 95% CI [0.06, 0.40]). Although the direct effects of motivation and reading time on weekly grades were not statistically significant, the total effect of audio-learning on weekly assignment grades, accounting for both direct and indirect pathways, was significant ($\beta = 0.19$, 95% CI [0.03, 0.35]). This suggests that the AI-assisted audio-learning modules had a cumulative positive impact on weekly performance by encouraging sustained weekly engagement through motivation and reading time.

5.7. AI-assisted audio-learning mitigates effects of ADHD symptoms

Finally, to assess our third research question: whether AI-assisted audio-learning was especially beneficial for students with greater ADHD symptom severity, we conducted subgroup analyses based on

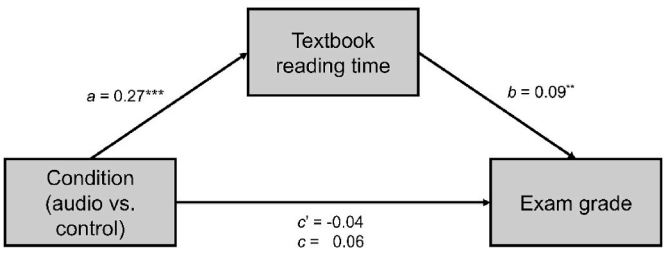

Fig. 2. The effect of AI-assisted audio-learning on exam grade mediated by reading time in textbooks.
Note: ***$p < .001$, **$p < .01$, *$p < .05$.

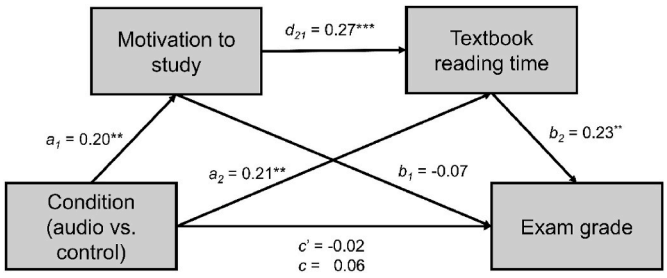

Fig. 3. The serial mediation effect of AI-assisted audio-learning on exam grade by both motivation and reading time in textbooks.
Note: ***$p < .001$, **$p < .01$, *$p < .05$.

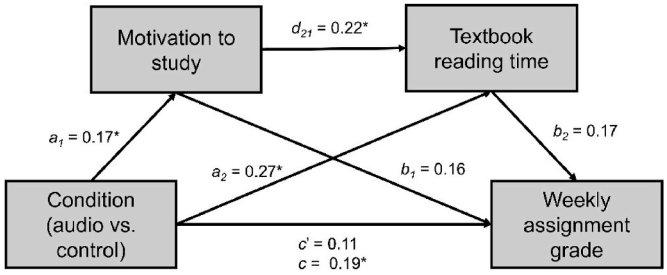

Fig. 4. The serial mediation effect of AL on weekly assignment grade by both motivation and reading time in textbooks.
Note: *95% bootstrapped confidence interval did not cross 0.

participants' engagement levels with the audio materials. The overall median listening time was 208 min. Fig. 5 displays these results. In the below-median listening time group (group median = 122 min), higher ADHD symptom severity was significantly associated with lower exam grades ($\beta = -0.50$, $p = .005$). However, there was no significant effect of condition (audio vs. control; $\beta = -0.05$, $p = .86$) or the interaction between ADHD symptom severity and condition ($\beta = -0.24$, $p = .45$).

In contrast, in the above-median listening time group (group median = 292 min), we found no main effect of condition ($\beta = 0.15$, $p = .62$). However, we found a significant interaction between ADHD symptom severity and condition ($\beta = 0.77$, $p = .01$). This suggests that AI-assisted audio-learning mitigated the negative effect of ADHD symptoms on academic performance for students who engaged more fully with the audio materials (Fig. 5).

6. Discussion

This pre-registered study aimed to 1) Evaluate the efficacy of AI-assisted audio-learning on academic achievement, 2) Explore how AI-assisted audio-learning affects academic achievement, focusing on motivation and reading engagement as underlying mechanisms, and 3) Assess the specific benefits of AI-generated audio-learning modules for students with ADHD.

