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CONTENTS

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Children as Emerging Investigators: Scientific Process Skills and Inquiry Ecology in Nature-Based Early Childhood Classrooms

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Abstract

This study examines the baseline scientific process skill profiles of 4–5-year-old children participating in a nature-based science program developed through a Turkish–U.S. partnership funded by TÜBİTAK. The intervention was aligned with both the Next Generation Science Standards (NGSS) for K–2 and the United Nations Sustainable Development Goals (SDGs), integrating early science learning with global sustainability competencies. Using a mixed-methods embedded case study design, pre-test data were collected from experimental ($n = 14$) and control ($n = 13$) groups attending a public preschool in Bloomington, Indiana. The Science Observation Form (Kuru & Akman, 2017) showed strong internal consistency (Cronbach's $\alpha = .896–.961$). Mann-Whitney U tests revealed significantly higher baseline scores for the experimental group on Scientific Process Skills ($U = 140.0$, $p = .017$) and total scores ($U = 132.5$, $p = .046$), with no differences on Problem Solving or Scientific Attitudes. Qualitative observations documented emergent inquiry behaviors, including prediction-testing cycles, explanatory language, variable awareness, and peer collaboration. The teacher reported strong curricular compatibility, indicating high ecological validity. These findings underscore the need for baseline-adjusted models in subsequent effect estimation and strengthen the evidence base for nature-based early science education within globally relevant sustainability frameworks.

Introduction

Early childhood represents a uniquely sensitive period for the development of scientific thinking, as young children naturally engage with their environment through observation, exploration, and questioning (Greenfield et al., 2024). The innate curiosity of preschool-aged children, when intentionally supported through developmentally appropriate pedagogical design, can be channeled into foundational scientific process skills—observing, classifying, predicting, measuring, inferring, and communicating—that serve as precursors to formal scientific reasoning (Speldewinde & Campbell, 2025). However, translating these natural behaviors into structured scientific competencies requires learning environments that provide rich, authentic opportunities for inquiry while respecting the play-based, experiential nature of early childhood learning (Trina et al., 2024).

In recent years, nature-based learning (NBL) has emerged as a particularly promising pedagogical approach for early science education. By situating learning in outdoor and nature-rich environments, NBL offers children direct, hands-on experiences with natural phenomena, fostering not only environmental awareness but also the core practices of scientific inquiry: asking questions, planning investigations, collecting data, and constructing explanations (Ardoin & Bowers, 2020; Brussoni et al., 2015; Chawla, 2015). The affordances of natural environments—soil that invites classification, wind that invites prediction, shadows that invite causal reasoning—provide unique opportunities for scientific thinking that are often absent in traditional classroom settings (Gibson, 1979; Mifflin, 2023). Nevertheless, despite growing enthusiasm for nature-based early childhood education, there remains a limited evidence base documenting precisely how such interventions influence young children's scientific process skills, particularly in cross-cultural and collaborative research contexts (Kavak, 2024; Sarı, 2022).

This study addresses this gap by presenting baseline findings from a nature-based science activity program implemented in a public preschool in Bloomington, Indiana, through a collaborative partnership between Turkish and U.S. researchers. The intervention was designed with a dual-alignment framework, integrating the Next Generation Science Standards (NGSS) for K–2 with the United Nations Sustainable Development Goals (SDGs). This dual alignment ensures that the program is not only pedagogically robust and internationally recognized but also positions early science education within a broader global framework of sustainability, equity, and responsible citizenship—a critical consideration given the urgent environmental challenges facing the next generation (UNESCO, 2017; Somerville & Williams, 2015).

The present study reports on the first phase of a larger embedded case study (Yin, 2003), focusing on pre-test data collected using the Science Observation Form (Kuru & Akman, 2017) and qualitative classroom observations. The research was guided by the following questions:
1. What are the baseline scientific process skill profiles of experimental and control groups before the intervention?
2. How do the groups compare in terms of total scores and sub-dimensions (scientific process skills, problem solving, scientific attitudes)?
3. What qualitative patterns of engagement and inquiry behavior emerge during the initial implementation of nature-based activities?
4. What methodological implications arise from baseline group differences for subsequent intervention effect analyses?

By integrating quantitative reliability and group comparison analyses with rich qualitative observations, this study contributes to the growing literature on nature-based early science education by offering a nuanced, context-sensitive understanding of how play in natural environments can serve as a fertile ground for the emergence of scientific reasoning in early childhood, while simultaneously advancing global sustainability competencies.

Theoretical Framework

The theoretical foundation of this study integrates three interconnected perspectives: (1) affordance theory (Gibson, 1979), which explains how environmental features invite specific learning behaviors; (2) experiential learning theory (Dewey, 1938; Kolb, 1984), which emphasizes learning through direct experience and reflection; and (3) sociocultural theories of play and learning (Vygotsky, 1978), which highlight the role of social interaction and guided participation in cognitive development. Together, these perspectives frame nature-based play as a unique pedagogical context in which children can actively construct scientific knowledge through exploration, experimentation, and communication.

Affordance Theory and Nature-Based Learning

Affordance theory posits that environments offer specific opportunities for action and learning that are perceived and taken up by individuals based on their capabilities and intentions (Gibson, 1979). In natural environments, affordances for scientific inquiry are abundant: soil offers opportunities for observation and classification; moving water offers opportunities for prediction and measurement; shadows offer opportunities for causal reasoning about light and position. Mifflin (2023) found that nature preschools afford STEM-related skills primarily through water features, climbable structures, and manipulable objects such as leaves, sticks, and stones. Similarly, Speldewinde and Campbell (2025) demonstrated that children in bush kindergarten settings spontaneously apply five interconnected science skills—observing, comparing, classifying, measuring, and communicating—when engaged in unstructured nature play. The present study extends this work by demonstrating how intentionally designed activities can amplify these natural affordances, guiding children's exploration toward specific scientific process skills without sacrificing the open-ended, play-based character of the experience.

Experiential Learning and Scientific Inquiry

Experiential learning theory (Dewey, 1938; Kolb, 1984) emphasizes that meaningful learning occurs through cycles of concrete experience, reflective observation, abstract conceptualization, and active experimentation. In nature-based settings, children naturally engage in these cycles: planting a seed (concrete experience), observing its growth over time (reflective observation), inferring that plants need water and sunlight (abstract conceptualization), and testing this inference by varying conditions (active experimentation). These cycles mirror the science and engineering practices outlined in the NGSS, including asking questions, planning and carrying out investigations, analyzing and interpreting data, and constructing explanations (NGSS Lead States, 2013). Research has consistently shown that experiential, inquiry-based approaches to early science education enhance children's ability to engage in these practices, supporting both cognitive development and scientific reasoning (Worth & Grollman, 2003; Greenfield et al., 2024).

Sociocultural Theory and Guided Participation

Vygotsky's (1978) sociocultural theory highlights the role of social interaction and adult guidance in moving children from what they can do independently to what they can achieve with support—the zone of proximal development. In the context of nature-based play, teachers act as facilitators who model scientific language, prompt predictions, encourage evidence-based reasoning, and scaffold children's emerging understanding. As noted in the teacher reflection document from this study, the classroom teacher integrated the nature-based activities into the existing curriculum with minimal disruption, preserving teacher agency while ensuring that children received appropriate guidance during inquiry activities. This alignment between theoretical principles and classroom practice is critical for the effectiveness of nature-based interventions (Ardoin & Bowers, 2020; Barrable & Barrable, 2024).

Dual Alignment: NGSS and Sustainable Development Goals

A distinctive feature of the present intervention is its dual alignment with both the NGSS for K–2 and the United Nations SDGs. The NGSS provide a coherent set of performance expectations organized around three dimensions: science and engineering practices (SEPs), disciplinary core ideas (DCIs), and crosscutting concepts (CCCs) (NGSS Lead States, 2013). For early childhood, these standards are appropriately scaffolded, with simplified vocabulary and concrete materials while maintaining the core practices of scientific inquiry. The SDGs, adopted by all United Nations member states in 2015, provide a shared blueprint for peace and prosperity for people and the planet, now and into the future (United Nations, 2015). Integrating the SDGs into early childhood science education positions young children as active contributors to sustainable futures, fostering not only scientific literacy but also environmental stewardship, social responsibility, and global citizenship (UNESCO, 2017; Somerville & Williams, 2015). The present intervention explicitly mapped each activity to relevant SDGs (see Table 1), ensuring that sustainability competencies are embedded within the science learning experience rather than treated as an add-on.

Method

In the sections below we describe the design of the research, the participants and context, and the intervention. We further describe the instrumentation and data analysis.

Research Design

This study employs an embedded case study design (Yin, 2003) with a mixed-methods approach, integrating quantitative data from the Science Observation Form (Kuru & Akman, 2017) and qualitative data from classroom observations and teacher reflections. The embedded design allows for multiple units of analysis (children, teachers, classrooms) within a single case (the nature-based play intervention), facilitating a holistic understanding of how the program influences children's scientific process skills. The study was conducted in two phases: (1) pre-test data collection and baseline analysis (reported here), and (2) intervention implementation and post-test assessment (ongoing).

Participants and Context

The study was conducted in a public preschool in Bloomington, Indiana USA serving children aged 4–5 years from diverse socioeconomic backgrounds. A stratified random sampling method was used to assign participants to experimental ($n = 14$) and control ($n = 13$) groups, ensuring comparability in age (all 4–5 years) and classroom environment. Parental consent was obtained for all participants, and the study was approved by the relevant institutional review board. All children were typically developing and attended the preschool on a full-time basis.

The experimental group received the nature-based play intervention, consisting of eight activity modules implemented over an 8-week period (see Table 1 for detailed activity descriptions). The control group continued with their regular science curriculum, which included some nature-based elements (e.g., occasional outdoor observation) but not the structured sequence of eight activities with explicit NGSS and SDG alignment. Pre-test data were collected by classroom teachers using the Science Observation Form, and additional qualitative observations were conducted by the researcher during the initial implementation week.

The Nature-Based Play Intervention: Dual Alignment with NGSS and SDGs

The intervention program comprised eight nature-based science activities, each designed to target specific scientific process skills while aligning with both NGSS performance expectations (for K–2) and relevant SDGs. Table 1 provides a comprehensive overview of the activity sequence, objectives, NGSS alignment, and SDG contributions.

Table 1. Nature-based science activity program: NGSS and SDG alignment

Activity	Core Scientific Focus	NGSS Alignment (K–2)	SDG Alignment	Key Scientific Process Skills
1. The Secret Life Beneath the Soil	Soil as habitat; living vs. non-living components	K-LS1-1 (basic needs of living things); K-ESS3-1 (organism-environment relationships)	SDG 15 (Life on Land)	Observation, classification, description, inference
2. Water Cycle Wonders	Evaporation, condensation, precipitation	K-ESS2-1 (weather observations); 2-ESS2-3 (water's distribution and forms)	SDG 6 (Clean Water); SDG 13 (Climate Action)	Prediction, observation, sequencing, cause-effect reasoning
3. Seeds of Change – From Seed to Plant	Plant growth stages; needs of living things	K-LS1-1 (basic needs of plants/animals)	SDG 2 (Zero Hunger); SDG 15 (Life on Land)	Prediction, longitudinal observation, data recording, responsibility
4. Wind Detectives – Exploring the Invisible	Wind as invisible force; effects on motion	K-ESS2-1 (weather patterns); K-PS2-1 (effects of pushes/pulls)	SDG 7 (Clean Energy); SDG 13 (Climate Action)	Prediction, experimentation, variable testing, explanation
5. Animal Architects – Homes in Nature	Animal habitats; adaptation and design	K-ESS3-1 (habitat needs); 1-LS1-1 (design solutions based on structures)	SDG 15 (Life on Land)	Observation, classification, model-building, design reasoning
6. Little Recycling Detectives	Waste sorting; reduce-reuse-recycle	K-ESS3-3 (solutions to reduce human impact)	SDG 11 (Sustainable Cities); SDG 12 (Responsible Consumption); SDG 13 (Climate Action)	Classification, problem solving, environmental reasoning, civic responsibility
7. Weather Watchers	Daily weather observation and recording	K-ESS2-1 (weather observations and patterns)	SDG 13 (Climate Action)	Observation, data representation, pattern recognition, descriptive language
8. Shadows and Light Explorers	Light as necessary for shadows; shadow variation	1-PS4-2 (visibility requires light); K-PS3-1 (sunlight as energy)	SDG 7 (Clean Energy)	Prediction, experimentation, measurement, causal reasoning, creative expression

(NGSS = Next Generation Science Standards; SDG = Sustainable Development Goal. NGSS performance expectations are structured for K–2; for ages 4–5, tasks are scaffolded with simplified vocabulary and concrete materials while maintaining science and engineering practices and crosscutting concepts.)

Each activity was designed to be implemented over 45–60 minutes, with some activities (e.g., Seeds of Change, Weather Watchers) extended across multiple days to support longitudinal observation and data collection. Activities followed a consistent pedagogical structure: (1) an introductory circle discussion to activate prior knowledge and generate questions; (2) hands-on exploration with natural or naturalistic materials; (3) structured data collection or classification; and (4) reflection and sharing to consolidate learning and develop scientific language. This structure aligns with recommended practices for inquiry-based early science education (Worth & Grollman, 2003; NSTA, 2014).

Instrumentation

This study employed a combination of quantitative and qualitative data collection instruments to provide a comprehensive assessment of children's scientific process skills. Quantitative data were obtained through a structured observation form designed to measure preschool children's science process skills, problem-solving tendencies, and attitudes toward science. Qualitative data were gathered through researcher-conducted classroom observations, teacher reflection journals, and informal debriefing conversations following the implementation sessions. Each data collection instrument is described in detail below.

Science Observation Form

The Science Observation Form (Kuru & Akman, 2017) is a 22-item observation-based instrument designed to assess preschool children's scientific process skills across three sub-dimensions: (1) Scientific Process Skills (14 items, e.g., "Makes detailed observations," "Makes inferences," "Classifies objects/events," "States predictions," "Identifies variables," "Interprets data"), (2) Problem Solving (3 items, e.g., "Solves problems multiple ways," "States problem"), and (3) Scientific Attitudes (5 items, e.g., "Confidence in science," "Perseverance," "Flexibility," "Recognizes learning"). Each item is rated on a three-point scale (1 = never, 2 = sometimes, 3 = always). The instrument has demonstrated acceptable validity and reliability in previous studies with Turkish preschool populations (Kuru & Akman, 2017) and was adapted for use in the U.S. context with minor wording modifications to ensure cultural appropriateness.

Qualitative Data Sources

Qualitative data were collected through three sources: (a) classroom observation notes recorded by the researcher during the initial implementation week, focusing on children's engagement, questioning, explanation behaviors, and peer interactions; (b) a teacher reflection document completed by the classroom teacher at the end of the implementation phase, documenting her perceptions of curricular fit, student engagement, observed cognitive shifts, and any challenges encountered; and (c) informal debriefing conversations between the researcher and the teacher following each activity session. These multiple sources were used to triangulate the quantitative findings and provide a richer, contextualized understanding of how the intervention was enacted in practice.

Data Analysis

The analysis of the collected data proceeded in two parallel yet integrated strands corresponding to the quantitative and qualitative components of the mixed-methods design. Quantitative analyses focused on descriptive statistics, internal consistency, and baseline group comparisons using nonparametric tests. Qualitative analyses employed thematic analysis to identify patterns and themes in the observation notes and teacher reflection documents. Each analytic approach is described in detail below.

Quantitative Analysis

Descriptive statistics (means, standard deviations) were calculated for total and sub-dimension scores for both groups. Internal consistency was assessed using Cronbach's alpha for the total scale and each sub-dimension, with acceptable thresholds set at $\alpha \geq .70$. Given the small sample size and non-normal distribution of some sub-dimensions as indicated by Shapiro-Wilk tests, Mann-Whitney U tests were used to compare groups at baseline, with Holm's adjustment for multiple comparisons to control Type I error. Effect sizes ($r = Z/\sqrt{N}$) were calculated for significant comparisons. All analyses were conducted using SPSS version 21.

Qualitative Analysis

Observation notes and the teacher reflection document were analyzed using thematic analysis following the six-phase approach outlined by Braun and Clarke (2006): (1) familiarization with the data, (2) generating initial codes, (3) searching for themes, (4) reviewing themes, (5) defining and naming themes, and (6) producing the report. The researcher first read all documents multiple times to achieve familiarity, then generated initial codes (e.g., "curiosity about invisible forces," "prediction language," "peer discussion," "explanation attempts," "variable awareness"). These codes were subsequently grouped into broader themes through an iterative process of comparison and refinement. Themes were reviewed and refined in consultation with a second researcher to ensure credibility and dependability. Representative quotes were selected to illustrate each theme, with pseudonyms used to protect participant confidentiality.

Validity and Reliability

Several strategies were employed to ensure the trustworthiness of the findings. For the quantitative component, internal consistency (Cronbach's alpha) was calculated for the total scale and sub-dimensions in both groups, with all values exceeding the conventional .70 threshold (see Findings). For the qualitative component, triangulation was achieved by comparing multiple data sources (observation notes, teacher reflection, debriefing conversations). Additionally, member checking was conducted by sharing preliminary qualitative findings with the classroom teacher to confirm accuracy and interpretation. The researcher also maintained a reflexive journal throughout data collection and analysis to bracket personal biases and assumptions, documenting decision points and alternative interpretations. Prolonged engagement in the classroom setting (the researcher was present for the full 8-week implementation period) further supported the credibility of the qualitative observations.

Results and Discussion

This section presents the baseline results from the pre-test phase of the study, organized according to the mixed-methods design. Quantitative findings include descriptive statistics, internal consistency estimates, and group comparisons derived from the Science Observation Form. Qualitative findings are drawn from classroom observation notes and the teacher reflection document, providing a contextualized understanding of children's engagement and inquiry behaviors during the initial implementation. The section concludes with an integration of quantitative and qualitative patterns to inform subsequent intervention analyses. Below, the quantitative baseline profiles are reported first.

Quantitative Baseline Profile

Internal Consistency of the Science Observation Form

The Science Observation Form demonstrated strong internal consistency at baseline for both groups. As shown in Table 2, Cronbach's alpha values for the total scale were .896 for the control group and .961 for the experimental group, indicating excellent reliability. Sub-dimension alphas ranged from .786 to .939, all exceeding conventional acceptability thresholds. These coefficients support the reliability of the instrument within this classroom-based sample and justify its use for subsequent comparative analyses.

Table 2. Internal consistency (Cronbach's Alpha) of the science observation form at baseline

Scale/Sub-dimension	Control Group (n = 13)	Experimental Group (n = 14)
Total Scale (22 items)	.896	.961
Scientific Process Skills (14 items)	.844	.928
Problem Solving (3 items)	.786	.842
Scientific Attitudes (5 items)	.828	.939

Descriptive Statistics and Group Comparisons

Table 3 presents descriptive statistics for total and sub-dimension scores for both groups. For the total score (maximum possible = 66), the control group had a mean of 36.08 (SD = 5.51), while the experimental group had a mean of 40.86 (SD = 8.19). For Scientific Process Skills (maximum = 42), the control group scored 20.46 (SD = 3.67), compared to the experimental group's 24.71 (SD = 4.92). Problem Solving (maximum = 6) showed a smaller difference: control group M = 3.77 (SD = 0.60), experimental group M = 3.93 (SD = 1.07). Similarly, for Scientific Attitudes (maximum = 18), the control group scored 11.85 (SD = 2.03), while the experimental group scored 12.21 (SD = 2.64).

