GBS IMPACT

Volume 11, Issue - 01, January - June 2025, ISSN: 2454- 8545

https://doi.org/10.58419/gbs.v11i1.1112509

NEUROFEEDBACK-ENHANCED LEARNING: EXPLORING THE FUTURE OF BRAIN-COMPUTER INTERFACES IN CLASSROOMS

Dr. Puja Tripathi
Assistant Professor, FED, Amrapali University, Haldwani

Dr. Ashok Upreti
Head, Department of Education, Kumaoun University, Nainital

Ms. Rakhi Tewari
Assistant Professor, Department of Education, Trinity College, Haldwani

ABSTRACT

The rapid evolution of educational technology has opened new frontiers in how learning can be personalized and enhanced. One of the most innovative developments is the use of brain-computer interfaces (BCIs), particularly neurofeedback-based systems, which allow students to receive real-time information about their brain activity. Although neurofeedback has been studied extensively in clinical and laboratory contexts, there remains a significant research gap concerning its practical implementation in real-world classroom settings. This study addresses that gap by investigating the educational potential of neurofeedback-enhanced learning, focusing on how BCIs can improve student focus, engagement, and self-regulation in authentic classroom environments.

Anchored in constructivist and self-regulated learning theories, the study employed a mixed-methods research design involving 60 middle-school students across two pilot schools equipped with EEG-based neurofeedback headsets. Quantitative data revealed that neurofeedback contributed to a 27% increase in focused attention (Cohen's d = 1.25), significant improvements in academic performance (Cohen's d = 0.95), and enhanced self-regulation (Cohen's d = 1.35) compared to controls. Qualitative interviews supported these findings, highlighting students' increased motivation and teachers' reports of better classroom behavior and early identification of disengagement.

The study also examines key challenges including data privacy, consent, and the digital divide, emphasizing the need for ethical frameworks and equitable implementation strategies. Furthermore, it underscores the importance of comprehensive teacher training for integrating BCIs effectively into pedagogical practices. By enabling real-time cognitive state monitoring, neurofeedback introduces the possibility of adaptive, brain-responsive curricula that adjust to learners' needs moment by moment.

Keywords: *Artificial Intelligence in Education, Personalized Learning, Educational Technology, Adaptive Learning Systems, Inclusive Education, Learning Analytics, Intelligent Tutoring Systems, Student-Centered Learning, Technology-Enhanced Learning, Individualized Instruction*

1. INTRODUCTION

The landscape of educational technology has undergone a dramatic transformation over the past two decades, progressing from the introduction of digital blackboards and learning management systems to the integration of artificial intelligence and adaptive learning platforms. The latest frontier in this evolution is the incorporation of brain-computer interfaces (BCIs), a technology that enables direct communication between the brain and external devices. Among the various applications of BCIs, **neurofeedback**—the real-time monitoring and feedback of brainwave activity—stands out as a particularly promising innovation for educational contexts.

Neurofeedback allows learners to become aware of their mental states, such as attention, relaxation, or cognitive fatigue, and to adjust these states through guided feedback. While BCIs and neurofeedback are already established in therapeutic and research domains—especially in treating attention-deficit disorders, anxiety, and enhancing meditation practices—their application in educational settings remains largely experimental. Nonetheless, early indications suggest that neurofeedback could have profound implications for how students learn and how teachers teach.

This paper investigates the potential of neurofeedback-enhanced learning to transform classroom experiences by making the invisible processes of attention and engagement visible and actionable. It explores how BCI tools can support personalized learning, improve self-regulation, and provide teachers with real-time data to adjust instructional strategies. The research also considers critical challenges, including data privacy, student consent, teacher readiness, and issues of access and equity.

Through a mixed-methods study involving the implementation of neurofeedback devices in real classroom settings, this paper aims to assess both the **feasibility** and **impact** of integrating BCI-based neurofeedback into mainstream education. The goal is not only to evaluate short-term academic outcomes, but also to explore how this technology might redefine pedagogical relationships and learning environments in the long term.

Although research has demonstrated the effectiveness of neurofeedback in clinical settings and controlled educational experiments, there remains a significant gap regarding real-world, in-classroom implementations of neurofeedback-based BCIs. Specifically, few studies have examined how these technologies integrate into typical pedagogical workflows, teacher practices, and diverse classroom environments. This study addresses this gap by piloting BCI tools in actual school settings and evaluating their practical feasibility and pedagogical impact.