While audio-learning did not directly impact exam grades (though it did improve weekly assignment grades), it increased both self-reported motivation and reading engagement. Crucially, we found that the increase in reading engagement, led to improved exam grades. Furthermore, exploratory analyses revealed that audio-learning influenced academic achievement by increasing motivation, which subsequently boosted reading engagement. Students using the audio-learning modules also performed better on weekly assignments, extending the benefits of audio-learning beyond final assessment outcomes. Finally, students with greater listening times experienced a reduction in the negative impact of ADHD symptoms on academic achievement.

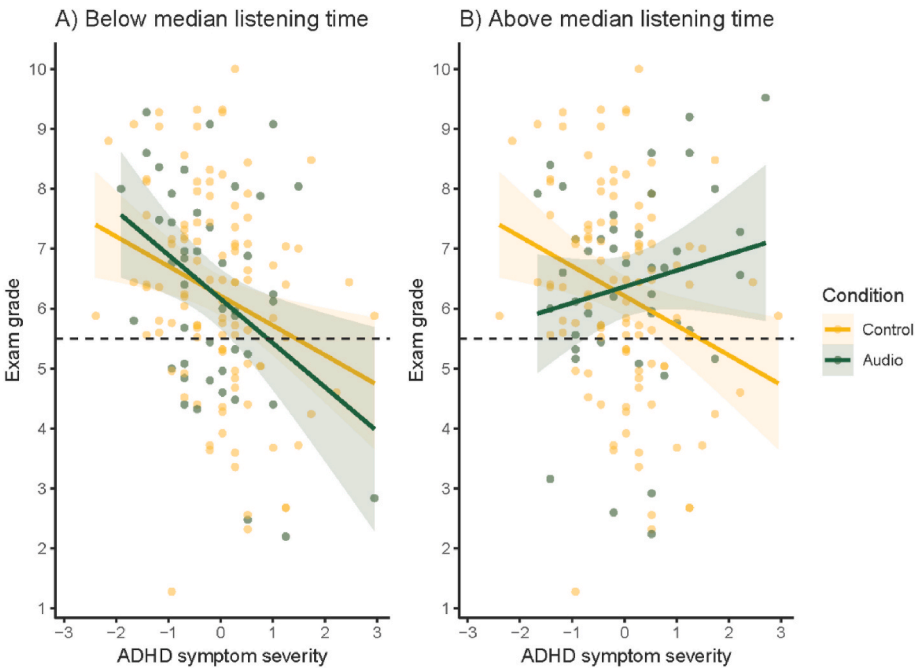

Fig. 5. The relationship between exam grades (y-axis) and ADHD symptom severity (x-axis) depending in condition and listening time.
Note: Shaded areas represent ± SEM. In the Dutch grading system, a 5.5 determines the threshold between passing or failing. The small number of participants with formal ADHD diagnoses made it unreliable to use actual diagnoses instead of symptom scores. A visualization of the effects of audio-learning modules on academic achievement for participants with formal ADHD diagnoses is provided in Supplementary Materials Fig. S3.

6.1. AI-assisted audio-learning, motivation and reading engagement

The finding that AI-assisted audio-learning increased motivation aligns with predictions based on Self-Determination Theory – stating that feelings of autonomy, competence and relatedness promote motivation (Ryan & Deci, 2000; Deci & Ryan, 2020). Audio-learning potentially enhanced students' feelings of autonomy by allowing them to engage with learning materials in flexible settings – on the go or while multitasking (see Supplementary materials Fig. S1 and Fig. S2 for usage data and Supplemental text I for usage feedback). This flexibility, combined with the lower cognitive demands of listening compared to reading, as posited by Cognitive Load Theory (Castro-Alonso & Sweller, 2020; Sweller, 2011, 2015, 2020), may have contributed to increased feelings of competence. Additionally, listening to a human voice, even when AI-generated, could have fostered a sense of social relatedness, further boosting motivation.

Despite the increase in motivation, audio-learning-induced motivation did not directly translate into improved exam grades. This is understandable, given that the AI-assisted audio modules provided summarized content, which, while motivating and accessible, still required students to engage more deeply with textbook material to fully grasp all course concepts. However, we found that listening to summarized content led to substantial increases in reading engagement, suggesting that the audio-learning modules not only stimulated curiosity but also encouraged students to spend more time with textbooks. This effect may be due to the audio summaries providing prior knowledge, which may have increased students' confidence to subsequently engage with the reading material.