Table 3. Baseline descriptive statistics and group comparisons

Variable	Control (n = 13) M (SD)	Experimental (n = 14) M (SD)	Mann-Whitney U	p	Effect Size (r)
Total Score	36.08 (5.51)	40.86 (8.19)	132.5	.046*	.38
Scientific Process Skills	20.46 (3.67)	24.71 (4.92)	140.0	.017*	.45
Problem Solving	3.77 (0.60)	3.93 (1.07)	88.0	.547	.12
Scientific Attitudes	11.85 (2.03)	12.21 (2.64)	86.5	.530	.04

*p < .05 (two-tailed). Effect size r calculated as $Z/\sqrt{N}$, with N = 27.

Mann-Whitney U tests indicated that the experimental group had significantly higher scores than the control group for the total score (U = 132.5, p = .046, r = .38) and for Scientific Process Skills (U = 140.0, p = .017, r = .45). No significant differences were found for Problem Solving (p = .547) or Scientific Attitudes (p = .530). Item-level analyses after Holm adjustment showed that the experimental group scored significantly higher on two items from the Scientific Process Skills sub-dimension: "Identifies variables" (U = 138.5, p = .008) and "Interprets data" (U = 135.0, p = .012). Interestingly, the control group scored significantly higher on "Measures objects" (U = 52.5, p = .023), suggesting that the two groups had different patterns of relative strength at baseline.

These baseline differences, particularly in the Scientific Process Skills domain, have important implications for subsequent analyses of intervention effects. Simple post-test comparisons would be confounded by initial group disparities; therefore, baseline-adjusted models (e.g., ANCOVA with pre-test scores as covariates) will be used to evaluate the intervention's true impact in the post-test phase. The finding that the experimental group began with higher scores on core scientific process skills also suggests that the intervention may be particularly well-suited to children who already have some emerging competencies in this area, a hypothesis that will be examined in future analyses.

Qualitative Observations: Patterns of Engagement and Inquiry

During the initial implementation of the nature-based activities, the researcher observed consistently high levels of engagement across all eight modules, with notable peaks during the wind (Activity 4), water (Activity 2), and shadow (Activity 8) activities. Children demonstrated several emergent inquiry behaviors that aligned closely with the items comprising the Scientific Process Skills sub-dimension of the quantitative instrument.

Theme 1: From Description to Explanation

A consistent pattern observed across multiple activities was children's gradual shift from simply describing what they saw to attempting causal explanations. During the water cycle activity (Activity 2), children initially produced descriptive statements about observable phenomena. After the demonstration with warm water and ice, however, their language shifted noticeably. One child remarked, "The water is going up because the sun makes it hot. Then it gets cold and makes rain." Another child added, "It's like a circle—it goes up and down and up again." The teacher reflected on this pattern in her post-implementation reflection: "By the third week, I noticed children using 'because' and 'so' much more often. They weren't just telling me what they saw—they were trying to explain why it happened. One child said, 'The shadow got bigger because I moved the light closer.' That's a real shift from how they talked at the beginning.". This movement from description to explanation is a core scientific practice and was observed most strongly in activities that involved observable but non-obvious mechanisms (water cycle, shadows, wind).

Theme 2: Prediction-Testing-Explanation Cycles

During the wind activity (Activity 4), children were asked to predict which objects (feathers, toy cars, scarves) would move most easily when placed in front of a fan. Many children spontaneously tested their predictions multiple times, adjusting their explanations based on the outcomes. The researcher's observation notes captured one such episode: "A child initially predicted that the toy car would move the most because 'it's big and strong.' After observing that the feather moved more easily, he revised his explanation: 'The feather is light, so the wind pushes it more. The car is heavy, so the wind can't push it as much.' He then tested the scarf, noting, 'The scarf is kind of light, so it moves a lot but not as much as the feather.' This spontaneous revision of explanation based on evidence was unprompted."

This type of prediction-testing-revision cycle—a simplified version of scientific methods—was observed across multiple activities and was particularly evident when the outcomes were somewhat surprising (e.g., a light object moving more than a heavy object, a shadow changing size when the light was moved).

Theme 3: Emerging Variable Awareness

The shadow activity (Activity 8) provided particularly clear evidence of children's emerging awareness of variables. Using flashlights, children explored how the size and direction of shadows change when the light source is moved. Several children spontaneously noted relationships that demonstrated variable awareness. One child stated, "If I put the light down low, the shadow gets big." Another child added, "If I move the light to the side, the shadow goes the other way." A third child experimented systematically, announcing, "See? When the light is close, the shadow is big. When I move it far away, the shadow gets small." This emerging understanding that changing one variable (light position) affects another (shadow size/direction) is a foundational skill for experimental design and was explicitly targeted in the activity design.

Theme 4: Peer Collaboration and Scientific Discourse

Throughout the activities, children frequently discussed their observations with peers, often spontaneously comparing results and building on each other's ideas. In the soil activity (Activity 1), two children examined their soil trays together:

*Child A: "I found a worm. It's alive because it's moving."**
*Child B: "I found a rock. It's not alive. Rocks don't move."**
*Child A: "Worms need dirt to live. The rock doesn't need anything."**
Child B: "So the worm is living, and the rock is non-living. We should put the worm in the living column."

This peer interaction was not directed by the teacher but emerged naturally from the shared exploratory context. The teacher noted in her reflection that such collaborative discussions became more frequent as the intervention progressed, suggesting that the nature-based activities supported not only individual scientific thinking but also the social construction of scientific knowledge.

Theme 5: Teacher-Perceived Cognitive Shifts

In the reflection document, the teacher identified three qualitative shifts she observed in her students over the 8-week intervention period: "First, they moved from passive observation to active testing. They stopped just watching and started trying things out—'What happens if I do this?' Second, they developed a greater tolerance for uncertainty. They didn't get frustrated when things didn't work the first time; they just tried again. And third, I heard more 'What if…?' questions. They were starting to think about variables before they even tested them." She also noted that the activities "fit naturally into our daily routine" and that she only needed to "swap a few lessons to better match ongoing classroom themes," indicating strong ecological validity. This finding is particularly important for scalability, as interventions that are perceived as compatible with existing classroom practices are more likely to be sustained.

Integration of Quantitative and Qualitative Findings

The qualitative observations provide a rich complement to the quantitative baseline data. While the experimental group began the study with higher scores on Scientific Process Skills, the observational data suggest that this advantage may not be solely a function of initial differences but also reflects the intervention's capacity to structure and amplify existing competencies. The high internal consistency of the instrument in both groups (.896–.961) supports its reliability for capturing these competencies, while the qualitative themes—prediction, testing, explanation, collaboration, variable awareness—map directly onto the items in the Scientific Process Skills sub-dimension (e.g., "Makes predictions," "Tests predictions," "Explains observations," "Cooperates with others," "Identifies variables"). Together, these findings suggest that nature-based play can serve as a fertile context for the emergence of early scientific reasoning, but that baseline-adjusted analyses will be essential to isolate the true intervention effect from pre-existing group differences.

Discussion

This study aimed to describe the baseline scientific process skill profiles of 4–5-year-old children in a nature-based play intervention and to examine qualitative patterns of engagement and inquiry during initial implementation. The findings contribute to the growing literature on nature-based early childhood science education in several important ways.

First, the study provides empirical support for the application of affordance theory (Gibson, 1979) to early science learning. The nature-based activities were intentionally designed to offer specific affordances for scientific inquiry: soil trays afforded observation and classification; fans and objects afforded prediction and testing; flashlights afforded variable manipulation. Children spontaneously took up these affordances, engaging in behaviors that mirror the science and engineering practices outlined in NGSS (NGSS Lead States, 2013). This aligns with recent work by Mifflin (2023) and Speldewinde and Campbell (2025), who found that nature-based settings afford STEM-related skills through both fixed features (e.g., water, climbable structures) and manipulable objects (e.g., leaves, rocks). However, the present study extends these findings by demonstrating that intentional activity design can amplify these affordances, guiding children's exploration toward specific scientific process skills without sacrificing the open-ended, play-based nature of the experience.

Second, the dual alignment of the intervention with both NGSS and the SDGs represents a novel contribution to the literature. While previous studies have examined nature-based early childhood education through either a science standards lens (e.g., NGSS alignment) or a sustainability lens (e.g., environmental education), few have explicitly integrated both frameworks within a single intervention design. By mapping each activity to relevant SDGs (see Table 1), the present study demonstrates how early science education can simultaneously foster scientific literacy and global sustainability competencies—an integration that is increasingly urgent given the environmental challenges facing the next generation (UNESCO, 2017; Somerville & Williams, 2015).

Third, the study highlights the importance of baseline-adjusted analyses in intervention research. The finding that the experimental group began the study with significantly higher Scientific Process Skills scores—despite random assignment—underscores the need for rigorous statistical controls when evaluating intervention effects. As noted in the baseline analysis, ANCOVA with pre-test scores as covariates will be used in the post-test phase to isolate the true effect of the nature-based play program. This is a methodological strength of the study, as many early childhood intervention studies fail to account for baseline differences, leading to inflated or biased effect estimates (What Works Clearinghouse, 2020). The strong internal consistency of the instrument in both groups (.896–.961) further supports its use in such adjusted models.

Fourth, the mixed-methods design, integrating quantitative reliability and group comparison analyses with rich qualitative observations, provides a more complete picture of the intervention's functioning than either method alone could offer. The qualitative findings not only corroborate the quantitative results but also illuminate the mechanisms underlying those results—for example, showing *how* children's prediction skills were activated during the wind activity, not merely that they scored higher on a prediction item. This integration of methods enhances both the internal validity and the ecological validity of the study (Creswell & Plano Clark, 2018).

Fifth, the qualitative findings have practical implications for early childhood educators seeking to integrate nature-based play into their curricula. The teacher's reflection that the activities "fit naturally into our daily routine" and that she only needed to "swap a few lessons" suggests that nature-based interventions can be implemented with high ecological validity—that is, without disrupting the existing classroom ecology. This is critical for scalability, as interventions that are perceived as "add-ons" or "extra work" are less likely to be sustained (Durlak & DuPre, 2008). Moreover, the observed shifts in children's language (from description to explanation), behavior (from passive watching to active testing), and social interaction (from individual play to collaborative discussion) provide concrete examples of how nature-based play can support the development of scientific reasoning in age-appropriate ways. These examples can be used in teacher professional development to illustrate what scientific process skills look like in practice and how they can be elicited through intentional activity design.

Limitations

This study has several limitations that should be acknowledged. First, the sample size is small (N = 27), which limits the generalizability of the findings and the statistical power of the group comparisons. The observed baseline differences, while statistically significant, should be interpreted with caution given the small sample. Second, the baseline non-equivalence between groups, while methodologically manageable, may reflect unmeasured confounding variables (e.g., prior science exposure at home, parental education, previous preschool experience) that were not assessed in this study. Third, the qualitative observations were conducted primarily during the initial implementation week, and it is possible that engagement patterns changed over time as children became more familiar with the activities. Fourth, the study is situated in a specific cultural and institutional context (a public preschool in the Midwestern United States), and the findings may not transfer directly to other settings, particularly those with different curricular standards, teacher training, or access to natural spaces. Fifth, the Science Observation Form, while validated in a Turkish context, has not been extensively validated in U.S. preschool settings; however, the high internal consistency observed in this study provides preliminary evidence of its reliability in this new context.

Conclusion

This baseline study of a nature-based play intervention for 4–5-year-old children provides evidence that (a) the Science Observation Form (Kuru & Akman, 2017) is a reliable instrument for assessing scientific process skills in this age group, with high internal consistency across both experimental and control groups; (b) the experimental group began the study with significantly higher Scientific Process Skills and total scores than the control group, necessitating baseline-adjusted analyses for subsequent intervention effect estimation; (c) the intervention was designed with a dual alignment to both NGSS for K–2 and the UN Sustainable Development Goals, providing a framework that integrates early science learning with global sustainability competencies; and (d) qualitative observations reveal that nature-based play activities elicit rich inquiry behaviors—including prediction-testing cycles, explanatory language development, variable awareness, and peer collaboration—that align with the core practices of scientific reasoning. The teacher's reflection further indicates that the intervention was perceived as compatible with the existing curriculum, suggesting strong ecological validity.

The dual alignment of the intervention with both NGSS and the SDGs represents a distinctive contribution to the field, demonstrating how early science education can simultaneously advance scientific literacy and sustainability competencies. As the world faces unprecedented environmental challenges, fostering these competencies from the earliest years of schooling is not merely desirable but essential. This study provides a foundation for future research examining the effectiveness of nature-based play interventions in promoting early scientific reasoning within a globally relevant sustainability framework.

Recommendations

For researchers, the findings underscore the importance of rigorous baseline measurement and adjusted analyses in intervention studies, as well as the value of integrating qualitative observations to understand the mechanisms underlying quantitative effects. Future research should (a) complete the post-test phase of this study using baseline-adjusted models to estimate the true intervention effect; (b) extend the study to a larger, more diverse sample to examine moderation by socioeconomic status, prior science exposure, or teacher experience; (c) conduct longitudinal follow-ups to assess the durability of any observed gains; and (d) explore cross-cultural comparisons, as the Turkish–U.S. collaboration that underpins this study offers a unique opportunity to examine how different curricular standards, teacher training, and cultural values shape the implementation and outcomes of nature-based science education.

For practitioners, the study provides concrete examples of how nature-based activities can be designed and implemented to foster specific scientific process skills, along with evidence that such activities can be integrated into existing classroom routines without disruption. The dual alignment with NGSS and SDGs offers a framework that teachers can use to justify nature-based play as a legitimate approach to meeting both science standards and sustainability education goals.

For policymakers, the study supports the growing call for nature-based early childhood education as a legitimate and effective approach to promoting early STEM learning, particularly in contexts where access to formal science instruction is limited. The alignment with internationally recognized frameworks (NGSS and SDGs) provides a rationale for investing in nature-based early childhood programs as a strategy for advancing both scientific literacy and global sustainability competencies.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in JESEH journal belongs to the authors. This study was conducted in accordance with ethical standards for research involving human participants. Ethical approval was obtained from the Indiana University Human Research Protection Program (HRPP) on December 9, 2025 (Protocol #28497; Enhancing Science Education Through Nature-Based Play in Early Childhood). Participation was voluntary, and all procedures ensured the confidentiality and anonymity of participants. No identifying information was collected or reported. The study adhered to all relevant institutional and international ethical guidelines for research with young children.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Investigating Students' Cognitive Processes in Learning Environments: A Scoping Review from a STEM Perspective

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Abstract

This study aims to systematically review the use of portable EEG technologies in learning environments for measuring and monitoring students' attention levels. In this context, peer-reviewed studies published between 2021 and 2025 were analyzed in terms of educational levels, research purposes, findings, advantages, and limitations. The review was conducted in accordance with the PRISMA-ScR framework, and 16 studies were included. The findings indicate that the majority of studies were conducted at the university level, while a limited number were conducted at other educational levels. It was determined that portable EEG technologies are mainly used to monitor attention levels, predict academic performance, and provide feedback through developed systems. In addition, EEG data provided important insights into cognitive load, learning performance, and social interactions, such as inter-brain synchronization. Overall, portable EEG technologies have significant potential to improve STEM learning environments and enable real-time, objective evaluation of cognitive processes. However, limitations such as data quality, movement restrictions, and challenges in long-term applications still persist. For future research, it is recommended that EEG data be integrated with learning analytics and that its use be expanded across different educational levels and stages of STEM education.

Introduction

Education is an activity that involves attention-demanding processes as well as other higher-order cognitive tasks related to learning and understanding (Orovas, Sapounidis, Volioti &Keramopoulos, 2024). One of the most important characteristics of the human brain in the learning process is cognition, which encompasses attention and information retention. Students' attention spans and their situational engagement during learning have consistently been the subject of research (Aggarwal, Lamba, Verma, Khuttan & Gautam 2021). Attention is very important for positive classroom behavior and emotional well-being. In the early school years, attention skills have significant effects on children's future academic success (Savina, 2026). Quantitatively measuring attention in the learning process is highly important, yet equally difficult. Traditional methods such as surveys and observations are subjective and limited in terms of accuracy (Rehman, Shi, Ullah, Wang & Ma, 2025). In previous studies, cognitive processes have generally been examined indirectly through observation, self-report, and performance-based methods. However, these approaches remain superficial in helping us understand cognitive processes. For example, students may appear disengaged while actively thinking, or they may give the impression of being attentive despite not showing meaningful engagement, or they may give the impression of being attentive even when not showing meaningful engagement. Therefore, such methods cannot precisely determine when a student's cognitive processes actually occur (Yang, Neville, and Riordáin, 2025; D'Mello, Dieterle & Duckworth, 2017). For instance, students may appear to be reading with deep attention, whereas the process they are engaging in may actually be mindless reading (Reichle, Reineberg & Schooler, 2010). Modern neurotechnologies offer new ways to improve and transform learning environments. The most important advantage of using these technologies is the enhancement of students' cognitive functions and the evaluation and future improvement of the educational process (Verbitskaya & Gaev, 2024). Cognitive neuroscience research is generally conducted in controlled laboratory settings. Therefore, its contributions to understanding learning in real-world environments are limited. However, in recent years, portable and wearable devices have become more accessible for classroom-based research. As a complement to existing educational research methods, these new technologies can provide insights into learning processes that are not reflected in classroom observations or learners' self-reports (Davidesco, Matuk, Bevilacqua & Poeppel, 2021).

The use of electroencephalogram (EEG) and other brain imaging techniques in education has paved the way for the field of neuroeducation. The primary goal of this field is to gain insight into the brain mechanisms involved in learning and to support the evaluation and improvement of educational methodologies based on students' brain responses (Orovas, Sapounidis, Volioti & Keramopoulos, 2024). EEG stands out not only for its ability to record the brain's electrical activity with high temporal resolution but also for its capacity to detect changes in this activity at the millisecond level. This feature makes EEG an ideal tool for examining dynamic brain processes such as learning (Yang, Neville & Riordáin, 2025). Portable EEG technologies can complement other classroom-based research methods and provide insights into cognitive processes (Davidesco, Matuk, Bevilacqua & Poeppel, 2021). Thanks to their portability, brain synchronization can be assessed within small groups or entire classrooms. This approach makes their interactions in learning environments visible, thereby enabling the examination of their effects on learning processes. (Dikker, Wan, Davidesco, Kaggen, Oostrik, McClintock, Rowland, Michalareas, Bavel, Ding & Poeppel, 2017). Portable EEG enables monitoring and enhancement of attention in natural educational settings. Future studies are needed to verify the long-term stability of portable EEG devices and to uncover the brain mechanisms underlying natural learning interactions (Wang, Zang & Johnstone, 2025).

STEM is a broad term that encompasses interdisciplinary skills integrating science, technology, engineering, and mathematics (Flegr, Kuhn & Scheiter, 2023). To understand the neural mechanisms underlying interest and learning in Science, Technology, Engineering, and Mathematics (STEM), it is important for fostering creativity and problem-solving skills, which are key drivers of technological and educational advancement. Traditional methods for measuring interest in STEM are often limited by bias, underscoring the need for more objective approaches (Candela-Leal, Alanis-Espinosa, Murrieta-Gonzalez et al., 2025). Cognitive neuroscience research is typically conducted in controlled laboratory settings that bear little resemblance to science, technology, engineering, and mathematics (STEM) classrooms. Recent advances in portable EEG technology allow researchers to collect brain data from students in real classroom environments (Davidesco, 2020).