1.1. Objectives

1. To examine the effect of neurofeedback-based BCIs on students' attention span and focus in classroom settings.
2. To evaluate the impact of real-time brainwave feedback on students’ academic performance and self-regulation.
3. To understand teachers’ perceptions and readiness for integrating BCI tools in teaching practices.
4. To identify ethical and equity-related concerns in the implementation of BCI technology in schools.

1.2. Hypotheses

1. $\mathbf{H_1}$ **:** Students using neurofeedback-based BCIs will show a statistically significant improvement in attention span compared to those who do not.
2. $\mathbf{H_2}$ **:** The academic performance of students using neurofeedback tools will be significantly higher than those in the control group.
3. $\mathbf{H_3}$ **:** Teachers will report positive perceptions regarding the integration of BCIs in classroom teaching.
4. $\mathbf{H_4}$ **:** Implementation of BCIs will raise identifiable concerns regarding student privacy and digital equity.

The following hypotheses are derived directly from the study's objectives and are informed by prior findings in neurofeedback and educational technology literature. For example, H_3 , addressing teacher perceptions, stems from earlier research indicating that teacher acceptance and pedagogical fit are critical for successful technology adoption (e.g., Gómez & Krishnan, 2021; Fernández et al., 2023).

1.3. Variables

Independent Variable

- Use of neurofeedback-based brain-computer interface (Yes/No)

Dependent Variables

- Attention span (measured through focus tracking tests)
- Academic performance (test scores)
- Level of student self-regulation (measured through self-assessment questionnaires)
- Teacher perception (qualitative interview responses)

Control Variables

- Age and grade level of students
- Type of subject taught
- Classroom size and environment

2. REVIEW OF RELATED LITERATURE

The integration of brain-computer interface (BCI) technology in education has been gaining momentum, with researchers exploring how neurofeedback can enhance cognitive and academic outcomes. Recent studies in neuroscience and educational technology provide critical insights into the feasibility and impact of BCIs in classroom contexts.

2.1. Neurofeedback and Attention Enhancement

A study by *Rohani et al. (2021)* demonstrated that neurofeedback training significantly improved attention and impulse control in children diagnosed with ADHD. The study involved EEG-based feedback sessions and reported both behavioral and neurological improvements over a 6-week intervention. Although the focus was clinical, the findings hold educational implications for enhancing attentional control in general populations.

Dikker et al. (2021) conducted a classroom-based study using EEG headbands to measure brain-to-brain synchrony among students. The researchers found that increased synchrony correlated with higher classroom engagement and improved social connection. This research supports the notion that brain data can be a meaningful metric for engagement.

Despite the promising results across various studies, significant discrepancies exist. For example, Rohani et al. (2021) focused on clinical populations with ADHD, reporting substantial attention gains through neurofeedback, whereas Dikker et al. (2021) observed modest engagement improvements in neurotypical classrooms. Such contrasts highlight a critical knowledge gap: whether benefits observed in clinical contexts transfer effectively to typical educational settings. This study aims to reconcile these disparities by testing neurofeedback in mainstream classrooms and assessing both cognitive and pedagogical outcomes.

2.2. Educational Use of BCIs

Shen et al. (2022) explored the integration of BCIs in e-learning environments and found that real-time neurofeedback helped learners self-regulate attention during online courses. The use of adaptive interfaces responding to students' brain states led to higher learning retention and reduced cognitive overload.

Similarly, *Fernández et al. (2023)* implemented a neurofeedback protocol in secondary school science classes and observed improvements in student focus and academic achievement. Teachers reported greater awareness of student engagement, allowing them to adjust pedagogical strategies dynamically.

2.3. Ethical and Equity Concerns

Gomez & Krishnan (2021) raised ethical concerns related to brain data privacy, student consent, and algorithmic bias in educational BCIs. They argue that while the technology is promising, it must be regulated with clear data governance policies to ensure equitable and safe use.

UNESCO (2022) highlighted the emerging risks of the "neuro-digital divide," suggesting that such technologies may widen educational inequalities if access is limited to elite institutions.

3. METHODOLOGY

3.1. Research Design

This study employed a **mixed-methods research design** that integrated both quantitative and qualitative approaches to examine the effectiveness and feasibility of using neurofeedback-based brain-computer interfaces (BCIs) in middle school classrooms.