Crucially, we demonstrated that audio-learning's effect on academic performance operated through both motivation and reading engagement. This suggests that while listening to summarized content alone may not directly improve exam scores, it sets in motion a sequence of study behaviors that ultimately lead to better outcomes. This is consistent with the broader literature on motivation and effort, which shows that motivated students are more likely to engage in effortful academic behaviors that positively impact their performance (Kramer et al.2024, 2023, 2021; Vansteenkiste et al., 2009; Vu et al., 2022; Westbrook & Braver, 2015).

The exploratory analysis of weekly assignments revealed that AI-assisted audio-learning also supports learning on a week-to-week basis. By supporting spaced repetition of material, a well-known effective learning technique (Dunlosky et al., 2013; Gordon, 1925; Kang, 2016; Toppino & Gerbier, 2014), AI-assisted audio-learning may enhance retention and understanding over time. This observation highlights the potential of AI-assisted audio-learning modules to promote continuous learning, not just final exam performance.

Our findings also align with prior research demonstrating the effectiveness of audio (-visual) educational tools in enhancing student learning outcomes. For example, Kay and Kletskin (2012) found that problem-based video podcasts were rated by students as highly engaging, useful, and effective for mastering complex mathematical concepts. Similarly, McKinney and colleagues (2009) demonstrated that students using lecture podcasts performed significantly better on exams than students who attended in-person lectures. Moreover, König (2021) highlighted the importance of delivery style, noting that teacher enthusiasm boosts podcast quality, fostering greater student interest, enjoyment, and motivation. These insights underscore the potential of well-designed audio-learning tools to support diverse educational needs and enhance learner engagement.

Recent studies further highlight the potential of generative AI in developing educational materials. For instance, Leiker et al. (2023) found that AI-generated and traditional instructor videos similarly improved learner knowledge and experience, but AI videos were far more efficient, costing $15 per minute versus $300 per minute for traditional production. In addition, others found that generative AI can improve student engagement and learning outcomes by delivering personalized learning materials (Pesovski et al., 2024). AI-generated quizzes proved to be particularly impactful, enabling students to self-assess and encouraging more study time, especially for those facing challenges with the subject. These findings underscore the potential of generative AI in education, providing scalable, cost-effective solutions that match traditional methods in effectiveness while enhancing

personalization, engagement, and global access to quality learning.

6.2. AI-assisted audio-learning and ADHD

We also explored the potential benefits of AI-assisted audio-learning for students with ADHD. The results suggest that students with more severe ADHD symptoms directly benefited from audio-learning, achieving passing grades at higher rates. This effect can be explained by Cognitive Load Theory: since individuals with ADHD often face motivation and working memory challenges (Sonuga-Barke et al., 2008). The shorter, more concise format of the audio-learning modules may have reduced the cognitive demands compared to reading longer texts. By lowering extraneous cognitive load, AI-assisted audio-learning modules may have helped these students manage their working memory resources during learning more effectively. Additionally, this (perceived) reduction in cognitive load may have enhanced their sense of competence, further boosting motivation.

Others have also noted how neurodiverse students benefit from non-traditional educational resources. For example, focus groups with neurodiverse students identified challenges like limited course flexibility and access to information as contributors to increased cognitive load, with strategies like pausing recordings and taking breaks helping to mitigate these issues (Le Cunff et al., 2024a). Audio-learning directly addresses these barriers by offering flexibility, the ability to pause and replay content, and an accessible alternative to text-heavy materials, making it a powerful tool for inclusive online education. In addition, a systematic review (Le Cunff et al., 2024b) identified strategies that lower cognitive barriers for neurodiverse learners, including redundant subtitles in audio and video materials, content chunking, personalization, and simplified language. Subtitles, for instance, reduce cognitive load for students with ADHD, though they may increase it for neurotypical learners (Brown et al., 2016; Lewis & Brown, 2012), while simplified text formats help students with autism process information more effectively (Štajner et al., 2017). The audio modules in the current study incorporated subtitles, which some participants found helpful for following along (Supplemental Text I). Additionally, the content was chunked, and efforts were made to simplify language. Further, the adaptability of AI to personalize content presents an interesting avenue for future exploration. Overall, findings of the current study align with earlier studies on the needs of neurodiverse learners and highlight the potential of AI-enhanced learning tools to help close the achievement gap between neurodiverse students and their peers.