This study aims to systematically examine the use of portable EEG technology in learning environments and to address the gap in the literature by evaluating existing applications and methodological approaches from a STEM perspective. Although previous studies have demonstrated that portable EEG has been used for various purposes in educational settings, the existing body of research varies in terms of educational levels, research purposes, and key findings. Therefore, there is a need for a comprehensive synthesis that identifies the overall trends in this field. This review aims to systematically map the existing literature, identify current research trends and research gaps, and provide directions for future research. In line with these objectives, the present review was conducted based on the following research questions:

1. At which educational levels have studies involving portable EEG technology in learning environments been conducted?
2. How are the purposes of using portable EEG technology to measure students' attention levels addressed in the literature?
3. What kinds of results do studies on the use of portable EEG technologies in learning environments reveal regarding the measurement and monitoring of students' attention processes?
4. What are the cognitive findings related to the use of mobile EEG technology across different educational levels?

Method

This study is a systematic review aimed at examining research conducted in learning environments using portable devices.

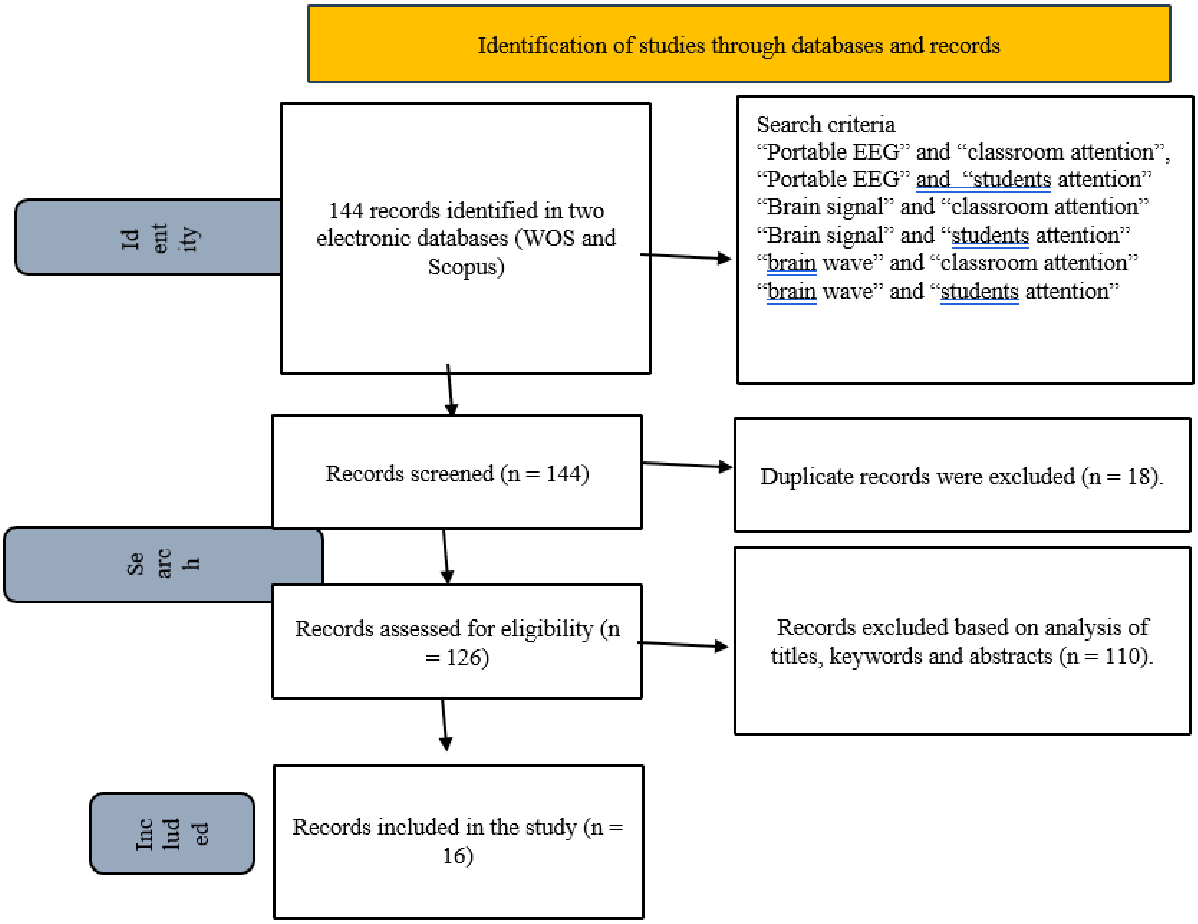
Literature Review Approach

In order to address the research questions, a scoping review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco et al., 2018). This study focused on peer-reviewed literature published between 2021 and 2025. This time frame was selected to reflect the use of portable EEG technologies in learning environments over the past five years. The literature search was conducted using the Scopus and Web of Science (WoS) databases. The selection of the databases was based on their broad multidisciplinary coverage across education, neuroscience, engineering, and computer science, as well as their ability to reflect the interdisciplinary nature of research on the use of portable EEG in educational settings. In addition, the search strategy was designed to balance comprehensiveness with methodological feasibility. Limiting the search to Scopus and Web of Science enabled the implementation of a predefined, transparent, and reproducible search strategy, while ensuring a systematic screening process aligned with the objectives and scope of this scoping review. A consistent set of search terms was used during the search. The search terms were applied in English. The advanced search in the databases was conducted as follows:

"Portable EEG" AND "classroom attention"
"Portable EEG" AND "students' attention"
"Brain signal" AND "classroom attention"
"Brain signal" AND "students' attention"
"Brain wave" AND "classroom attention"
"Brain wave" AND "students' attention"

The Boolean operator "AND" was used during the search process to reach the targeted articles. In terms of inclusion criteria, this review covers peer-reviewed journal articles published between 2021 and 2025 that portable EEG technologies in learning environments. In this study, research conducted in educational contexts that used EEG was included. Studies involving non-portable EEG technologies, those conducted outside learning environments, clinically oriented studies, review-type studies, and studies without full-text access were excluded. The studies obtained through the literature review were subjected to a screening process. First, 144 articles were identified. Duplicate studies were removed. A total of 126 articles remained. Finally, titles, abstracts, and keywords were analyzed, and studies outside the research scope were excluded. As a result, the final set of studies to be included in the review (n = 16) was determined. This scoping review was conducted in accordance with the PRISMA-ScR guidelines. These stages are presented in Table 1.

Table 1. Articles reviewed in line with the research objective



Results

Research Question 1: **At which educational levels have studies involving the use of portable EEG technology in learning environments been conducted?**

The majority of the studies included in the review were conducted at the university level. Studies at the preschool, primary, and secondary school levels are limited in number. These studies are presented in Table 2.

Table 2. Descriptive characteristics of the studies included in the review

Order	Author(s) and year	Article title	Participants
1	Aggarwal, Lamba, Verma, Khuttan & Guatam, (2021)	A preliminary investigation for assessing attention levels for Massive Open Online Courses learning environment using EEG signals: An experimental study	University student
2	Shaw, Patra, Pradhan & Mishra (2023)	Attention Classification and Lecture Video Recommendation Based on Captured EEG Signal in Flipped Learning Pedagogy	44 Students (17-20 Age)
3	Mutlu-Bayraktar, Özel, Altındiş & Yılmaz (2022)	Split-attention effects in multimedia learning environments: eye-tracking and EEG analysis	44 University student
4	Zheng, Ma, Yue & Yang (2023)	Effects of different types of cues and self-explanation prompts in instructional videos on deep learning: evidence from multiple data analyses	72 University student
5	Shaw & Patra (2022)	Classifying students based on cognitive state in flipped learning pedagogy	84 University student
6	Hsu & Chen (2021)	An EEG Study on Students' Learning in Practical and Theory- Based Hospitality Courses	33 University student
7	Lin, Tang, Ma, Liu & Ding (2023)	The impact of media diversity and cognitive style on learning experience in programming video lecture:A brainwave analysis	15 University student
8	Cardoso & Zaro (2023)	Monitoring Learning in Nursing using the Electroencephalogram and Intrinsic Motivation Inventory–IMI	17 University student
9	Shaw, Mohanty, Patra & Pradhan (2023)	1D Multi-Point Local Ternary Pattern: A Novel Feature Extraction Method for Analyzing Cognitive Engagement of students in Flipped Learning Pedagogy	44 University student
10	Chen, Xu & Zhang (2024)	Inter-brain coupling analysis reveals learning-related attention of primary school students	35 Primary school student
11	Juárez-Varón, Juárez-Varón Mengual-Recuerda & Andres, (2024)	A Neurotechnological Study to Quantify Differences in Brain Activity Using Game-Based Learning: Gamification vs. Traditional Teaching	20 University student
12	Grammer, Xu & Lenartowicz (2021)	Effects of context on the neural correlates of attention in a college classroom	23 University student
13	Xie, Dong, Yang, Luo, Ren, Zhang, He, Jia, Yang, Jiang, Gao, Chen (2025)	CNN-Transformer network for student learning effect prediction using EEG signals based on spatio-temporal feature fusion	16 University student
14	Guo, Zhu, Wu, Bao & Liu (2022)	Emotional Activity Is Negatively Associated With Cognitive Load in Multimedia Learning: A Case Study With EEG Signals	42 University student
15	Xu, Torgrimson, Torres, Lenartowicz & Grammer (2022)	EEG Data Quality in Real-World Settings: Examining Neural Correlates of Attention in School-Aged Children	46 Kindergarten to 4th-grade students
16	Fuentes-Martínez, Romero, Lopez-Gordo Minguillon & Rodríguez-Álvarez (2023)	Low-Cost EEG Multi-Subject Recording Platform for the Assessment of Students' Attention and the Estimation of Academic Performance in Secondary School	34 Secondery school

Research Question 2: How are the purposes of using portable EEG technology to measure students' attention levels addressed in the literature in learning environments?

When the aims of the reviewed studies were analyzed, it was found that although portable EEG technologies are; primarily used to measure attention, they were also used for other purposes. The identified purposes were categorized into groups. The aims were organized under seven categories. Since a single study may have multiple purposes, it may appear in more than one category. The scope and purposes of using portable EEG technology to measure attention levels in learning environments in these studies are presented in Table 3.

Table 3. Categories of the studies included in the review

Scope	Detail	Author–Year
To directly determine and assess students' attention levels	To assess students' attention levels in massive open online course environments using brain signals.	Aggarwal, Lamba et al. (2021)
	To detect students' attention levels during class by applying classification techniques to EEG brain wave data.	Shaw, Patra, Pradhan & Mishra (2023)
	To objectively determine students' attention levels while watching pre-recorded lecture videos in flipped learning environments.	Shaw, Mohanty, Patra & Pradhan (2023)
	To examine how different instructional contexts in the classroom (student-initiated vs. teacher-initiated activities) affect student attention using portable EEG measurements, and to reveal attention differences that behavioral observations and self-reports cannot capture.	Grammer, Xu & Lenartowicz, (2021)
	To monitor students' attention levels in a classroom environment.	Xu, Torgrimson, Torres, Lenartowicz & Grammer (2022)
	To assess students' attention and address issues in online education, such as students turning off their cameras and microphones.	Fuentes-Martinez, Romero et al. (2023)
To compare an implemented intervention with traditional instruction	To compare the attention levels of learners in massive open online course (MOOC) environments with those in traditional classroom instruction	Aggarwal, Lamba et al. (2021)
	To investigate the neural activity exhibited by students during practical and theoretical classes	Hsu & Chen (2021)
	To comparatively examine brain activity during gamified and traditional instruction in classroom settings.	Juárez-Varón, Juárez-Varón Mengual-Recuerda & Andres (2024)
	To examine how different instructional contexts in the classroom (student-initiated vs. teacher-initiated activities) affect student attention using portable EEG measurements, and to reveal attention differences that cannot be captured through behavioral observations and self-reports.	Grammer, Xu & Lenartowicz, (2021)
To observe the effects of divided attention in learning environments	To examine split attention in multimedia learning environments.	(Mutlu-Bayraktar, Özel, Altındiş & Yılmaz (2022)
To develop a new system to provide feedback on students' attention levels and to assess them	A recommendation system called FlipRec is developed to re-suggest videos on which students showed inattention.	Shaw, Patra, Pradhan & Mishra (2023)
	A prototype (model) is developed to monitor students in flipped learning by passively recording their individual brain waves as they engage with instructional videos.	Shaw & Patra (2022)
	To evaluate the learning process of undergraduate nursing students who voluntarily participated in the study using a pilot virtual environment (VM).	Cardoso & Zaro (2023)
	to determine students' attention levels while watching pre-recorded lecture videos in flipped learning environments and to develop an effective EEG-based analysis and classification method for this purpose	Shaw, Mohanty, Patra & Pradhan (2023)
	To develop a new method based on inter-brain attention coupling rather than individual attention measures in order to more accurately determine learning-related attention in primary school students, and to test the	Chen, Xu & Zhang (2024)

	predictive power of this method for academic achievement	
	To propose a hybrid CNN–Transformer (HCT) model that enables the discrimination of high- and medium-level learning outcomes from EEG signals recorded during learning	Xie, Dong, Yang, Luo, Ren, Zhang, He, Jia, Yang, Jiang, Gao & Chen (2025)
	To develop a new low-cost EEG-based platform to assess students' attention and predict their academic performance in online education	Fuentes-Martinez, Romero et al. (2023)
to examine the effects of an implemented program/system on brain waves	To examine the combined effects of media diversity and cognitive style on university students' sustained attention, learning engagement, cognitive load, and learning outcomes from the perspective of EEG signals	Lin, Tang, Ma, Liu & Ding (2023)
	To investigate the relationship between emotional activity and cognitive load using EEG signals from the perspective of emotion dynamics during multimedia learning	Guo, Zhu, Wu, Bao & Liu, (2022)
	EEG data are used to determine participants' attention levels and learning engagement while watching instructional videos.	Zheng, Ma, Yue & Yang (2023)
to evaluate the collectability and quality of EEG data in different environments	To examine the feasibility of mobile EEG across different ecological contexts by collecting EEG data both in a field laboratory under a controlled one-on-one interaction setting and during real classroom lessons conducted in the same school	Xu, Torgrimson, Torres, Lenartowicz & Grammer (2022)
to relate attention levels to academic achievement	To develop a new low-cost EEG-based platform to assess students' attention and predict their academic performance in online education by addressing issues such as students' ability to turn off cameras and microphones to protect their privacy.	Fuentes-Martinez, Romero et al. (2023)

As shown in Table 3, the findings indicate that the purposes of the studies are mostly grouped under the categories of "directly determining and evaluating students' attention levels" and "providing feedback or evaluation of students' attention levels by developing new systems." In addition, a limited number of studies were found to fall under the categories of "evaluating the collectability and quality of EEG data in different environments" (n = 1), "observing the effects of divided attention in learning environments" (n = 1), and "associating attention levels with academic achievement" (n = 1). It is observed that EEG is used in measurement and evaluation processes or in determining the effectiveness of learning environments. These findings show that EEG research primarily focuses on cognitive processes. Considering the specific purposes of the studies, it is evident that EEG technologies are also used in video lectures, flipped learning methods, and online learning environments.

Research Question 3: What kinds of results do studies on the use of portable EEG technologies in learning environments reveal regarding the measurement and monitoring of students' attention processes?

Developed Systems and Attention Analysis

In e-learning and flipped learning environments, systems designed to identify students with low attention have been shown to be effective. These systems can identify lecture videos in which students fail to maintain attention and provide appropriate content recommendations. This enables the identification of students with low attention levels and provides personalized support (Shaw, Patra, Pradhan & Mishra, 2023). It is also indicated that such systems are suitable for the real-time and objective assessment of both students' attention and their subsequent academic performance (Fuentes-Martinez, Romero et al., 2023).

Video Lecture Designs, Media Types, and Cognitive Load

In video-based learning, textual and visual cues presented to students have been found to positively affect learning (Zheng, Ma, Yue & Yang, 2023). In addition, a negative relationship has been observed between cognitive load and emotional engagement. This has been considered an important indicator in the design of video lectures. It is emphasized that learning environments should be designed to balance students' emotional engagement while reducing cognitive load and enhancing learning (Guo, Zhu, Wu, Bao & Liu, 2022). Findings based on EEG data indicate that the diversity of video types used in video lectures has significant effects on learning. The effects of different materials, such as presentations, tablet drawing, and animations, were examined; it was found that tablet drawing increased students' focus and engagement in learning compared to animation use. However, it was revealed that both animated materials and tablet drawing materials lead to a higher cognitive load compared to presentations (Lin, Tang, Ma, Liu & Ding, 2023)

Limitations and Contributions of EEG Use

Findings on EEG use indicate that this technology has certain limitations for long-term applications. It has been noted that factors such as the requirement for participants to remain still and the limited duration of applications may affect the results obtained (Zheng, Ma, Yue & Yang, 2023). At the same time, EEG provides teachers with valuable, objective feedback, thereby enhancing effectiveness in both face-to-face and online learning environments. Feedback obtained from EEG data can be appropriately interpreted by teachers and used to guide instruction. It is low-cost while still helping to predict students' academic performance (Fuentes-Martinez, Romero et al., 2023). EEG signals are a powerful tool for understanding differences in cognitive states related to classroom instruction that cannot be observed solely through behavior (Grammer, Xu & Lenartowicz, 2021). EEG signals have been found to provide objective feedback to teachers and contribute to the improvement of instructional processes in both face-to-face and online learning environments. In particular, a significant relationship between beta waves and academic performance has been identified, and it has been suggested that this relationship can guide the learning process. Additionally, even low-cost portable EEG systems have been shown to be functional in predicting students' academic performance (Fuentes-Martinez, Romero et al., 2023). EEG signals have been identified as a powerful tool for understanding students' cognitive states beyond observable behaviors (Grammer, Xu & Lenartowicz, 2021). It is stated that EEG data provides an important basis for dynamic monitoring and prediction of the learning process, while also contributing to students' self-regulation of their learning (Xie, Dong, Yang et al., 2025).

Comparison of Learning Environments

EEG-based studies suggest that students' attention levels vary across different learning environments. In particular, higher attention levels have been reported in e-learning and gamified learning environments than in traditional classroom instruction (Aggarwal, Lamba, Verma et al., 2021; Juárez-Varón, Mengual-Recuerda, and Andrés, 2024).

Research Question 4: What are the cognitive findings related to the use of mobile EEG technology across different educational levels?

EEG Data at Primary and Secondary School Levels

According to the reviewed studies, it is confirmed that monitoring attention levels in primary school students in learning environments is feasible and that EEG data can be collected from young children in natural settings, and that EEG data can be collected (Xu, Torgrimson, Torres, Lenartowicz & Grammer, 2022). In addition, no direct relationship was found between attention and academic performance among primary school students. However, a positive relationship was identified between students' academic performance and inter-brain attentional coupling with their peers in the classroom. This suggests that learning may be associated not only with individual attention but also with socio-cognitive interactions (Chen, Xu and Zhang, 2024). In studies conducted with high school students, a direct relationship was found between the beta band and academic performance. It has been demonstrated that even low-cost EEG platforms are functional and can be used to predict students' academic performance. It is stated that such systems can contribute to instructional processes by providing teachers with data-driven feedback (Fuentes-Martinez, Romero et al., 2023).