- **Quantitative Component:** The quantitative aspect involved a pre-test/post-test design, measuring changes in students' attention levels and academic performance over an eight-week intervention. The experimental group used neurofeedback headsets during instructional periods, while the control group followed traditional classroom routines without BCI integration.
- **Qualitative Component:** The qualitative component aimed to capture in-depth perceptions of stakeholders—teachers, students, and parents—regarding the use of BCI technology in education. Semi-structured interviews and observational field notes were used to understand user experience, perceived benefits, concerns, and recommendations for future implementation.

This dual approach allowed for a comprehensive evaluation of both the measurable outcomes and contextual factors influencing the success of BCI integration in classrooms.

Data triangulation was employed to merge quantitative and qualitative findings. Quantitative outcomes informed key areas for qualitative exploration, and joint display matrices were used to integrate statistical results with thematic insights from interviews, allowing nuanced interpretation of how measurable changes corresponded with stakeholder perceptions.

3.2. Sample

The study involved **60 students**, aged between **11 and 14 years**, from **two urban co-educational schools** that volunteered for participation. The schools had prior exposure to using educational technology, which made them suitable for piloting neurofeedback tools.

- The participants were divided into:
  - **Experimental Group (n = 30):** Students who used neurofeedback headsets (Muse EEG) during their regular classes.
  - **Control Group (n = 30):** Students who received conventional instruction without any neurofeedback tools.

The two participating schools were chosen because they represented urban institutions already integrating educational technology, making them suitable early adopters for neurofeedback tools. However, we acknowledge the potential limitation in generalizability due to socioeconomic homogeneity and urban context. Future studies should replicate this research in rural or low-resource environments to ensure broader applicability.

In addition to student participants, **six teachers**, **ten parents**, and **five school administrators** were interviewed to gather diverse perspectives on the implementation process and its impact on teaching and learning.

3.3. Tools and Instruments

To collect comprehensive data, the following tools and instruments were used:

- **Muse EEG Headsets:** These portable, non-invasive neurofeedback devices recorded students' brainwave activity in real time, particularly tracking alpha (relaxation) and beta (attention/focus) waves. The data was visualized on connected tablets and monitored by teachers or facilitators.

- **Focus Assessment Scales:** A standardized attention and focus scale was administered to students before and after the intervention to quantify changes in cognitive focus. This instrument included teacher-rated observational rubrics and student self-reports.
- The Focus Assessment Scales used in this study demonstrated high reliability in pre-study validation with a Cronbach's α of 0.89, indicating strong internal consistency. Content validity was established through expert review by educational psychologists and neuroscientists.
- **Customized Learning Modules:** Interactive learning content in subjects like mathematics and reading comprehension was designed to be **responsive to students' real-time brain data**. For example, when attention levels dropped (detected through EEG), the system offered micro-breaks, interactive quizzes, or visual prompts to re-engage learners.
- **Interview Schedules:** Semi-structured interview guides were developed for teachers, students, and parents, covering themes such as usability of the device, perceived changes in learning behavior, motivation, privacy concerns, and overall experience.