6.3. Limitations, strengths and future directions

While this study provides promising evidence for the benefits of AI-assisted audio-learning, there are several limitations that future research should address. First, although we hypothesize that audio-learning reduces cognitive load, this was not directly measured. Future studies should incorporate specific measures of cognitive load to confirm whether audio-learning is indeed less taxing than traditional reading, especially for students with ADHD. Additionally, the relatively small number of students with clinical ADHD in our sample calls for larger, more diverse cohorts to draw stronger conclusions about the effectiveness of AI-assisted audio-learning for this group. Future studies should also explore other forms of neurodiversity, such as dyslexia and autism spectrum disorder, as well as the potential co-occurrence of these conditions, to better understand how AI-assisted learning tools can support diverse learners. Nonetheless, our findings demonstrate that students with higher ADHD symptom severity especially benefited from AI-assisted audio-learning.

Another limitation of our study is the inability to assess the impact of AI-assisted audio learning on different exam question types, such as multiple-choice versus open-ended questions. This prevents us from determining if the intervention differentially enhances skills like word recognition for multiple-choice questions or concept comprehension for open-ended ones. Future research should examine performance across different question types to identify where AI-assisted audio learning is most effective.

Other limitations include the lack of blinding, which may have introduced bias, as participants were aware of the intervention they received. However, it is worth noting that in educational interventions, complete blinding is often impractical or unfeasible, as students naturally become aware of the resources they are using and may discuss them with each other. Further, the mediation effects (e.g., motivation and reading engagement) provide robust evidence that the observed effects are attributable to the audio intervention itself, rather than participants' awareness of the study design. Still, future research could implement an active control condition where participants receive an alternative intervention (e.g., non-AI-generated audio materials or AI-generated video content). In addition, while we measured audio usage, we could not confirm the extent to which participants actively listened to the material, as it is possible they pressed play without fully engaging. Future research could address this limitation by incorporating attention-monitoring tools, such as embedded quiz questions to verify active listening. Further, the audio materials were hosted on a secure platform that required individual logins, making it unlikely that participants could share the content. However, the possibility of sharing cannot be completely ruled out.

Finally, as pre-registered, participants in the experimental group who listened to less than 20% of the audio-learning materials were excluded from the analysis. This decision was made to evaluate the audio-learning modules' efficacy among those who actively engaged, as including non-engaged participants would conflate the effects of the intervention with a lack of exposure. Additionally, including non-engaged participants would create an unfair comparison with the control group, as their lack of engagement would align them more closely with controls than active users. However, it is worth noting that individuals may have different learning preferences, and audio-based learning is not effective or appealing for everyone. The exclusion of approximately half of the participants in the experimental group suggests that the audio-learning modules may not have been sufficiently engaging for all students. Future studies should explore strategies to improve engagement, while also considering individual learning preferences and identifying the factors that influence why some students choose to engage and others do not.

Despite these limitations, the study has notable strengths. Unlike much of the previous research on audio-learning, this study employed a randomized controlled trial design with a large sample size, allowing for causal inferences. Furthermore, this study is the first to provide empirical evidence on the impact of AI-assisted audio-learning on student motivation, learning behaviors and outcomes. Finally, this study addresses how AI-generated audio content can promote inclusive learning, particularly benefiting students experiencing learning difficulties.

6.4. Conclusion

In conclusion, this pre-registered study demonstrates that AI-assisted audio-learning enhances academic achievement by increasing motivation and reading engagement. These results underscore the value of integrating AI-assisted audio-learning modules as a flexible, accessible tool within digital learning environments. Importantly, students with greater ADHD symptom severity appear to benefit particularly from audio-learning, suggesting that AI-assisted learning tools can help bridge achievement gaps. As educational technologies continue to evolve, AI-enhanced learning tools offer promising avenues for addressing diverse learner needs and improving educational outcomes across the board.

CRediT authorship contribution statement

Nanda R. Jafarian: Writing – review & editing, Software,

Methodology, Investigation, Formal analysis. **Anne-Wil Kramer:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to clarify writing style. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The audio-learning materials used in this study were developed by the authors in collaboration with Anywyse B.V. The senior author is partly employed by Anywyse B.V (1 day/week). However, employment played no role in the validity of the results. The study was pre-registered and code has been made publicly available. Data is available upon request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.caeai.2024.100357.

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