EEG Data at the University Level

Undergraduate studies indicate that attention levels differ between practical and theoretical courses, suggesting that different instructional contexts are associated with different patterns of brain activity (Hsu and Chen, 2021).

In addition, gamified activities have been found to elicit higher attention than traditional learning activities (Juárez-Varón, Mengual-Recuerda, & Andrés, 2024). Furthermore, student-initiated activities elicit higher attention than instructor-initiated activities. Overall, attention levels are reported to be higher in learning situations where students are actively engaged (Grammer, Xu, & Lenartowicz, 2021). It has also been observed that attention levels vary across learning environments. For example, in e-learning environments, attention levels tend to increase as the lesson progresses, whereas in classroom settings, initially high attention levels decrease over time (Aggarwal, Lamba, Verma et. al., 2021). At the undergraduate level, EEG-based systems have been developed to analyze EEG data collected during online learning and predict students' learning outcomes (Xie, Dong, Yang et al., 2025). Students' attention levels at the university level have been classified as attentive/inattentive (Shaw, Mohanty, Patra & Pradhan, 2023; Shaw, Patra, Pradhan & Mishra, 2023). Studies conducted with undergraduate students show that different multimedia presentation formats are associated with students' emotional engagement. In this context, a negative relationship between emotional activity and cognitive load has been identified (Guo, Zhu, Wu, Bao & Liu, 2022).

Discussion

This study aims to synthesize and evaluate research on portable EEG for measuring attention in learning environments from a STEM perspective, focusing on educational levels, research purposes, obtained results, advantages, and limitations. The analysis of the selected 16 journal articles shows that portable EEG technology in learning environments is primarily used to directly measure attention and to develop new systems.

The use of EEG technology has been predominantly among university-level students, with a limited number of studies conducted at preschool, primary, and secondary school levels. Lee, Ahn, Park, 2022, similarly, it has been reported that portable EEG is most frequently used at the university level in academic contexts, mainly in science-related fields, and is employed to measure students' attention using mobile EEG. Yang, Neville & Riordáin (2025)'s study shows that the use of portable EEG in educational environments involves students at secondary and university education levels. STEM education is structured to suit students' developmental stages at different educational levels and to enable the development of engineering design skills (Bybee, 2013; Honey, Pearson & Schweingruber, 2014). It should be emphasized that the widespread adoption of EEG-based studies across different educational levels suggests the potential of this technology to evaluate STEM learning processes in a multidimensional way.

The objectives of the examined studies were grouped under seven categories. It was determined that most objectives focus on directly examining students' attention levels and on developing new systems to provide feedback on them. Similarly, Wang, Zhang & Jonstone (2025) identified three objectives in their systematic review: evaluating the effects of learning-related factors on attention, developing algorithms and software for attention monitoring and improvement, and validating the data quality of portable EEG devices. In addition, the present study included a limited number of articles that aimed to evaluate the collectability and quality of EEG data across different environments, observe the effects of divided attention in learning environments, and examine the relationship between attention levels and academic achievement. These findings indicate that research objectives related to EEG usage are predominantly concentrated on the investigation of cognitive processes.

Recent technological advances have led to the increasing use of immersive and digital learning technologies in educational settings, highlighting the need to better understand their cognitive effects on learners (Makransky et al., 2019; Skulmowski & Xu, 2022; Khan et al., 2025). However, some perspectives suggest that such technologies may distract attention or increase mental workload. These concerns highlight the need for objective methods to assess individuals' cognitive load when using these technologies.Cognitive research can be applied across various disciplines, including learning sciences, STEM, psychology, neuroscience, and education. Attention and cognitive load indicators obtained through EEG can provide important evidence for evaluating how students' learning processes change in STEM learning environments. Based on this information, EEG-based indicators of attention and cognitive load can provide important evidence for evaluating how students' learning processes change in STEM learning environments.

Active learning requires students to direct their attention to learning activities and to carry out the learning process by establishing relationships between topics and concepts (Şahinel, 2003). The findings of studies investigating the use of portable EEG technologies in learning environments to measure and monitor students' attention processes are addressed under the following themes: developed systems, video-based lessons, limitations and advantages of EEG use, and comparisons of learning environments.

EEG-based systems have been shown to identify students with low attention, detect lessons in which students fail to maintain attention, and provide personalized support for students with low attention levels (Shaw, Patra, Pradhan, & Mishra, 2023), as well as assess students' academic achievement both in real time and at subsequent stages (Fuentes-Martinez, Romero et al., 2023).

Findings from the video lesson processes indicate that video diversity plays an important role in learning; the use of tablet drawing and animation has been shown to enhance attention compared to traditional presentations, though it also increases cognitive load (Lin, Tang, Ma, Liu & Ding, 2023). A negative relationship has been found between cognitive load and emotional engagement. It has been emphasized that learning environments should be designed to reduce cognitive load and enhance learning (Guo, Zhu, Wu, Bao & Liu, 2022). EEG technologies are effective in measuring cognitive load fluctuations and attention during learning processes (Antonenko, Paas, Grabner & van Gog, 2010). Activities that contain a large number of information elements create cognitive load. For effective learning, instructional design should be structured to reduce unnecessary cognitive load and facilitate learning (Sweller, 2011). In designed STEM activities, monitoring the process with EEG can provide feedback on situations such as the emergence of unnecessary cognitive load, thereby contributing to the redesign of activities and supporting students' learning processes.

Its low cost, the ability to provide objective feedback in both face-to-face and online educational environments, and the potential for teachers to interpret EEG data to guide instruction are among its key advantages (Fuentes-Martinez, Romero et al., 2023). EEG also helps predict students' academic performance (Fuentes-Martinez, Romero et al., 2023) and serves as a powerful tool for understanding cognitive states that cannot be observed solely through behavior (Grammer, Xu, & Lenartowicz, 2021). Furthermore, EEG enables dynamic monitoring of the learning process and supports students in monitoring and regulating their own learning (Xie, Dong, Yang et al., 2025). However, obtaining high-quality EEG recordings, inferring causality, and measuring dynamic interactions in natural learning contexts remain challenging (Davidesco, Matuk, Bevilacqua, Poeppel, & Dikker, 2021). The use of portable EEG also has limitations in long-term applications (Wang, Zhang & Jonstone, 2025). These technologies provide insights into learning processes that may not be detectable in classroom settings or accurately reflected in students' self-reports; however, further research is needed to determine their unique contributions (Davidesco, Matuk, Bevilacqua, Poeppel, & Dikker, 2021). As research in this area increases . Factors that decrease or enhance across STEM fields; it is expected that, beyond general knowledge of the learning process, students' cognitive states will be evaluated second-by-second or minute-by-minute. Factors that increase or decrease attention levels during the process will be identified individually, revealing previously overlooked findings.

According to the studies examined, it is feasible to collect EEG data from students in preschool and primary school settings and to monitor their attention levels (Xu, Torgrimson, Torres, Lenartowicz and Grammer, 2022). It has been found that students' academic performance is positively associated with attention coupling in EEG data among their peers in the classroom. This suggests that learning may be related not only to individual attention but also to social-cognitive interactions. However, no significant relationship was found between individual attention and academic performance (Chen, Xu & Zang, 2024). In studies conducted at the high school level, EEG data have been reported to be functional and useful for predicting students' academic performance. It is also stated that EEG-based systems can provide data-driven feedback to teachers, thereby contributing to instructional processes (Fuentes-Martinez, Romero et al., 2023). In learning environments, inter-brain synchronization, student engagement, and learning outcomes can provide informative results (Dikker et al., 2017; Bevilacqua et al., 2019). Social interactions have been relatively underexplored in human neuroscience, as most studies have been conducted in controlled laboratory settings with individual participants. Social interactions in STEM contexts and offer promising opportunities for interdisciplinary research. There is evidence that student engagement, memory retention, and social dynamics are reflected in similarities in brain responses between teachers and students (Davidesco, 2020).

The majority of studies conducted at the university level focus on developing EEG-based systems. It has been shown that these EEG-based systems improve students' learning performance (Kim, Chae, Kim & Im, 2023) by analyze data and predict students' learning outcomes (Xie, Dong, Yang et al., 2025), classifying their attention states, and providing feedback such as "attentive" or "inattentive" (Shaw, Mohanty, Patra & Pradhan, 2023; Shaw, Patra, Pradhan, & Mishra, 2023). Studies indicate that such feedback systems enhance learning performance (Kim, Chae, Kim & Im, 2023). Theobald et al. (2020) support calls for traditional lectures in STEM disciplines to be replaced by evidence-based, active-learning-focused lesson designs and indicate that innovations in teaching strategies can increase equality in higher education.

Conclusion

This study aims to examine the use of portable EEG technologies in learning environments focusing on educational levels, research purposes, findings, advantages, and limitations. It was determined that the majority of the reviewed studies were conducted at the university level, while a limited number were conducted at the university level. In contrast, a limited number were conducted at the preschool, primary, and high school levels. The findings indicate that portable EEG technologies are used to monitor students' attention levels, predict learning performance, and provide feedback based on attention states. These technologies have the potential to provide individualized support, guide instructional processes, and improve student performance during learning. It has been observed that the use of portable EEG provides valuable data on cognitive load, learning performance, and attention. In addition, EEG data have been shown to reflect not only individual attention processes but also inter-brain synchronization associated with social interactions. EEG data were found to be functional in predicting academic performance at the high school and university levels. At the primary school level, no direct relationship was found between attention and academic achievement; instead, the alignment of inter-brain synchronization among students was highlighted. The main advantages of these technologies include providing objective data, being low-cost, and offering real-time feedback during learning processes. However, limitations such as movement restrictions in long-term use and issues related to data quality have also been identified.

Recommendations

Overall, portable EEG technologies are considered to have significant potential in STEM education for the multidimensional evaluation of learning processes, analysis of attention and cognitive load, and improvement of instructional processes. Future research is recommended to conduct more studies across different educational levels, to examine cognitive processes in STEM activities in greater detail, to compare students' cognitive processes across different learning environments, to expand applications that provide feedback based on these processes, and to integrate EEG data with learning and attention analytics.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in JESEH journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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An Investigation of the Relationship Between Science Teachers' Effective Science Teaching and Entrepreneurship Education Levels

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Abstract

This study examined the relationship between science teachers' effective science teaching levels and their entrepreneurship education levels. A descriptive, correlational survey design was employed. The sample consisted of 94 science teachers working in middle schools in Kırıkkale province during the 2023–2024 academic year. Data were collected using the *Effective Science Teaching Scale* and the *Entrepreneurship Scale for University Students*. Descriptive statistics, independent samples t-tests, one-way ANOVA with LSD post hoc comparisons, and Pearson correlation analysis were conducted. The findings indicated that science teachers demonstrated high levels of both effective science teaching and entrepreneurship education. Significant differences were found in effective science teaching according to professional seniority and gender. Additionally, entrepreneurship education levels differed significantly by educational background and gender. Correlation analysis revealed a statistically significant and positive relationship between effective science teaching and entrepreneurship education levels.

Introduction

Rapid developments in science and technology have substantially transformed the role of teachers, who constitute one of the core components of educational systems. This transformation has increased expectations regarding teachers' professional qualifications, pedagogical competencies, and their ability to adapt to emerging educational demands. In science education, where scientific literacy and innovation-oriented thinking are increasingly emphasized, the quality of science teachers has become particularly critical. Teachers' personal characteristics, professional competencies, and levels of effective science teaching play a decisive role in achieving curricular objectives and ensuring meaningful learning experiences (Öztürk, 2021). Previous research has extensively examined effective science teaching among pre-service and in-service science teachers (Hudson et al., 2005; Lewis et al., 2019, 2020; Mamba & Putsoa, 2018; Öztürk, 2021; Rahman Talukder et al., 2021; Yavuz, 2020). These studies highlight that effective teaching requires the strategic use of diverse instructional approaches, pedagogical flexibility, and the ability to create student-centered learning environments. Accordingly, both teachers' professional qualifications and their instructional preferences are considered fundamental determinants of effective science instruction (Cücük et al., 2018).

In parallel with global educational transformations, entrepreneurship education has gained increasing attention as an essential component of 21st-century skills. Entrepreneurship education aims to equip individuals with innovative thinking, problem-solving abilities, initiative-taking behaviors, and value-creation competencies (San-Martín et al., 2021). Within this framework, teachers are not only transmitters of knowledge but also facilitators of entrepreneurial mindsets. Therefore, teachers' entrepreneurial competencies are regarded as critical in fostering entrepreneurial skills among students. Existing studies have investigated entrepreneurship levels among pre-service and in-service science teachers (Akbulut, 2019; Bolaji, 2012; Çavdar et al., 2018; Deveci, 2018; Köken & Çelik, 2021; Leffler, 2020; San-Martín et al., 2022; Sarı et al, 2022).

Research conducted in Turkiye indicates that science activities, experiments, and inquiry-based practices contribute positively to the development of entrepreneurial characteristics (Çelik et al, 2015). Furthermore, instructional approaches such as STEM education (Deveci, 2018; Yamak et al., 2019), cooperative learning (Peltonen, 2015), project-based learning (Tarhan & Gülmez, 2021), and technopark visits (Bayram & Çelik, 2022) have been reported to support entrepreneurial skill development. These findings suggest that instructional practices in science education may intersect conceptually with entrepreneurship-related competencies.

From a theoretical perspective, entrepreneurial competencies such as creativity, proactivity, and opportunity recognition are conceptually aligned with the demands of effective science teaching, which requires instructional innovation, adaptability, and the integration of real-world problems into classroom practice. Effective science teaching, particularly within inquiry-oriented and constructivist frameworks, involves experimentation with diverse strategies and the creation of authentic problem-based learning environments (Peltonen, 2015; San-Martín et al., 2021). Within Bandura's (1997) social cognitive framework, teachers' professional behaviors are shaped by their self-efficacy beliefs—that is, their confidence in their ability to organize and execute actions required to manage instructional challenges. Teachers with stronger efficacy beliefs are more likely to adopt innovative practices and student-centered approaches. Because entrepreneurial orientation similarly involves acting under uncertainty and initiating change, it may strengthen instructional self-efficacy and thereby support the implementation of effective science teaching practices.

Despite the growing body of research on effective science teaching and entrepreneurship education as separate domains, no study has directly examined the relationship between science teachers' effective science teaching levels and their entrepreneurship education levels. Considering the increasing emphasis on innovation, creativity, and entrepreneurial thinking in contemporary education systems, understanding the potential association between these two constructs appears particularly important. Therefore, this study aims to examine the relationship between science teachers' effective science teaching and their entrepreneurship education levels. By addressing two critical dimensions of contemporary science education simultaneously, this study seeks to contribute to the literature by providing empirical evidence on whether entrepreneurship-related competencies are associated with effective science teaching practices.

Based on the literature, numerous studies have examined instructional approaches, teaching methods, and entrepreneurship education in science education contexts among both pre-service and in-service teachers. However, no study has directly investigated science teachers' effective science teaching levels in relation to their entrepreneurship education levels. The absence of research integrating these two increasingly prominent dimensions highlights a significant gap in the literature. Accordingly, this study aims to examine the relationship between science teachers' effective science teaching and entrepreneurship education levels. By simultaneously addressing two critical components of contemporary science education, this research seeks to provide empirical evidence regarding their potential association. Understanding this relationship may contribute to improving instructional practices, informing teacher development initiatives, and supporting evidence-based educational policy decisions. The study addresses the following research questions (Q_s):

Q_1. What are science teachers' levels of effective science teaching?
Q_2. Do science teachers' effective science teaching levels differ according to gender, professional seniority, and educational background?
Q_3. What are science teachers' levels of entrepreneurship education?
Q_4. Do science teachers' entrepreneurship education levels differ according to gender, professional seniority, and educational background?
Q_5. Is there a significant relationship between science teachers' effective science teaching and entrepreneurship education levels?

Method

Study Design

This study employed a quantitative, cross-sectional correlational design. Correlational research aims to determine the presence and degree of relationships between two or more variables without manipulating them (Creswell & Creswell, 2018; Fraenkel et al., 2012). In line with the overall purpose of the study and the research questions, this design was considered appropriate for examining the relationship between science teachers' effective science teaching levels and their entrepreneurship education levels, as well as the strength of this association.

Study Sample

A convenience sampling method was employed to determine the study sample. Convenience sampling involves selecting participants who are readily accessible to the researcher and is commonly used in educational research when constraints related to time, cost, and accessibility are present (Creswell & Creswell, 2018; Etikan et al., 2016). The sample consisted of 94 science teachers working in public middle schools in Kırıkkale province during the 2023–2024 academic year. Of the participants, 58 (61.7%) were female and 36 (38.3%) were male. The distribution of teachers according to gender, professional seniority, and educational background is presented in Table 1.

Table 1. Frequency and percentage distributions of the sample

Variable	Category	f	%
Gender	Female	58	61.7
	Male	36	38.3
Teaching experience (years)	6–10 years	13	13.8
	11–15 years	34	36.2
	16–20 years	28	29.8
	21 years and above	19	20.2
Educational level	Bachelor's degree	70	74.5
	Master's degree	24	25.5
Total		94	100

Data Collection Tools

The data collection instruments used in this study consisted of three sections. The first section included a *Personal Information Form* composed of three items designed to obtain demographic information about the participants, including gender, professional seniority, and educational background. These variables were examined in relation to the main study variables.

The second section included the *Effective Science Teaching Scale*, originally developed by Hudson, Skamp, and Brooks (2005) and adapted into Turkish by Yavuz (2020). The scale consists of 29 items rated on a five-point Likert scale and comprises four subdimensions: Personal Development, Self-Confidence, Pedagogical Skills, and Curriculum Knowledge. Total scores range from 29 to 145, with higher scores indicating higher levels of effective science teaching. The original study reported a Cronbach's alpha coefficient of .96, while the internal consistency coefficient calculated for the present study was $\alpha = .95$.

The third section included the *Entrepreneurship Scale for University Students*, developed by Yılmaz and Sünbül (2009). Although originally designed to measure entrepreneurship levels among university students, the scale has been widely used across different educational levels and professional groups. The instrument consists of 36 items rated on a five-point Likert scale and is structured as a single-factor scale. Total scores range from 36 to 180, with higher scores indicating higher levels of entrepreneurship. Based on total scores, entrepreneurship levels are categorized as very low (36–64), low (65–92), moderate (93–123), high (124–151), and very high (152–180). The original study reported a Cronbach's alpha coefficient of .90, and the reliability coefficient for the present study was calculated as $\alpha = .95$.

Data Analysis

The data collected in the study were entered into a computer environment and analyzed using IBM SPSS Statistics (Version 25.0). Prior to conducting the analyses, the normality assumption was examined by evaluating skewness and kurtosis values. Since the skewness and kurtosis coefficients ranged between −2 and +2, the data were considered to meet the assumption of normal distribution (George & Mallery, 2010). Accordingly, parametric statistical techniques were employed in line with established statistical procedures (Büyüköztürk, Çokluk, & Köklü, 2020). Descriptive statistics (frequency, mean, and standard deviation) were calculated to summarize the data. Independent samples t-tests and one-way analysis of variance (ANOVA) were conducted to examine group differences. Post hoc comparisons were performed using the LSD test. Pearson's correlation coefficient was used to determine the strength and direction of the relationship between the variables.

Findings

Findings Related to the First Sub-Problem (Q_1)

The findings regarding science teachers' levels of effective science teaching are presented in Table 2.