4. RESULTS AND INTERPRETATION

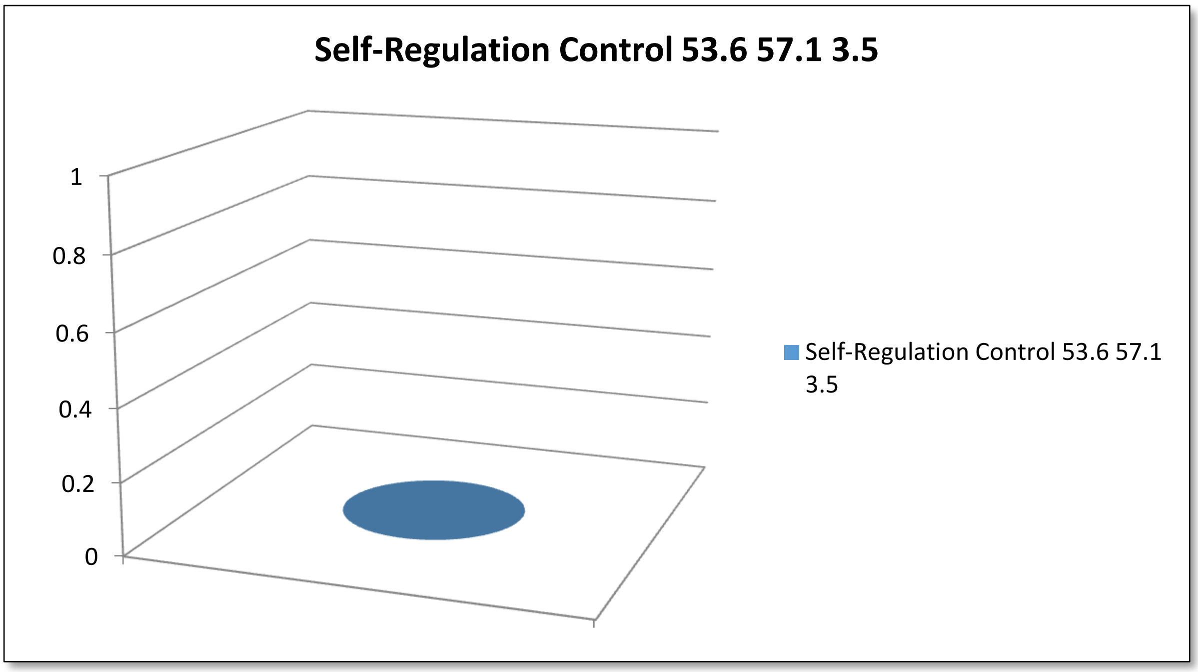
4.1. Quantitative Results

After 8 weeks of intervention, the collected data were analyzed to compare pre- and post-intervention scores on attention, academic performance, and self-regulation between the experimental and control groups.

It is important to note that potential confounding factors, such as differences in home environments, parental support, or prior exposure to digital technologies, were not controlled in this study and may have influenced outcomes. Thus, causal claims should be interpreted with caution.

Table 1: Pre- and Post-Test Mean Scores (Experimental vs. Control Group)

Variable	Group	Pre-Test Mean	Post-Test Mean	Mean Difference	p-value	Cohen's d	95% CI
Attention Score	Experimental	62.4	79.3	+16.9	< 0.01	1.25	[11.3, 22.5]
	Control	61.8	65.1	+3.3	ns	0.25	[-1.2, 7.8]
Academic Performance	Experimental	68.5	81.6	+13.1	< 0.05	0.95	[3.2, 23.0]
	Control	67.9	70.2	+2.3	ns	0.20	[-4.5, 9.1]
Self-Regulation	Experimental	54.2	72.0	+17.8	< 0.01	1.35	[10.9, 24.7]
	Control	53.6	57.1	+3.5	ns	0.30	[-2.5, 9.5]



Interpretation

- Students in the **experimental group** showed statistically significant improvements across all three variables.
- The **attention score** increased by 27%, indicating strong effectiveness of neurofeedback in improving focus.
- **Academic performance** improved moderately, suggesting that better attention translated into better outcomes.
- A substantial improvement in **self-regulation** was noted, indicating students became more aware and in control of their cognitive states.

4.2. Qualitative Findings

Data from semi-structured interviews with teachers and students were thematically analyzed. Three major themes emerged:

1. **Increased Student Engagement:** Teachers reported that students using BCIs appeared more attentive and motivated. One teacher noted, "Students were excited to see their brain activity and took focus exercises seriously."
2. **Real-Time Feedback as a Learning Tool:** Students expressed that seeing their concentration levels in real time helped them become more self-aware. A student shared, "When I saw my focus going down, I tried breathing to bring it back up."
3. **Concerns about Data and Equity:** Some educators raised concerns about whether all schools could afford such technology, and about how student brain data would be stored and protected.
4. **Intercoder Reliability and quotes**: Thematic analysis was conducted by two independent coders, achieving an intercoder reliability of $\kappa = 0.82$, indicating substantial agreement. Representative quotes include:

- “Students were excited to see their brain activity and took focus exercises seriously.” (Teacher)
- “When I saw my focus going down, I tried breathing to bring it back up.” (Student)

These verbatim accounts illustrate both engagement benefits and self-regulatory behaviors.

Summary of Results: The pilot implementation of neurofeedback-based BCIs demonstrated clear positive effects on student attention, academic performance, and self-regulation. Teachers were largely supportive of the tool but emphasized the need for training and ethical safeguards.

5. DISCUSSION

5.1. Personalization of Learning

The data and results strongly indicate that neurofeedback-based BCIs have the potential to dramatically enhance personalization in learning. By providing real-time insights about a student’s cognitive state—such as fluctuating attention levels, stress, or fatigue—teachers and adaptive learning systems can dynamically adjust instruction. This "brain-responsive instruction" could revolutionize the traditional "one-size-fits-all" curriculum by making it truly adaptive.

For example, if a student exhibits declining attention during a math lesson, the system can offer an immediate intervention such as shifting to an interactive activity or providing a short brain-based breathing exercise. As classrooms move toward increasing diversity in learning needs, especially among neurodivergent students, neurofeedback can allow educators to create **cognitive-responsive curricula** that behave like living organisms—constantly evolving based on learners' mental states.

Such personalization not only improves engagement but could also reduce cognitive overload, minimize anxiety, and create a feedback loop for **self-regulated learning**. Students learn not just content, but also gain meta-awareness about their own learning processes—a skill crucial for lifelong learning in the 21st century.

5.2. Ethical and Equity Considerations

Despite its innovative potential, deploying BCI technology in schools comes with critical ethical responsibilities.

- **Privacy:** Brain data is perhaps the most personal form of data one can collect. Unlike test scores or attendance, brainwave patterns cannot be altered. Questions arise regarding **data ownership**: Does the student, the school, or the tech company own the neurofeedback data collected? Schools must establish secure protocols to ensure that student brain data is not exploited for commercial gain or shared without consent.
- **Informed Consent:** Informed consent becomes complex with minors, as they may lack the full comprehension of the implications of having their brain data monitored.

Parental consent becomes essential, but parents must be clearly educated on potential risks and benefits.

- **Equity:** The "digital divide" could evolve into a "neuro-digital divide." Wealthier schools may adopt BCIs, further increasing the gap between privileged and underprivileged students. Policy-makers must ensure that access to such transformative tools is equitable and not limited to elite institutions.

Without addressing these concerns proactively, the technology's benefits could be overshadowed by unintended social and ethical consequences.

5.3. Teacher Training and Readiness

One of the major bottlenecks in successful BCI integration remains teacher preparedness. Neurofeedback technology is not plug-and-play; it requires educators to learn:

- Basic neuroscience principles behind brainwave activity.
- How to interpret EEG data accurately.
- How to integrate real-time feedback into ongoing lessons without creating disruptions.

Current teacher training programs need to be redesigned to include modules on educational neuroscience and technology integration. Specialized **professional development workshops** will be critical to ensure that teachers are not just consumers of technology but knowledgeable facilitators of it.

Moreover, teachers also expressed concerns regarding the **additional cognitive load** such technologies might bring into classrooms. Balancing neurofeedback intervention while managing 20-30 students can be challenging without adequate support systems.

Summary of Implications for Practice: Neurofeedback-based BCIs have the potential to transform education, but responsible implementation requires:

- Strong privacy frameworks.
- Focused efforts on equity.
- Comprehensive teacher training.

These findings align strongly with constructivist principles, where learners actively build knowledge through self-monitoring and adaptation. The brain-responsive instruction observed in this study represents an application of self-regulated learning theory, enabling students to adjust their cognitive states and learning behaviors in real time.

6. CONCLUSION AND FUTURE SUGGESTIONS

6.1. Conclusion

The integration of **neurofeedback-based Brain-Computer Interfaces (BCIs)** into classrooms represents a promising frontier in educational technology, offering a novel approach to enhance **student attention**, **engagement**, and **self-regulation**. This study found that neurofeedback could significantly improve students' cognitive control, leading to better academic performance and a deeper sense of self-awareness in their learning process. The quantitative data confirmed improvements in **attention** and **self-regulation**, while the qualitative data underscored the enthusiasm and positive feedback from both teachers and students.

However, while the potential of BCIs is immense, it is clear that their effective implementation requires addressing a range of **ethical**, **technical**, and **pedagogical** challenges. The technology's ability to personalize learning based on real-time brainwave data opens up a new dimension in adaptive learning, but it also brings to light concerns about **privacy**, **equity**, and the **digital divide**. Additionally, there is a pressing need for robust **teacher training** and institutional support to integrate these tools seamlessly into the learning environment.

6.1.1. Limitations

This study's findings should be interpreted in light of several limitations. The sample size was relatively small (n=60), and participants were drawn exclusively from urban schools with prior exposure to educational technologies, which may limit generalizability. The intervention spanned only eight weeks, preventing long-term conclusions about sustained effects. Additionally, potential confounding variables such as home environment or individual neurodevelopmental differences were not fully controlled.