Table 2. Science teachers' levels of *Effective Science Teaching*

Subscale	N	Min.	Max.	x̄	Number of Items	SD	SE
Personal Development	94	43.00	60.00	54.30	12	4.41	0.45
Self-Confidence	94	27.00	40.00	35.40	8	3.40	0.35
Pedagogical Skills	94	18.00	30.00	26.00	6	2.56	0.26
Curriculum Knowledge	94	11.00	15.00	13.73	3	1.30	0.13
Total	94	105.00	145.00	129.43	29	10.67	1.19

As presented in Table 2, the mean total score of science teachers on the *Effective Science Teaching Scale* was 129.43. The observed scores ranged from 105.00 to 145.00. The minimum and maximum possible scores for each subdimension are also provided in the table. Regarding subdimensions, the mean scores for Personal Development, Pedagogical Skills, and Self-Confidence were relatively lower compared to the Curriculum Knowledge subdimension.

Findings Related to the Second Sub-Problem (Q_2)

The findings regarding science teachers' effective science teaching levels according to gender and educational background were analyzed using independent samples t-tests, while differences based on professional seniority were examined using one-way analysis of variance (ANOVA). The results are presented in Tables 3, 4, and 5

Table 3. An independent-samples t-test was conducted to examine whether *Effective Science Teaching Scale* scores differed by gender.

						t-test		
Subscale (SE)	Gender		N	x̄	SD	t	df	p
Personal Development	Female	58	55.09	4.31	.57			
	Male	36	53.03	4.33	.72	2.25	92	.02
Self-Confidence	Female	58	35.91	3.45	.45			
	Male	36	34.56	3.19	.53	1.91	92	.06
Pedagogical Skills	Female	58	26.34	2.74	.36			
	Male	36	25.44	2.16	.35	1.67	92	.09
Curriculum Knowledge	Female	58	13.72	1.37	.18			
	Male	36	13.75	1.20	.20	-.093	92	.93
Total	Female	58	131.07	10.98	1.44			
	Male	36	126.78	9.63	1.60	1.93	92	.06

As shown in Table 3, a statistically significant difference was found between male and female teachers in the Personal Development subdimension of the *Effective Science Teaching Scale*, in favor of female teachers ($p < .05$).

Table 4. An independent-samples t-test was conducted to examine whether *Effective Science Teaching Scale* scores differed according to educational level.

Subscale	Educational Level	N	x̄	SD	SE	t-test		
						t	df	p
Personal Development	Bachelor's degree	70	53.91	4.52	.54	-1.45	92	.15
	Master's degree	24	55.42	3.97	.81			
Self-Confidence	Bachelor's degree	70	35.36	3.16	.38	-.18	92	.86
	Master's degree	24	35.50	4.10	.84			
Pedagogical Skills	Bachelor's degree	70	25.77	2.63	.31	-1.49	92	.14
	Master's degree	24	26.67	2.26	.46			
Curriculum Knowledge	Bachelor's degree	70	13.63	1.30	.16	-1.34	92	.18
	Master's degree	24	14.04	1.30	.27			
Total		70	128.67	10.64	1.27	-1.18	92	.24
		24	131.63	10.55	2.15			

As shown in Table 4, no statistically significant difference was found in science teachers' effective science teaching levels according to educational background ($p > .05$).

Table 5. A one-way ANOVA was performed to compare the total and subscale scores of the *Effective Science Teaching Scale* across different levels of teaching experience

Subscale	Teaching experience (years)	N	x̄	SD	Source	SS	df	MS	F	p
Personal Development	6-10	13	53.46	4.45	Between Groups	188.95	3	62.98	3.49	.02
	11-15	34	55.44	3.52						
	16-20	28	52.39	5.06	Within Groups	1620.71	90	18.01		
	21 and above	19	55.63	3.98						
	Total	94	54.30	4.41	Total	1809.66	93			
Self-Confidence	6-10	13	35.23	2.74	Between Groups	75.69	3	25.23	2.27	.09
	11-15	34	35.85	3.46						
	16-20	28	34.14	3.58	Within Groups	1000.74	90	11.12		
	21 and above	19	36.53	3.18						
	Total	94	35.39	3.40	Total	1076.44	93			
Pedagogical Skills	6-10	13	25.69	2.21	Between Groups	51.93	3	17.31	2.79	.05
	11-15	34	26.59	2.08						
	16-20	28	24.96	3.28	Within Groups	558.07	90	6.20		
	21 and above	19	26.68	1.92						
	Total	94	26.00	2.56	Total	610.00	93			
Curriculum Knowledge	6-11	13	13.46	1.45	Between Groups	4.72	3	1.57	.92	.43
	11-15	34	13.65	1.41						
	16-20	28	13.68	1.33	Within Groups	153.63	90	1.71		
	21 and above	19	14.16	90						
	Total	94	13.73	1.30	Total	158.35	93			
Total	6-10	13	127.85	9.77	Between Groups	930.71	3	310.24	2.91	.04
	11-15	34	131.53	9.78						
	16-20	28	125.18	11.85	Within Groups	9596.27	90	106.63		
	21 and above	19	133.00	9.13						
	Total	94	129.43	10.64	Total	10526.98	93			

As presented in Table 5, effective science teaching levels differed significantly according to professional seniority ($p < .05$). To determine which groups differed from each other, post hoc comparisons were conducted. Since the assumption of homogeneity of variances was satisfied for both the total scale score and its subdimensions, the Least Significant Difference (LSD) test was employed (see Table 6).

Table 6. LSD post hoc test results for *Effective Science Teaching Scale* scores by teaching experience

Teaching experience (years) (i)	Teaching experience (years) (j)	Mean Difference (i-j)	SE	p
6-10	11-15	-3.68	3.37	.28
	16-20	2.67	3.47	.44
	21 and above	-5.16	3.72	.17
11-15	6-10	3.68	3.37	.28
	16-20	6.35*	2.64	.02
	21 and above	-1.47	2.96	.62
16-20	6-10	-2.67	3.47	.44
	11-15	-6.35*	2.64	.02
	21 and above	-7.82*	3.07	.01
21 and above	6-10	5.15	3.72	.17
	11-15	1.47	2.96	.62
	16-20	7.82*	3.07	.01

Findings Related to the Third Sub-Problem (Q_3)

As shown in Table 6, teachers with 21 years or more of professional seniority scored significantly higher on both the total scale and its subdimensions compared to those with 16–20 years of experience ($p < .05$). Similarly, teachers with 11–15 years of seniority also demonstrated significantly higher scores than those with 16–20 years of experience ($p < .05$). Additionally, no participants in the study had 1–5 years of professional seniority. Table 7. presents the findings related to science teachers' effective science teaching levels.

Table 7. Science teachers' levels of entrepreneurship education

	N	Min.	Max.	x̄	SD	SE
Entrepreneurship education	94	92.00	178.00	140.86	15.54	1.60

As presented in Table 7, the mean score obtained from the *Entrepreneurship Scale* was 140.86. Based on the scale's classification criteria, scores between 124 and 151 indicate a high level of entrepreneurship; therefore, the participating teachers demonstrated a high level of entrepreneurship.
The observed scores ranged from 92.00 to 178.00.

Findings Related to the Fourth Research Problem (Q4)

The entrepreneurship education levels of science teachers were analyzed using independent samples t-tests for gender and educational background variables and one-way ANOVA for professional seniority. The results are presented in Tables 8, 9, and 10.

Table 8. An independent-samples t-test was conducted to examine whether *Entrepreneurship Scale* scores differed by gender.

	Gender	N	x̄	SD	SE	t-test		
						t	df	p
Entrepreneurship education	Female	58	143.33	16.09	2.11	1.98	92	.05
	Male	36	136.89	13.93	2.32			

As shown in Table 8, entrepreneurship education levels differed significantly by gender, with female teachers scoring higher than male teachers ($p \leq .05$).

Table 9. An independent-samples t-test was conducted to examine whether *Entrepreneurship Scale* scores differed according to educational level.

	Education level	N	x̄	SD	SE	t-test		
						t	df	p
Entrepreneurship education	Bachelor's degree	70	138.00	15.76	1.88	-2.83	92	.006
	Master's degree	24	148.33	12.38	2.53			

As presented in Table 9, entrepreneurship education levels differed significantly according to educational background, with teachers holding postgraduate degrees scoring higher than those with undergraduate degrees ($p < .05$).

Table 10. A one-way analysis of variance (ANOVA) was conducted to examine whether *Entrepreneurship Scale* scores differed according to teaching experience.

	Teaching experience (years)	N	x̄	SD	Source	SS	df	MS	F	p
Entrepreneurship education	6-10	13	140.23	20.89	Between Groups	182.47	3	60.82	.246	.86
	11-15	34	142.53	15.22						
	16-20	28	139.14	16.61	Within Groups	22288.73	90	247.65		
	21 and above	19	140.84	10.42						
	Total	94	140.86	15.54	Total	22471.20	93			

As presented in Table 10, entrepreneurship education levels did not differ significantly according to professional seniority ($p > .05$).

Findings Related to the Fifth Research Problem (Q5)

Because the normality assumption was satisfied, Pearson's product–moment correlation coefficient was calculated to determine the strength and direction of the relationship between effective science teaching and entrepreneurship education levels. The findings are presented in Table 11.

Table 11. The relationship between science teachers' levels of effective science teaching and their levels of entrepreneurship education

Scale		Entrepreneurship education	Effective Science Teaching
Entrepreneurship education	r	1	.63
	p		.00
	N	94	94
Effective Science Teaching	r	.63	1
	p	.00*	
	N	94	94

*Correlation is significant at the .05 level (2-tailed).

As presented in Table 11, a positive and statistically significant correlation was found between scores on the *Effective Science Teaching Scale* and the *Entrepreneurship Scale* ($p < .05$). The correlation analysis revealed a strong, positive, and statistically significant relationship between the total scores of the *Effective Science Teaching Scale* and the *Entrepreneurship Scale* ($r = .63$, $p < .05$). In addition, the results of Pearson's product–moment correlation analysis examining the relationships between the subdimensions of the *Effective Science Teaching Scale* and entrepreneurship education scores are presented in Table 12.

Table 12. Pearson product–moment correlation analysis

Scale	N	Personal Development	Self-Confidence	Pedagogical Skills	Curriculum Knowledge
Entrepreneurship Scale	94	r= .56	r= .57	r= .62	r= .54

p <. 05

As presented in Table 12, a moderate, positive correlation was found between entrepreneurship education scores and the Personal Development ($r = .56$, $p < .05$), Self-Confidence ($r = .57$, $p < .05$), and Curriculum Knowledge ($r = .54$, $p < .05$) subdimensions of the *Effective Science Teaching Scale*. A strong, positive correlation was observed between entrepreneurship education and the Pedagogical Skills subdimension ($r = .62$, $p < .05$).

Results and Discussion

In this study, science teachers were found to demonstrate high levels of effective science teaching. Similar findings are consistent with the results of studies conducted by Yavuz (2020) with classroom and science teachers and Öztürk (2021) with science teachers, which also reported high levels of effective science teaching. Research on entrepreneurship education emphasizes the role of pedagogical frameworks that balance disciplinary, professional, and entrepreneurial purposes to effectively contextualize teaching practices within specific domains, such as science education (Ramsgaard & Blenker, 2022). Therefore, in implementing effective science teaching, teachers' content knowledge and pedagogical competencies play a decisive role, as they enable the planning and enactment of meaningful learning experiences. Additionally, the effective use of technology-supported digital learning environments has emerged as a key factor in enhancing the quality of science instruction (Song & Sparks, 2019). In Pierro's (2019) study, it was indicated that teachers' personal characteristics and their prior science learning experiences influence their science teaching practices.

In the present study, science teachers' competency levels in the Personal Development, Pedagogical Skills, and Self-Confidence subdimensions were found to be lower compared to their competency level in the Curriculum Knowledge subdimension. Teachers demonstrated relatively higher competency in Curriculum Knowledge than in the other subdimensions of the scale. Similar findings in the literature indicate that science teachers' knowledge of effective teaching strategies and their implementation can vary across different teaching domains (Aydın Sesli & Akpolat, 2024; Mamba & Putsoa, 2018). In addition, research on pedagogical content knowledge suggests that effective science teaching requires the integration of subject matter knowledge and pedagogical understanding to make scientific concepts comprehensible to learners (Kind, 2009). Recent research also indicates that teachers' pedagogical content knowledge and instructional practices are important determinants of effective science teaching and student outcomes.

No statistically significant differences were observed between the total score and the Self-Confidence, Pedagogical Skills, and Curriculum Knowledge subdimension scores of the *Effective Science Teaching Scale* and the gender variable. However, female teachers demonstrated a statistically significant difference in the Personal Development subdimension of effective science teaching compared to male teachers. Comparable findings in the literature report gender-based differences in related teacher characteristics: Güler and Bilici (2016) found that secondary school teachers' science teaching attitudes varied by gender; Demirkol, Kartal, and Taşdemir (2022) identified gender differences in attitudes toward STEM activities among science teachers; and Turan and Çelik (2024) documented gender-related differences in science teachers' information and technology literacy. These results align with previous research suggesting that female teachers may exhibit higher levels of certain instructional and professional attributes. It has been suggested that such differences may relate to female teachers' greater effectiveness in employing instructional strategies (as indicated in some studies reporting higher interpersonal relation and planning competencies in female educators) and their relative strengths in communication, collaboration, and professional development engagement.

No significant difference was found between gender and the total scores of the Effective Science Teaching Scale, as well as the sub-dimensions of Self-Confidence, Pedagogical Skills, and Curriculum Knowledge. However, female teachers demonstrated a statistically significant difference in favor of the Personal Development sub-dimension. Güler and Bilici (2016) reported significant differences in favor of female teachers regarding secondary school teachers' Technological Pedagogical Content Knowledge (TPACK) levels. Similarly, Demirkol, Kartal, and Taşdemir (2022) found that female science teachers exhibited more positive attitudes toward STEM activities, while Turan and Çelik (2024) revealed significant differences in favor of female teachers in terms of information and technology literacy. The findings obtained in the present study are consistent with the existing literature and indicate a significant effect in favor of female teachers. This situation may be associated with female teachers' more effective use of instructional strategies (Karakış, Gürcan, & Demirtaş, 2009) and their greater competence in communication, collaboration, and professional development (Aktağ & Walter, 2005).

No significant differences were found between the total score and the Self-Confidence, Pedagogical Skills, and Curriculum Knowledge subdimension scores of the *Effective Science Teaching Scale* and the gender variable. However, female teachers exhibited a statistically significant difference in the Personal Development subdimension of effective science teaching beliefs. Güler and Bilici (2016) reported significant gender differences in Technology Pedagogical Content Knowledge levels among secondary school teachers; Demirkol, Kartal, and Taşdemir (2022) found significant gender differences in science teachers' attitudes toward STEM activities; and Turan and Çelik (2024) identified significant gender differences in science teachers' information and technology literacy, all in favor of female teachers. These findings are consistent with the current results and suggest a significant effect in favor of female teachers. This situation is thought to be related to female teachers' more effective use of instructional strategies (Karakış, Gürcan & Demirtaş, 2009) and their greater competence in communication, collaboration, and professional development (Aktağ & Walter, 2005). These findings align with the current results and suggest that gender-related differences may emerge in certain dimensions of effective teaching, such as personal development, even when no differences are observed in other instructional subdimensions.

The results indicated that educational level did not have a statistically significant effect on science teachers' effective science teaching levels. This finding is consistent with the results reported by Öztürk (2021), who also found no significant differences in effective science teaching based on educational level. Similarly, Biçer, Uzoğlu, and Bozdoğan (2019) concluded that science teachers' views on STEM did not vary significantly according to their educational level. These findings suggest that higher academic qualifications alone may not necessarily translate into differences in instructional effectiveness or teaching-related beliefs. Rather, factors such as teaching experience, professional development engagement, and contextual variables may play a more decisive role in shaping effective science teaching practices.

Significant differences were found in science teachers' effective science teaching levels based on professional seniority. Teachers with 21 years or more of experience and those with 11–15 years of experience scored significantly higher than teachers with 16–20 years of experience, indicating a non-linear relationship between seniority and effective science teaching. Previous research conducted in Türkiye suggests that teachers with 11–20 years of experience tend to use a greater variety of instructional materials in the teaching–learning process (Lal & Sarı, 2015), while teachers with more than 20 years of experience may reach higher levels of career satisfaction that positively influence their instructional practices (Öztürk, 2021). From a social cognitive perspective, these findings can be interpreted through Bandura's (1997) concept of *mastery experiences*, which represent the most influential source of self-efficacy beliefs. As teachers accumulate successful instructional experiences over time, their perceived competence and instructional confidence may strengthen; however, such development does not necessarily follow a strictly linear pattern. Fluctuations across seniority groups may therefore reflect variations in accumulated mastery experiences, career stage transitions, and contextual factors such as job satisfaction and organizational climate rather than experience alone determining teaching effectiveness.

The results revealed that science teachers demonstrated entrepreneurship education levels corresponding to the "High Entrepreneurship" category. This finding is consistent with previous research conducted with both preservice and in-service teachers, which similarly reported high levels of entrepreneurial tendencies among educators (Armut & Kılınç, 2018; Aydoğmuş, 2019; Demir, Karataş & Metin, 2021; Gördes, 2023). Studies specifically focusing on science education have likewise indicated elevated entrepreneurship levels among preservice science teachers (Akbulut, 2019; Öztürk, 2021; Öztürk, Önder & Güven Yıldırım, 2019) and in-service science teachers (Deveci, 2018; Köken & Çelik, 2021). Moreover, research suggests that participation in entrepreneurial activities is closely linked to entrepreneurship education (Çelik & Pektaş, 2022). In line with the present findings, this relationship implies that higher levels of entrepreneurial disposition among teachers may foster more effective engagement with entrepreneurship education, thereby contributing positively to instructional practices and educational outcomes.

A statistically significant difference was found in teachers' entrepreneurship education levels in favor of female teachers. This finding aligns with previous research reporting higher entrepreneurial tendencies among female preservice teachers (Ateş, 2018; Lee, 2021; Selanik Ay, Duban & Aydoğdu, 2024). Similarly, Ekşioğlu (2021) found that female science teachers demonstrated significantly higher levels in the use of 21st-century teaching skills, which are closely associated with innovation, adaptability, and proactive engagement in instructional contexts. The observed gender difference may also be interpreted in light of socio-emotional and motivational competencies. Research suggests that emotional awareness, self-regulation, intrinsic motivation, adaptability to change, empathy, and advanced social skills may contribute to individuals' entrepreneurial dispositions (Tican, 2020). These characteristics could partially explain why female teachers in the present study exhibited higher levels of entrepreneurship education.

The findings indicated that science teachers' entrepreneurship education levels did not differ significantly according to professional seniority. This result aligns with previous research reporting no significant relationship between teaching experience and entrepreneurial tendencies among teachers (Demir, Karataş & Metin, 2021; Köken & Çelik, 2021). These findings suggest that entrepreneurial disposition may be influenced more by personal and professional development factors than by years of experience alone. In contrast, a statistically significant difference was observed with respect to educational level, favoring teachers who had completed postgraduate education. Baran (2014) found that science teachers engaged in postgraduate studies tend to be more open to innovations in their field, while Biçer, Uzoğlu, and Bozdoğan (2018) reported higher professional competency levels among science teachers with postgraduate qualifications. Taken together, these findings indicate that advanced academic engagement may enhance teachers' entrepreneurial orientation, possibly by fostering critical thinking, innovation awareness, and openness to change.