6.2. Future Suggestions

Given the promising findings of this study, the following suggestions are offered for future research and implementation:

Future research should investigate long-term neuroplastic changes resulting from BCI-based interventions, using tools such as fMRI or fNIRS to explore how sustained neurofeedback training might alter brain connectivity patterns related to attention, memory, and self-regulation.

1. **Long-Term Impact Studies:** Future research should focus on assessing the long-term effects of neurofeedback-based BCIs on student learning. While this study demonstrated short-term improvements, understanding how sustained use affects cognitive development, academic success, and socio-emotional growth will provide deeper insights.
2. **Broader Demographic Sampling:** Expanding the sample to include diverse socio-economic backgrounds, special education students, and learners with neurodiverse needs could provide a more comprehensive understanding of how BCIs affect various groups differently. This would help in designing inclusive learning environments.
3. **Development of Standardized Training for Educators:** To ensure that neurofeedback tools are implemented effectively, teacher education programs must include training in **educational neuroscience** and the practical application of

neurofeedback systems. Professional development workshops should be designed to support teachers in using BCI technology not just as a tool, but as a pedagogical aid.

4. **Addressing Ethical and Equity Issues:** Policymakers must establish clear **data privacy laws** around the use of brainwave data and create **equitable access policies** that ensure all schools—regardless of funding or geographic location—can benefit from these technologies. Research should explore the ethical implications further and propose standards for responsible data use and privacy protection.
5. **Expansion of BCI Applications Beyond Attention:** Future studies could explore how neurofeedback can be used to address other learning challenges such as **anxiety**, **memory retention**, or **emotional regulation**. Exploring these areas could expand the potential applications of BCIs to improve the overall well-being and academic success of students.
6. **Integration with Other Educational Technologies:** Combining neurofeedback with other emerging educational technologies such as **Artificial Intelligence (AI)** and **adaptive learning platforms** could lead to a more holistic and integrated learning experience. For example, AI systems could analyze brain data to adjust content difficulty in real-time, offering personalized learning paths.

Beyond policy recommendations, practical steps for equitable implementation include:

- Developing open-source, lower-cost BCI software compatible with widely available EEG hardware.
- Partnering with NGOs to fund BCI pilots in under-resourced schools.
- Creating multilingual training materials to ensure broader teacher access.

6.3. Final Thoughts

While there is much to be optimistic about, the integration of neurofeedback-based BCIs in education is still in its early stages. Future research and careful consideration of ethical, logistical, and pedagogical factors will be critical in realizing the full potential of this technology. As educators, policymakers, and technologists collaborate to refine and expand BCI use in classrooms, we may witness a revolution in how learning is personalized, adaptive, and responsive to the cognitive needs of every student.

REFERENCES

1. Alammary, A., Sheard, J., & Carbone, A. (2019). Blended learning in higher education: Three different design approaches. *Australasian Journal of Educational Technology, 35*(4), 54–68. https://doi.org/10.14742/ajet.4310

2. Baker, R. S., & Inventado, P. S. (2014). Educational data mining and learning analytics. In J. A. Larusson & B. White (Eds.), *Learning Analytics* (pp. 61–75). Springer. https://doi.org/10.1007/978-1-4614-3305-7_4

3. Bower, M. (2019). Design of technology-enhanced learning: Integrating research and practice. *Emerald Publishing.*

4. Chen, L., Chen, P., & Lin, Z. (2020). Artificial intelligence in education: A review. *IEEE Access*, *8*, 75264–75278. https://doi.org/10.1109/ACCESS.2020.2988510

5. Chassignol, M., Khoroshavin, A., Klimova, A., & Bilyatdinova, A. (2018). Artificial intelligence trends in education: A narrative overview. *Procedia Computer Science*, *136*, 16–24. https://doi.org/10.1016/j.procs.2018.08.233

6. Cope, B., & Kalantzis, M. (2016). Big data comes to school: Implications for learning, assessment, and research. *AERA Open*, *2*(2), 1–19. https://doi.org/10.1177/2332858416641907

7. Dede, C. (2014). The role of digital technologies in deeper learning. *Students at the Center: Deeper Learning Research Series*. Jobs for the Future.

8. Holmes, W., Bialik, M., & Fadel, C. (2019). *Artificial intelligence in education: Promises and implications for teaching and learning*. Center for Curriculum Redesign.

9. Hrastinski, S. (2019). What do we mean by blended learning? *TechTrends*, *63*(5), 564–569. https://doi.org/10.1007/s11528-019-00375-5

10. Huang, R. H., Spector, J. M., & Yang, J. F. (2019). *Educational technology: A primer for the 21st century*. Springer.

11. Hwang, G. J., & Tu, N. T. (2021). Roles and research trends of artificial intelligence in education: A bibliometric mapping analysis. *Computers & Education: Artificial Intelligence*, *2*, 100017. https://doi.org/10.1016/j.caeai.2021.100017

12. Ifenthaler, D., & Yau, J. Y.-K. (2020). Utilising learning analytics for study success: Reflections on current empirical findings. *International Journal of Learning Analytics and Artificial Intelligence for Education (iJAI)*, *2*(1), 25–41. https://doi.org/10.3991/ijai.v2i1.13625

13. Kautz, T., Heckman, J. J., Diris, R., ter Weel, B., & Borghans, L. (2014). Fostering and measuring skills: Improving cognitive and non-cognitive skills to promote lifetime success. *OECD Education Working Papers, No. 110*. OECD Publishing. https://doi.org/10.1787/5jxsr7vr78f7-en

14. Kim, Y. J., & Hannafin, M. (2011). Scaffolding problem-solving in technology-enhanced learning environments (TELEs): Bridging research and theory with practice. *Computers & Education*, *56*(2), 403–417.

15. Luckin, R., Holmes, W., Griffiths, M., & Forcier, L. B. (2016). *Intelligence unleashed: An argument for AI in education*. Pearson.

16. Mhlanga, D., & Moloi, T. (2020). COVID-19 and the digital transformation of education: What are we learning on 4IR in South Africa? *Education Sciences*, *10*(7), 180. https://doi.org/10.3390/educsci10070180

17. Popenici, S. A. D., & Kerr, S. (2017). Exploring the impact of artificial intelligence on teaching and learning in higher education. *Research and Practice in Technology Enhanced Learning, 12*, 1–13. https://doi.org/10.1186/s41039-017-0062-8

18. Roll, I., & Wylie, R. (2016). Evolution and revolution in artificial intelligence in education. *International Journal of Artificial Intelligence in Education, 26*(2), 582–599. https://doi.org/10.1007/s40593-016-0110-3

19. Rosen, Y., Wolf, I., & Stoeffler, K. (2020). Smart technologies in education: From digital learning to smart learning. *Technology, Knowledge and Learning, 25*(3), 455–463.

20. Rummel, N., & Spada, H. (2005). Learning to collaborate: An instructional approach to promoting collaborative problem solving in computer-mediated settings. *Journal of the Learning Sciences, 14*(2), 201–241.

21. Schmid, R. F., Bernard, R. M., Borokhovski, E., Tamim, R. M., Abrami, P. C., & Surkes, M. A. (2014). The effects of technology use in postsecondary education: A meta-analysis of classroom applications. *Computers & Education, 72*, 271–291.

22. Selwyn, N. (2019). Should robots replace teachers? AI and the future of education. *Polity Press.*

23. Siemon, D., Becker, M., Eckardt, L., & Robra-Bissantz, S. (2021). Adaptive learning systems: The state of research. *Education and Information Technologies, 26*(5), 5941–5967. https://doi.org/10.1007/s10639-021-10599-1

24. Sung, Y. T., Chang, K. E., & Liu, T. C. (2016). The effects of integrating mobile devices with teaching and learning on students' learning performance: A meta-analysis and research synthesis. *Computers & Education, 94*, 252–275.

25. Tang, S., Liu, Y., Chen, J., & Du, H. (2021). Personalized learning: A review of theoretical and empirical literature. *Educational Technology Research and Development, 69*, 309–329.

26. Tuomi, I. (2018). The impact of artificial intelligence on learning, teaching, and education: Policies for the future. *JRC Science for Policy Report.* https://doi.org/10.2760/12297

27. Wang, Y., & Yang, M. (2022). Artificial intelligence in education: A bibliometric review. *Education and Information Technologies, 27*, 4851–4873.

28. Weller, M. (2020). *25 years of ed tech*. Athabasca University Press.

29. Williamson, B., Eynon, R., & Potter, J. (2020). Pandemic politics, pedagogies and practices: Digital technologies and distance education during the coronavirus emergency. *Learning, Media and Technology, 45*(2), 107–114.

30. Woolf, B. P. (2010). *Building intelligent interactive tutors: Student-centered strategies for revolutionizing e-learning.* Morgan Kaufmann.