A strong, positive, and statistically significant correlation was found between science teachers' effective science teaching levels and their entrepreneurship education levels. This finding suggests that higher entrepreneurial orientation is associated with greater instructional effectiveness in science education. From a social cognitive perspective, this relationship may be explained through Bandura's (1997) self-efficacy theory. Teachers with stronger self-efficacy beliefs are more likely to take initiative, adopt innovative strategies, and persist in challenging instructional situations—characteristics that also define entrepreneurial orientation. Therefore, effective science teaching and entrepreneurship education may share a common psychological foundation grounded in elevated self-efficacy beliefs. Consistent with this interpretation, previous studies indicate that teachers' entrepreneurial tendencies are related to self-confidence, professional interest, and domain expertise (Ülgen Aydınlık, 2015), and that inquiry-based practices, STEM-oriented interventions, and entrepreneurship-integrated instructional models positively influence entrepreneurial levels (Bayram & Çelik, 2023; Çelik et al, 2015; Deveci, 2018). Together, these findings suggest that entrepreneurship education and effective science teaching may mutually reinforce one another.

Recommendations

Based on the findings of the study, the following recommendations are proposed:

1. It was found that science teachers scored higher in the Curriculum Knowledge subdimension compared to the Personal Development, Pedagogical Skills, and Self-Confidence subdimensions. In order to

promote high-quality science instruction, in-service training programs focusing on personal development, pedagogical competencies, and self-confidence may be organized to support teachers in these areas.
2. Examining teachers' levels of effective science teaching and entrepreneurship education can help identify their strengths and areas for improvement, thereby informing the development of educational policies and instructional practices.
3. Although numerous studies exist on effective science teaching and entrepreneurship education separately, research addressing these two constructs together remains limited. Therefore, the findings of the present study are considered to contribute to the field of science education by integrating these two dimensions.
4. While the present study relied on scale-based quantitative data, future research may incorporate classroom observations and qualitative data to provide deeper insights into teachers' instructional practices and entrepreneurial orientations.
5. Future studies may expand the current research by including additional variables to examine which factors predict teachers' effective science teaching and entrepreneurship education levels.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in JESEH journal belongs to the authors

* Ethical approval for this research was approved by the Scientific Research and Ethics Committee of Kırıkkale University with the decision dated February 21, 2024 (No: E.234670).

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Research at the Intersection of Science Education and Neuroscience: A Bibliometric and Content Analysis

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Abstract

Along with the growing interest in neuroscience and advances in the field, research on the neuroscience of science learning has increased considerably. Despite the growing body of literature, comprehensive review studies integrating bibliometric and content analysis perspectives remain limited. To address this gap, this study aims to provide a comprehensive analysis of research integrating science education and neuroscience using bibliometric and content analysis methods. The data for this study comprise 288 articles published between 1992 and 2024, retrieved from the Web of Science database. The scientific mapping software VOSviewer and SciMAT were used for data analysis and visualization of the relevant literature. Research results indicate that neuroscience research in science education has seen significant growth in recent years. The United States is the country with the highest levels of productivity, impact, and collaboration. The leading journal in the field is the ‘‘Journal of Chemical Education’’, and Yu-Cin Jian has been identified as the most productive researcher. The most-cited article, authored by Makransky et al. (2019), has received 769 citations. Keyword co-occurrence analysis revealed shifts in research focus over the field's thematic evolution. The results of the content analysis showed that the most commonly used neurocognitive tools are eye tracking and electroencephalography, whereas tools such as brain stimulation, galvanic skin response, and functional near-infrared spectroscopy are used quite sparingly. From a methodological perspective, it has been determined that the studies largely rely on quantitative research designs, that participants consist predominantly of university students, and that sample sizes are generally small. This study provides a comprehensive framework regarding the themes shaping the field, its intellectual structure, its evolution, and trends over time, and serves as a fundamental reference point for future research.

Introduction

Learning is not merely a cognitive process; it is a complex and dynamic process shaped by the interplay of numerous factors, including emotional, social, and interest-related aspects, as well as physical and psychological states (Antonopoulou et al., 2023; Granado De La Cruz et al., 2025). Educational neuroscience is an interdisciplinary field that aims to understand the neural mechanisms underlying learning and to integrate this knowledge into educational practices. This field integrates findings from psychology, educational sciences, and neuroscience to conduct an in-depth examination of how learning works in the brain (Thomas et al., 2019). The primary goal of educational neuroscience is to develop more effective teaching strategies that enhance the learning process by elucidating the neurobiological foundations of cognitive processes such as learning, memory, attention, motivation, and emotion (Thomas & Arslan, 2025). Additionally, educational neuroscience aims to support learners’ active participation in knowledge production and ensure the retention of learned information (Altuntaş et al., 2024). This approach goes beyond traditional educational research and offers new perspectives on learners’ individual differences and neurocognitive learning difficulties (Pradeep et al., 2024).

Educational neuroscience not only provides a theoretical understanding but also offers the opportunity to objectively observe learning processes through the methods neuroscience provides, thereby contributing to grounding educational practices in scientific evidence (Thomas, 2018). Among these tools, electroencephalography (EEG) is a neurophysiological technique used to study and enhance learning processes by monitoring electrical signals in the brain (Leikin et al., 2025). Among other imaging tools, functional near-infrared spectroscopy (fNIRS) provides information about brain regions involved in cognitive processes by measuring changes in blood oxygenation. This technique is an imaging method that uses near-infrared light to assess oxygenation and blood flow in brain areas (Pinheiro et al., 2024). Functional magnetic resonance imaging (fMRI) is a neuroimaging technique that measures brain activity by detecting signals related to blood oxygen levels (Oliver, 2011; Rashid et al., 2020). Transcranial magnetic stimulation (TMS) is a non-invasive brain stimulation technique that uses magnetic fields to stimulate specific regions of the brain (Gongalla et al., 2026). On the other hand, eye tracking is a non-invasive technique used to measure and track eye movements and fixation patterns during various learning tasks and interactions with instructional materials (Ulukök Yıldırım & Sönmez, 2024).

The field of educational neuroscience contributes to the development of teaching methods in various areas, including language acquisition, reading, science education, and, with a particular focus on mathematics education, to support learners' educational experiences. Science education not only aims to provide students with scientific knowledge and skills but also to foster their abilities in scientific thinking, problem-solving, and critical analysis (Holbrook & Rannikmae, 2007). In this context, understanding science concepts, developing scientific process skills, and improving the ability to generate solutions for complex scientific problems are highly important (Liu & Huang, 2015). The role of neuroscience in science education is to better understand the cognitive challenges students face and the strategies they use when learning science. For example, processes such as mentally manipulating chemical formulas or grasping abstract scientific concepts require specific cognitive loads and brain activations (Liu & Huang, 2015). Neuroscientific techniques provide objective data on the effectiveness of learning processes by tracking changes in students' brains during such tasks (Pradeep et al., 2024). This data can offer valuable insights for designing science courses, developing instructional materials, and personalizing students' learning experiences (Ballesta-Claver et al., 2024; Vaughn et al., 2020). In this way, neuroscience enriches both the theoretical and practical aspects of science education, paving the way for more effective and student-centered approaches. As a key field shaping the future of science education, the neuroscience of science education enables us to gain a deeper understanding of learning processes and to incorporate this knowledge into educational practices. Consequently, in recent years, researchers have focused on this interdisciplinary interaction between science education and neuroscience (Cho & Yeh, 2026), and neuroscience-based research in science education has been increasing at both the theoretical and practical levels.

A study compiling neuroscience-based research in science education reveals that researchers such as Dubinsky, Michlin, and Pate have emerged as leading figures in this field; there has been a marked increase in publications, particularly since 2020; and the majority of research on this topic is being conducted in the USA (Bakır et al., 2023). However, it is important to note that the study considered only research in the Web of Science (WoS) database and did not provide a detailed analysis of the studies examined. This includes lacking information on the specific scientific fields and skills they focused on, the participant profiles they targeted, and the neurocognitive tools that were used. In Turkey, neuroscience research in education has gained momentum since 2013, though it has largely remained at the theoretical level (Taşkıner-Şereflioğlu & Kılıç-Mocan, 2021).

Unlike previous studies, the present study examines research at the intersection of neuroscience and science education from a broad historical perspective. It adopts an integrated bibliometric approach by combining SciMAT and VOSviewer software and employs various bibliometric indicators, including the h-index, citation counts, centrality, density, and total link strength (TLS), to provide deeper insights into the field. In addition, the study analyzes the intellectual landscape, emerging trends, and thematic development of the literature through keyword and citation analyses. Content analysis was also employed to provide both a global perspective and structural depth regarding the integration of neuroscience and science education. In this context, the study addresses important gaps in the literature by conducting a large-scale bibliometric and content analysis of publications published between 1992 and 2024. Thus, by offering a detailed overview of the field, the study enhances understanding of the development, current status, and future directions of neuroscience-related research in science education.

Bibliometric analysis provides a comprehensive, data-driven understanding of publication trends, highly cited articles, key contributors, collaboration patterns, thematic structures, and the evolution of the field. The content analysis examined the neurocognitive tools employed in the studies, participant characteristics, research designs, and sample sizes.

Method

In this study, a combination of bibliometric and content analysis was employed to gain insights into studies integrating science education with neuroscience using WoS data, trace the evolution of these research areas over the years, and identify trends in the field. Relying solely on a single research method can introduce limitations and, to some extent, bias (Gao et al., 2020). Therefore, in this integrated approach, quantitative bibliometric tools were used to map critical elements such as authors, countries, and citations, as well as the relationships among these elements and their evolution. Content analysis was also used to examine topics and content in depth and to provide stronger insights through a qualitative systematic review (Sahar & Munawaroh, 2025; Wahyuningrum et al., 2023).

Data Collection Method

The WoS database, a major scientific resource, is used to access the dataset for this study. Known for its high quality, advanced data extraction capabilities, rigorous editorial processes, and reputable journals, the WoS is one of the most suitable databases for bibliometric analysis (Lu et al., 2024). Additionally, this internationally recognized database is selected because it is a reliable source frequently used in various research fields (Maral, 2026). To identify relevant studies, a comprehensive and efficient search strategy was developed by drawing on the academic literature cited in previous systematic and bibliometric reviews on the subject (Leikin et al., 2025). A systematic search was conducted in the WoS database in December 2025 using the final search query shown in Figure 1.

Records identified from WoS database
Search within: Title, Abstract, and Keywords

Search Keywords:*(Neuroscience OR neurocognition OR neuroimaging OR ElectroEncephaloGraphy OR EEG OR Event-Related Desynchronization OR ERD OR Event-Related Potentials OR ERP OR Magnetic Resonance Imaging OR MagnetoEncephaloGraphy OR MEG OR MRI OR Functional Magnetic Resonance Imaging OR Fmrı OR Functional Near-Infrared Spectroscopy OR fNIRS OR Galvanic Skin Response OR GSR OR "eye tracking" OR "eye movement" OR "brain stimulation") AND ("science" OR "physics" or "chemistry" or "biology") AND ("education" OR "instruction" OR "teaching" OR "learning" OR "problem solving"*)

Excluded: Records published in 2025 and 2026
Document Type: Article
WoS Categories: ''Education and Educational Research", "Education Scientific Disciplines", "Psychology Educational''
WoS Index: ESCI, A&HCI, SCI-EXPANDED, SSCI,
Language: English
Excluded: Early Access and Open publisher- invited reviews
Excluded: Irrelevant studies

Studies included in the bibliometric analysis

Figure 1. WoS database searching steps

The search is performed in the "topic" field to retrieve all relevant studies. The initial search yielded 8,081 published documents. The years 2025 and 2026 (n=1,341) were excluded from the analysis. Subsequently, 1,027 articles are identified after applying a filter to the publications in the "Education and Educational Research," "Education Scientific Disciplines," "Education Special," and "Psychology Educational" categories in the WOS database. The search results are narrowed down to 733 articles, and the articles are selected. By applying a language filter, only articles written in "English" are included in the analysis, reducing the dataset to 683. After selecting the ESCI, SSCI, SCI-EXPANDED, and A&HCI indexes, 36 studies are excluded, leaving 647 for analysis. After excluding Early Access articles and publisher-invited review papers, the dataset consisted of 642 publications. Full-text versions of studies whose relevance to the scope could not be clearly determined are accessed and reviewed. A total of 354 articles unrelated to the research topic are excluded from the dataset.

Following this comprehensive filtering process, the final sample of 288 articles is downloaded in "Plain Text" format and used for the bibliometric and content analyses. Details regarding the search process are presented in Figure 1.

To identify studies suitable for content analysis, the full texts of 288 articles obtained through bibliometric analysis are reviewed by two researchers. During this process, studies that directly used at least one neurocognitive assessment tool are included. The full texts of the studies meeting this criterion are included in the analysis. A total of 183 articles that do not focus on the specified criterion and instead addressed neuroscience through theoretical and indirect approaches are excluded. Consequently, 105 articles containing direct neurocognitive data and constituting original empirical research are included in the content analysis.

Data Analysis

This study employes content analysis and bibliometric analysis to provide an overview of research in science education and neuroscience. Content analysis is a qualitative method for identifying cognitive schemas and extracting meaningful insights from the literature (Prashar & Sunder, 2020). The content analysis focused on the neurocognitive tools used in the studies, the participant groups, the sample sizes, and the research designs.

Bibliometric analysis is a popular data-driven research method that enables the quantitative examination of a specific research field or topic using statistical methods (Zhang et al., 2025). This analysis combines two main procedures: performance analysis and scientific mapping. Performance analysis involves assessing the volume and publication impact of institutions, journals, publications, authors, and countries (Panday et al., 2025). On the other hand, scientific mapping focuses on the relationships among research components, revealing the dynamics and structural organization of the research field (Pizzi et al., 2020). As part of the bibliometric analysis, trends in publication, geographic distribution, leading authors, relevant journals in the field, collaboration patterns, citation analysis, keyword co-occurrence analysis, and co-citation networks were examined.

Two software programs, VOSviewer (Van Eck & Waltman, 2014) and SciMAT (Cobo et al., 2012), were used to conduct scientific mapping and performance analysis. Using VOSviewer, citation analysis, co-authorship analysis, and keyword co-occurrence analysis were conducted. The VOSviewer program, which enables the exploration and visualization of scientific maps, is an extremely comprehensive and user-friendly tool that analyzes the networks of relationships among authors, journals, countries, institutions, and keywords (Van Eck and Waltman, 2014). This software creates a network structure composed of nodes representing each element in the dataset, with the network connections illustrating the relationships that emerge (Dogru et al., 2025). The size of the circles indicates the importance of concepts or frequently referenced elements.

To conduct a longitudinal analysis of the structural and dynamic development of the relevant field, the SciMAT software (Cobo et al., 2012) was used. Using the SciMAT software, a key tool in bibliometrics, strategic diagrams were created to categorize themes within the research field, and a thematic evolution map was developed to examine their evolution over time. SciMAT categorizes themes into four groups in two-dimensional strategic diagrams. Motor themes are characterized by high centrality and density. These themes encompass research areas that have developed extensively and are highly influential. Highly developed and isolated themes: These themes have low centrality and high density values and have weak connections to other themes; they encompass marginal topics that, while well-developed in their own right, are becoming increasingly less significant within the field. Emerging or declining themes: These are themes characterized by low centrality and high density, representing areas that emerge or fade over time. Basic and transversal themes consist of fundamental topics with low density and high centrality and have the potential to significantly impact the field as a whole (Nurani, 2025). On the thematic evolution map, the size of the spheres reflects the number of related documents and scales proportionally with the increase in the number of documents. Continuous lines between clusters indicate that the related themes share a common main theme. This signifies a conceptual connection. Dashed lines, on the other hand, appear when the connection is based on keywords and indicate a non-conceptual relationship. The thickness of continuous or dashed lines is determined by the inclusion index and represents the number of overlapping themes or keywords (Özköse & Ayaz, 2026).

Before the analyses, the dataset underwent cleaning and was prepared for bibliometric analysis. To this end, spelling errors, variations in keywords, singular-plural usage, abbreviations, and synonyms were identified and corrected. Before proceeding to the thematic analysis in this study, three distinct time periods were established in SciMAT to examine the evolution of the relevant literature. By evaluating both the conceptual and historical turning points in the literature and the number of publications, three periods were identified for the analysis: 1992–2012, 2013–2018, and 2019–2024.

Results

Annual Scientific Production

Figure 2 shows the scientific output over time of research integrating science education with neuroscience, while Figure 3 shows the distribution of citations.

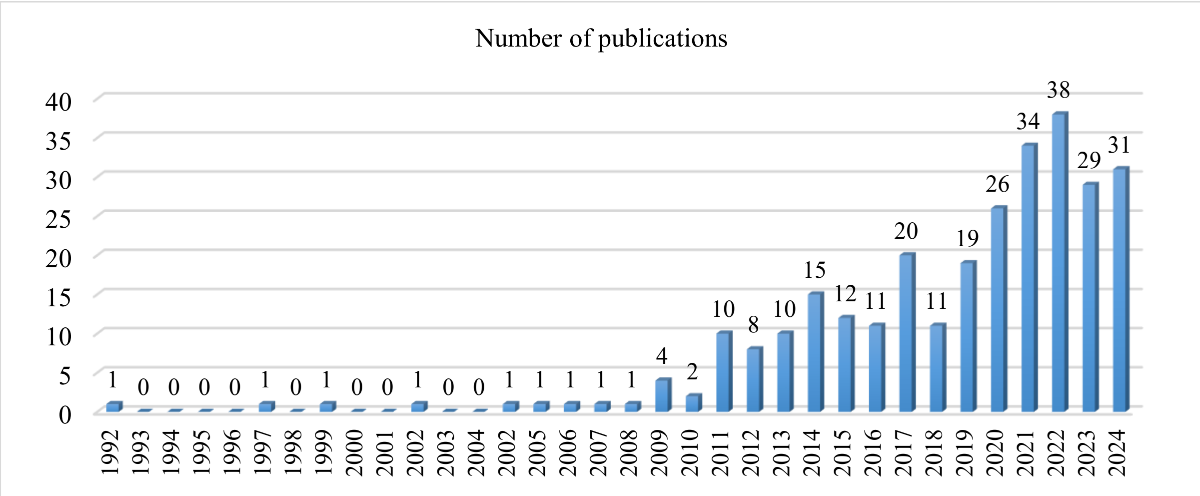

Figure 2. The number of publications according to years

A review of Figure 2 shows that the first publication in this research area dates back to 1992. From 1992 to 2009, publication activity remained low. Although initial developments were slow, the number of publications reached double digits for the first time in 2011. Although a slight decline was observed in 2012, the number of publications increased significantly between 2013 and 2017, reaching 10-15 documents. Since 2017, a fluctuating upward trend in the number of publications has continued. The highest number of publications was recorded in 2022, reaching 38. Additionally, a significant portion of the total academic output was produced between 2020 and 2024.

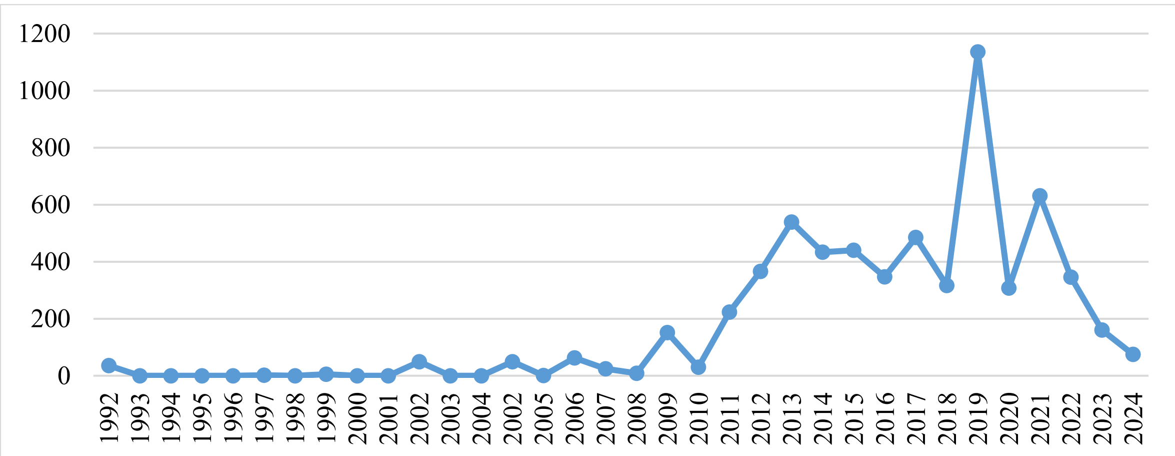

Figure 3. Number of citations by year

Graphical data on research integrating neuroscience with science education indicate that the field got off to a slow start and exhibited a very low citation rate between 1992 and 2005. Since 2006, however, a steady upward trend has been observed. In particular, 2013, 2015, and 2017 stand out for their higher citation counts. The field reached its highest citation level in 2019 with 1136 citations. A relative decline has been observed since 2022. This trend is likely attributable to the fact that articles published in recent years initially received fewer citations, rather than a loss of influence in the field.

Analysis of Country/Region Distribution

Figure 4 presents detailed information on the top 15 countries that have contributed the most publications to the field and received the most citations.

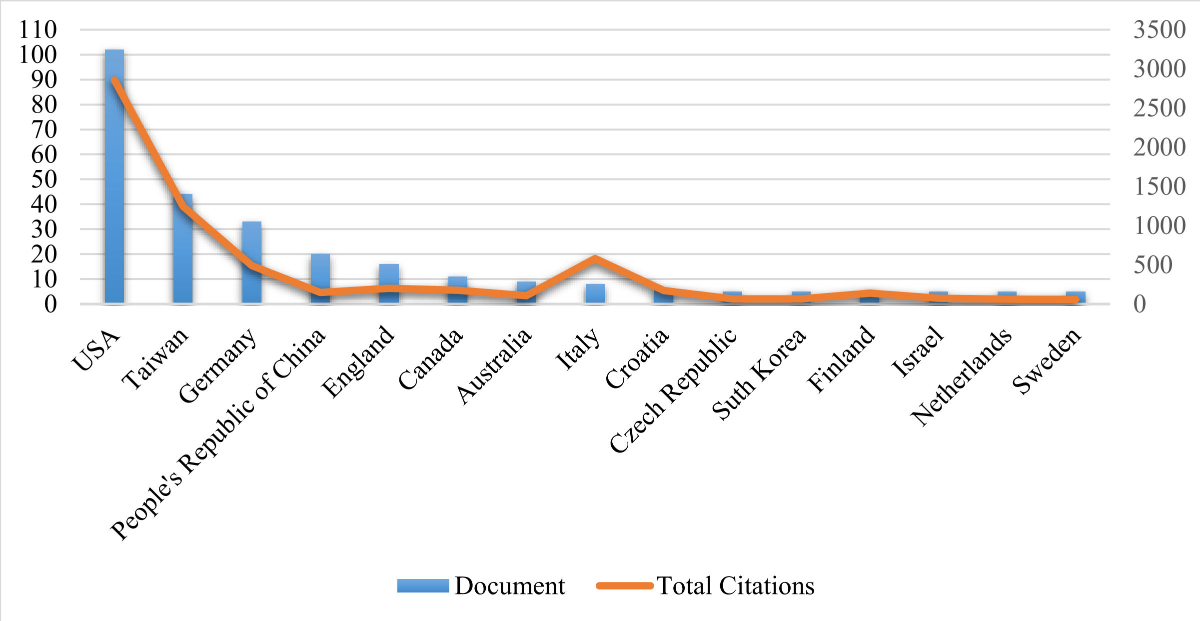

Figure 4. Distribution of publications and citations by country/territory (Top 15)

As shown in Figure 4, the USA ranks first in terms of both the number of publications and total citations, with 102 publications and 2,859 citations. Taiwan (44 publications, 1,247 citations) and Germany (33 publications, 489 citations) are among the countries following the USA in terms of publications. These countries have contributed to advancing neuroscience in science education. England (16 publications, 200 citations) and Canada (11 publications, 175 citations) have also made notable contributions through their publication output. Although Italy has a lower number of publications, it has garnered a significant number of citations. The network of co-authorship between countries was visualized using VOSviewer software and is presented in Figure 5. For this analysis, the minimum number of articles per country was set at five. Sixteen countries met this criterion, yielding a network comprising five clusters.

Figure 5. Co-authorship networks of countries

A review of Figure 5 reveals that international collaboration in this field remains limited. The USA has the highest level of collaboration, with a total connectivity score of 13. Taiwan and Germany are other countries demonstrating strong collaborations with high total connectivity scores. The USA and Taiwan exhibit intense collaboration. On the other hand, Germany has weaker connections with other countries but is engaged in collaboration with other European nations.

Source Analysis

Table 1 presents a list of the top ten journals that have published research integrating neuroscience with science education over the years.

Table 1. Top 10 most influential journals

Rank	Source	Documents	Citations	TLS
1	Journal of Chemical Education	20	405	26
2	Computers & Education	19	1146	58
3	Physical Review Physics Education Research	18	325	26
4	Frontiers in Education	16	95	17
5	Mind, Brain and Education	13	141	7
6	Research in Science Education	12	92	11
7	Journal of Science Education and Technology	11	115	17
8	International Journal of Science and Mathematics Education	10	300	42
9	Education Sciences	9	83	5
10	CBE–Life Sciences Education	8	147	3

Table 1 reveals that the "Journal of Chemical Education," "Computers & Education, and "Physical Review Physics Education Research" are the leading journals in terms of both the number of publications and total citations. In particular, "Computers & Education" has the highest number of citations, with 1,146. In terms of the number of issues published, these journals follow journals such as "Frontiers in Education", "Mind, Brain and Education", and "Research in Science Education". This distribution indicates that research on the integration of science education and neuroscience is represented in journals focused on disciplinary studies, educational technology, neuropedagogy, and that this research area is addressed across a broad spectrum.

Leading Authors in Terms of Productivity and Citations

A total of 832 authors contributed to the research in the publications included in the analyzed dataset. Authors with at least 5 publications were included in the study; 10 authors met this threshold. The top ten authors who contributed most significantly to the current research topic, along with the number of publications they produced and the total citations these publications received, are listed in Table 2.

Table 2. Top 10 most influential authors

Rank	Author	Documents	Citations
1	Jian, Yu-Cin	9	180
2	Tsai, Meng-Jung	8	451
3	Yang, Fang-Ying	8	395
4	Mason, Lucia	7	539
5	Bubic, Andreja	6	171
6	Palmovic, Marijan	6	171
7	Planinic, Maja	6	171
8	Susac, Ana	6	171
9	Pluchino, Patrik	5	426
10	Mayer, Richard E.	5	1055

According to the Table 2, Yu-Cin Jian leads the other authors as the researcher with the highest number of publications, nine in total, related to the subject of this study. He is followed by Meng-Jung Tsai and Fang-Ying Yang, each with eight study. These three authors share a common approach in that they address cognitive processes, visual information processing, and attention distribution in the context of science learning through eye tracking based experimental research. Lucia Mason is another prominent author in this field, having contributed to seven publications on the subject. Authors such as Andreja Bubic, Marijan Palmovic, Maja Planinic, and Ana Susac are among the other contributors to this field of research. Although Richard E. Mayer has contributed 5 publications to the field, he is researcher with the highest total number of citations, at 1055.

Figure 6 illustrates the co-authorship network of authors collaborating on research in the field of integrating science education and neuroscience. In this visualization, every author in this field has at least five publications. As shown in Figure 6, this collaborative group comprising Andreja Bubic, Marijan Palmovic, Maja Planinic, and Ana Susac forms a shared academic network. The connections among the authors in this group indicate that they are affiliated with the same research group or share a similar field of study.

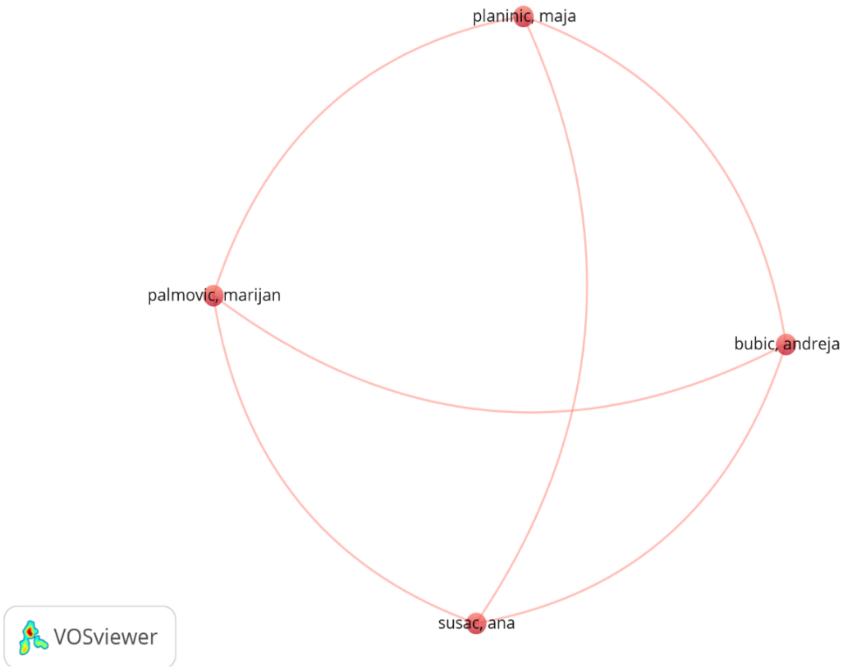

Figure 6. Co-authorship networks of authors

Influential Documents

Table 3 presents the most frequently cited articles in the field of research integrating science education and neuroscience. Table 3 reveals that these most cited documents in the current field are centered on cognitive processes, visual attention, immersive technologies, and multimedia learning. Methodologically, eye tracking has been used as the primary data collection tool in these studies.

Table 3. Most cited articles

Rank	Authors	Publication Year	Title	Total Citations
1	Makransky, G., Terkildsen, T. S., & Mayer, R. E.	2019	Adding immersive virtual reality to a science lab simulation causes more presence but less learning	769
2	Tsai, M. J., Hou, H. T., Lai, M. L., Liu, W. Y., & Yang, F. Y.	2012	Visual attention for solving multiple-choice science problem: An eye-tracking analysis	204
3	Parong, J., & Mayer, R. E.	2021a	Cognitive and affective processes for learning science in immersive virtual reality	195
4	Mason, L., Tornatora, M. C., & Pluchino, P.	2013a	Do fourth graders integrate text and picture in processing and learning from an illustrated science text? Evidence from eye-movement patterns	174
5	Mason, L., Pluchino, P., Tornatora, M. C., & Ariasi, N.	2013b	An eye-tracking study of learning from science text with concrete and abstract illustrations	126
6	Miller, B. W.	2015	Using reading times and eye-movements to measure cognitive engagement	97
7	Tsai, M. J., Huang, L. J., Hou, H. T., Hsu, C. Y., & Chiou, G. L.	2016	Visual behavior, flow and achievement in game-based learning	96
8	She	2009	The impact of multimedia effect on science learning: Evidence from eye movements	88
9	Susac, A. N., Bubic, A., Kaponja, J., Planinic, M., & Palmovic, M.	2014	Eye movements reveal students' strategies in simple equation solving	79

The most cited study, titled "Adding immersive virtual reality to a science lab simulation causes more presence but less learning", was published in the Journal of Learning and Instruction and has received 769 citations. This study demonstrates that incorporating immersive virtual reality into virtual learning simulations reduces students' learning levels, even though they experience a greater sense of presence in the immersive virtual reality environment.

The second most cited study, titled "Visual attention for solving multiple-choice science problems: An eye-tracking analysis", was conducted by Tsai et al. (2012) has received 204 citations. In this study, analyzes students' visual attention while solving a multiple-choice science problem using eye-tracking data, highlighting their cognitive strategies during multiple-choice questions.

The third most cited study, conducted by Parong and Mayer (2021a), has been referenced 195 times in the scientific community. The research explored differences in academic learning between a course delivered in an immersive virtual reality environment and a traditional course delivered via a desktop computer. Starting from the fourth position, the number of citations for the studies ranges from 79 to 174. Among these highly cited articles, eye tracking technology stands out as the most widely used tool.

Keyword Analysis

SciMAT was used to analyze the co-occurrence of keywords in research that integrates the fields of science education and neuroscience.

Structural and Thematic Development

The level of keyword overlap can be determined by examining the evolution of keywords over time. Upward and diagonal arrows indicate the number of keywords that were not used in the subsequent period, that is, those that were eliminated. Downward and diagonal arrows indicate the keywords newly added in the subsequent period. The horizontal arrows pointing to the right show the percentage of keywords that match or overlap across periods, while the circles represent the keywords used in each period. Figure 7 illustrates the evolution of keywords over different periods.

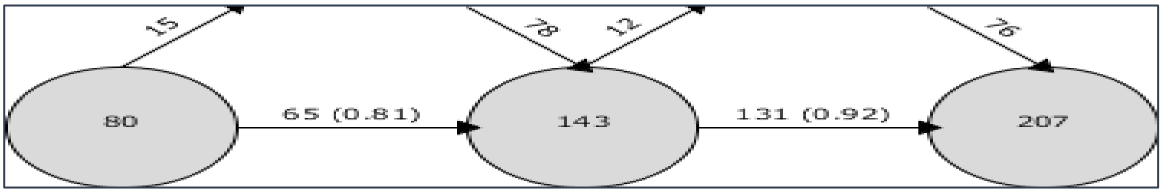

Figure 7. Continuity of keywords between intervals (Period 1: 1992–2012; Period 2: 2013–2018; Period 3: 2019–2024)

As shown in the overlay map in Figure 7, 80 different keywords were identified during the 1992–2012 period. Of these, 65 were retained, while 15 were lost in the subsequent phase. Approximately 81% of the keywords identified in the first period were carried over to the second period. Between 2013 and 2018, 78 new keywords were added, bringing the total to 143. Of these keywords, 12 were removed in the subsequent period, while 131 remained in the next time frame. During the most recent analysis period, 76 additional keywords were added to the research on the subject, bringing the total to 207. The increase in the number of keywords peaked during this period. The gradual emergence of new keywords confirms a significant evolution in the field, indicating that it has advanced considerably and that keyword diversity has increased. The themes associated with each period have been visualized using strategic diagrams.

Period 1 (1992–2012)

Figure 8 presents a strategic diagram showing the quadrants representing the themes of research integrating science education and neuroscience during the 1992–2012 period.

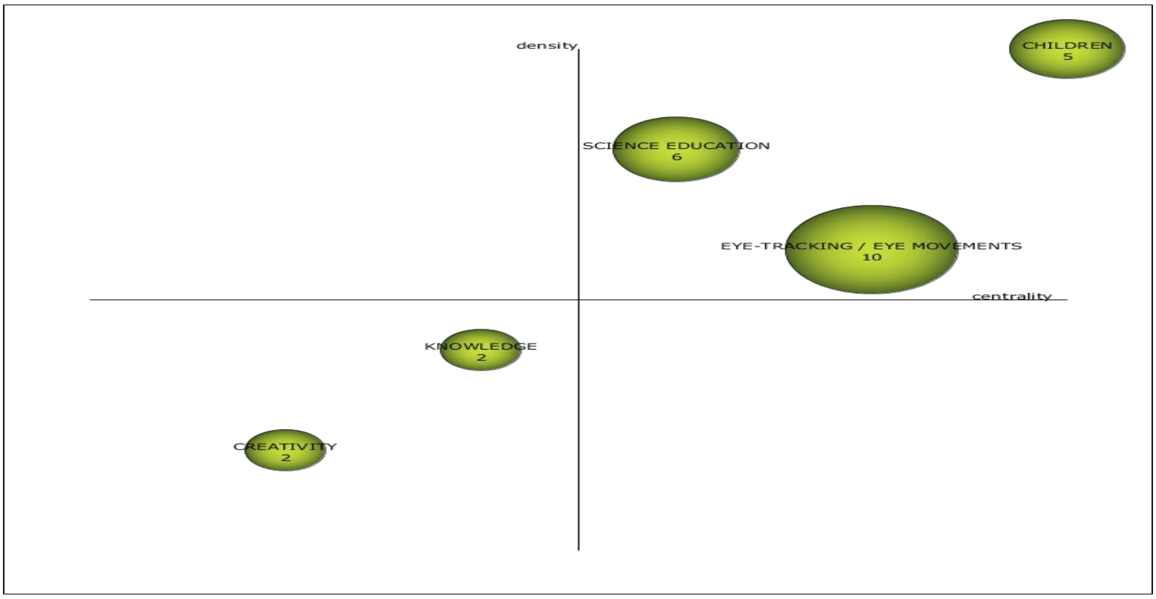

Figure 8. Period 1 (1992–2012) strategic diagram (h-index)

As shown in Figure 8, there are a total of five thematic clusters in the first period. Between 1992 and 2012, the themes of science education, children, and eye tracking/eye movements appear in the first quartile, indicating that these themes were the prominent research focuses of that period. Among these topics, eye tracking and eye movements have emerged as the most popular research topics of the current period. Neuroscience-based approaches have focused particularly on child learning during this period, and analyses of science learning processes have primarily used eye tracking methods. The themes of "knowledge" and "creativity" are located in the lower-left quadrant of the strategic diagram and represent emerging or declining themes. This suggests that academic interest in these themes has waned during the relevant period or that their conceptual frameworks may not yet be sufficiently developed.

Period 2 (2013–2018)

Figure 9 presents a strategic diagram showing the positioning of themes within the quadrant for the 2013–2018 period.

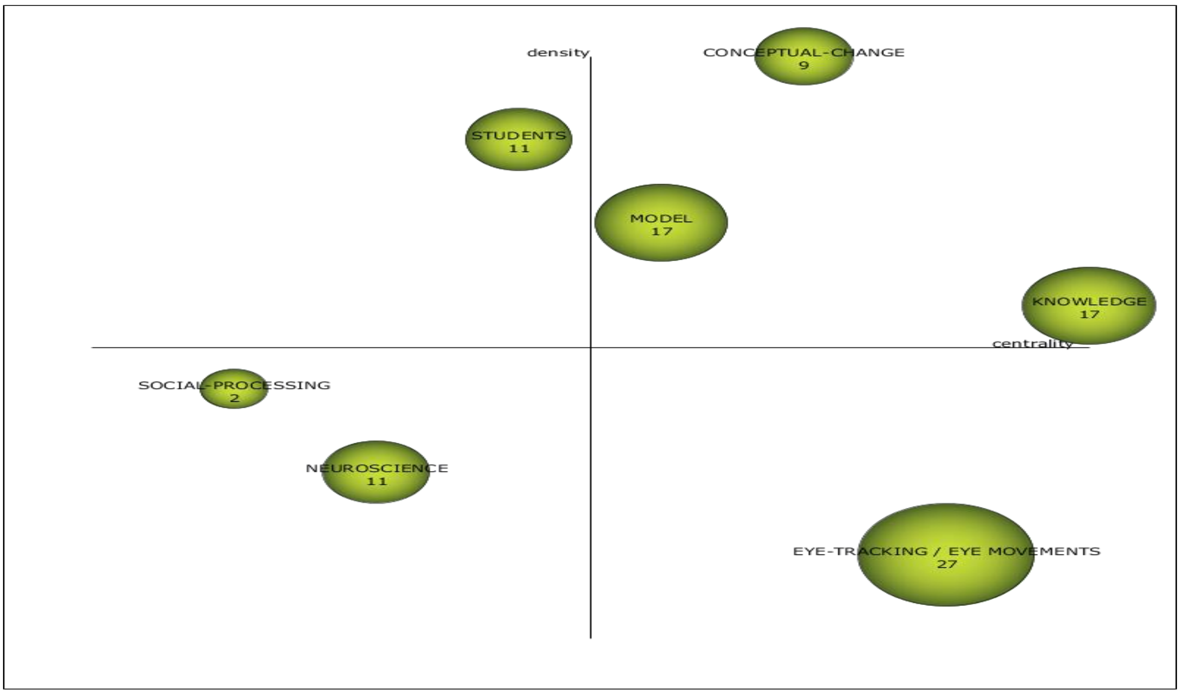

Figure 9. Period 2 (2013–2018) strategic diagram (h-index)

The distribution of themes during the 2013–2018 period shows significant differences compared to the previous period. It is evident that the themes of "knowledge" and "eye tracking/eye movements" continued to be studied during this period. Among these themes, "eye tracking/eye movements" had the highest h-index. In the second phase, the themes of "knowledge" and "conceptual change" were identified as driving themes. In contrast, the "students" theme appears to be a highly developed and isolated theme. The themes of "social processing" and "neuroscience" are associated with emerging or declining themes, those that are losing their significance. Although the theme of eye tracking/eye movements first emerged as a basic and transversal theme, it is now regarded as the sole foundational theme underpinning the field's conceptual basis during this period. It is evident that, during the 2013–2018 period, research integrating science education and neuroscience continued to be structured around eye tracking-based process analyses; that learning increasingly came to be explained through individual cognitive profiles; and that neuroscientific methods were linked to learning constructs such as knowledge construction, theoretical model generation, and conceptual change.

Period 3 (2019–2024)

Figure 10 presents a strategic diagram showing the positioning of the themes for the current phase (2019–2024) within the quadrant.

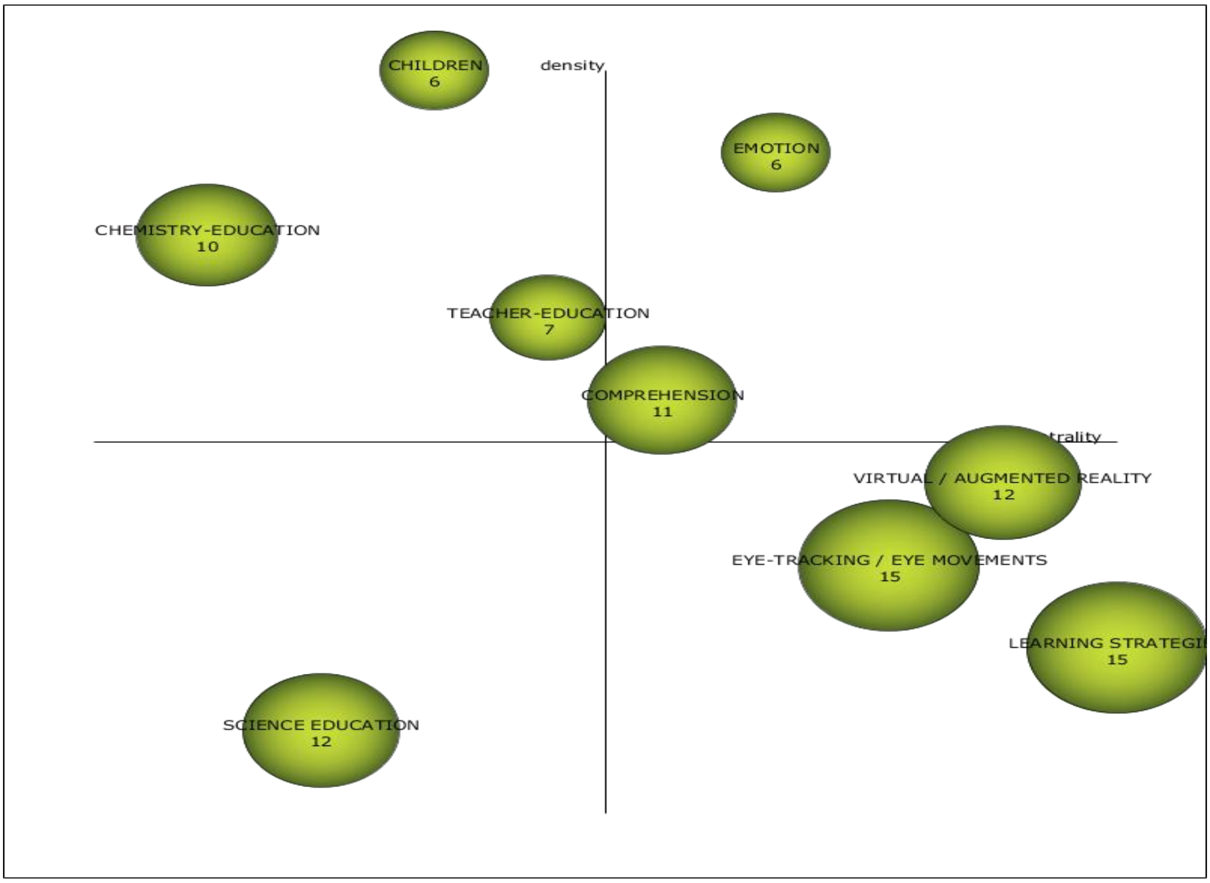

Figure 10. Period 3 (2019–2024) strategic diagram (h-index)

As shown in Figure 10, nine thematic clusters were identified during this period. Among these, the themes of "children," "science education," and "eye tracking/eye movements" were revisited. Additionally, there was a marked shift in thematic trends during this period compared to the previous one. While the themes of "emotion" and "comprehension" stand out as central to this period, those of "children," "chemistry education," and "teacher education" fall into the category of highly developed and isolated themes. The theme of "science education" is listed as an emerging or declining theme. Virtual and augmented reality, learning strategies, and eye tracking/eye movements are among the basic and transversal themes in this field, suggesting that further research is needed to advance our understanding of this period. These themes also have the highest h-index values, indicating that recent research in science education has integrated the understanding of learning processes, cognitive and emotional processes, learning strategies, and innovative learning environments and interventions.

Thematic Evolution Analysis

The thematic evolution map presented in Figure 11 illustrates the development of themes addressed in research integrating science education and neuroscience over the periods 1992–2012, 2013–2018, and 2019–2024. When the thematic evolution of terms is examined from a vertical perspective, it can be seen that the themes emerging in each period correspond to the results presented in the thematic diagram. When examined from a horizontal perspective, it is observed that new branches emerge and the number of groups increases over time.

Figure 11. Thematic evolution based on the h-index

Upon examining the map in Figure 11, it can be observed that there are more non-conceptual relationships than conceptual ones, and that new keywords emerge gradually. The "eye tracking/eye movements" theme is present in all three time periods, and there is a conceptual connection among them. This situation demonstrates that eye tracking-based process analyses constitute a significant research focus and a consistent area of inquiry in neuroscience-based research within the field of science education. Another research area is "science education-neuroscience-science education," which strongly represents the research track that integrates science education with neuroscience.

It can be seen that there were a few themes in the first period. While the themes of "eye tracking/eye movements" and "knowledge" continued into the second period, the other three themes evolved into different themes. The "eye tracking/eye movements" theme had a significant relationship with the "conceptual change" theme. A total of seven themes were identified in the second period. Of the seven themes identified for this period, "eye tracking/eye movements" persisted into the third period. In comparison, the remaining six themes were found to have evolved into new themes in the following period. By the final period, it was observed that the capacity for themes to evolve had increased, the total number of themes improved, and nine distinct themes emerged. The themes of "children" and "science education," which emerged in the first period and disappeared in the second, reappeared in the third period. In addition, the themes of "learning strategies," "virtual/augmented reality," "comprehension," "emotion," "chemistry education," and "teacher education" appeared for the first time during this period.

Results of the Content Analysis

Neurocognitive Tools Used in the Studies

The neurocognitive tools used in studies in the field of science education are presented in Figure 12.

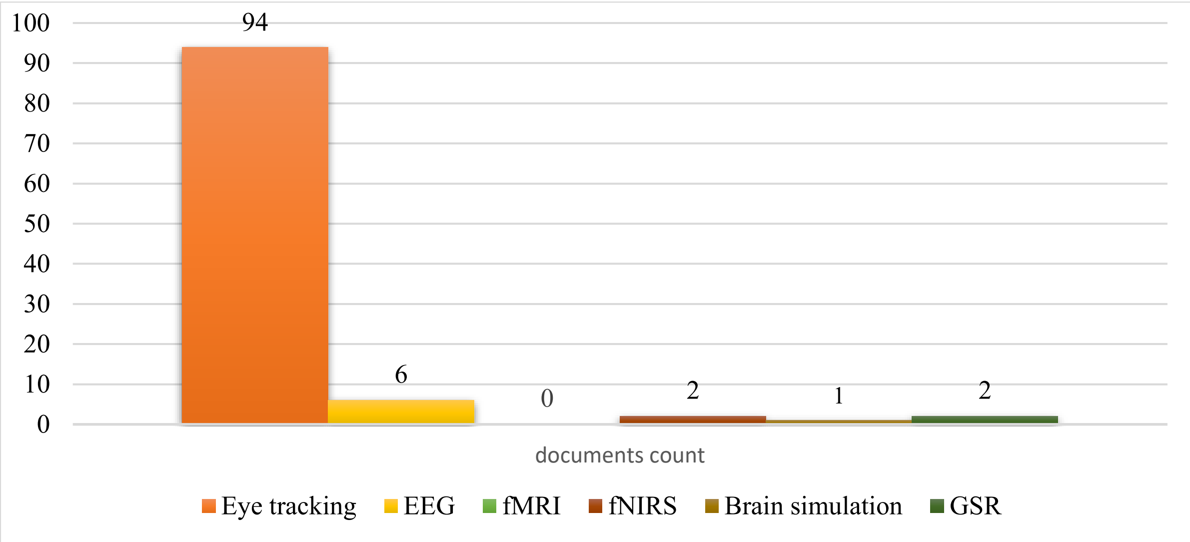

Figure 12. Neurocognitive tools used in research

The distribution of the studies included in our research indicates that the most commonly used tools in neurocognitive research are eye tracking and EEG. It is believed that this preference stems from the fact that these methods are becoming increasingly affordable and are based on reliable methodological foundations. Galvanic Skin Response (GSR) and fNIRS techniques have been used rarely. The brain-simulation technique has been included in only a few studies. Figure 13 shows the number of studies using neurocognitive techniques, including eye tracking, EEG, fNIRS, and GSR.

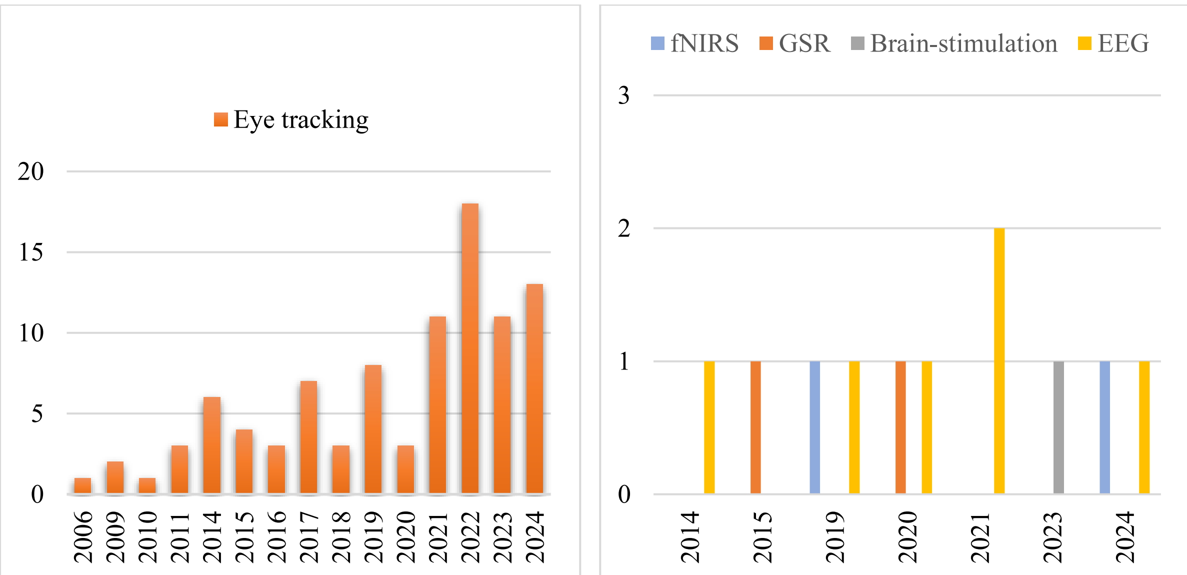

Figure 13. Neurocognitive tools used in the studies and their temporal distribution

The first use of eye tracking technology in research occurred in 2006, and the number of annual publications remained below 10 until 2020. The highest number of publications was recorded in 2022, with 18 publications. This increase reflects the growing importance of eye tracking in science education, its increased accessibility, and greater recognition by researchers. Furthermore, none of the studies reviewed utilized MRI or fMRI. The use of EEG, fNIRS, GSR, and brain stimulation techniques was minimal, and it appears that these tools have been employed primarily in recent years.

Groups of Participants in the Studies

Groups of participants examined in the studies are presented in Figure 14.

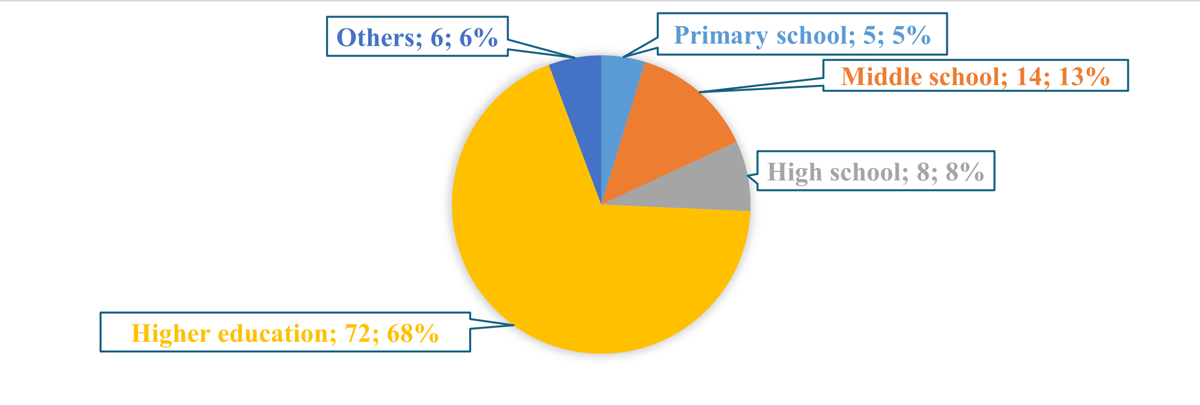

Figure 14. Distribution of studies by groups of participants

Upon examining Figure 14, it is evident that although all participant groups except the preschool period are addressed in the studies, these levels are not treated equally. The university level accounts for the highest percentage at 68% (72), followed by the middle school level at 13% (14). Only 5 studies (5%) focused on elementary school children. In addition, 6 of the studies (6%) focused on more than one group of participants, including teachers, faculty members, and visitors. Figure 15 shows the distribution of studies using various neurocognitive tools by educational level.

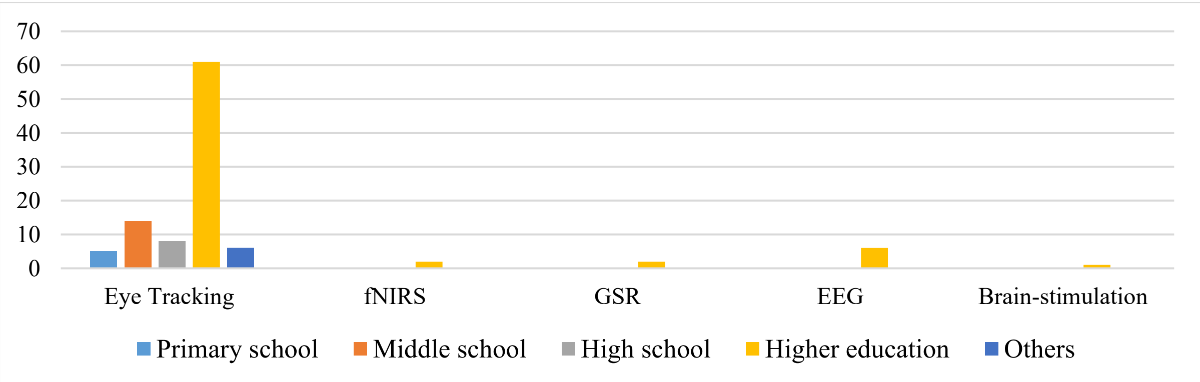

Figure 15. Use of neurocognitive tools at different educational levels

The vast majority of eye tracking studies have been conducted on university students. There are fewer studies using eye tracking with smaller groups, such as middle school students (14 studies), high school students (8 studies), and elementary school students (5 studies). In contrast, it appears that other neurocognitive tools, such as EEG, GSR, brain stimulation, and fNIRS, are not used at all at the elementary, middle, and high school levels, but are limited to the higher education population.

Research Methodology and Sample Size

Statistical information regarding the research methods used in studies integrating science education with neuroscience is presented in Figure 16.

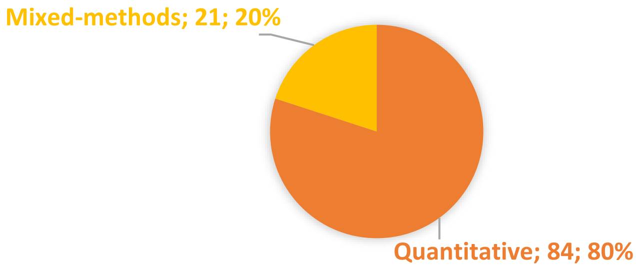

Figure 16. Research methodology

An examination of neuroscience research in science education reveals that these studies are predominantly designed using quantitative research methods. The distribution of sample sizes in articles published within the scope of studies integrating science education and neuroscience is listed in Table 4.

Table 4. Distribution of publications by sample size

Sample size	f
1-10	8
11-30	30
31-50	26
51-70	17
71-90	7
91-110	6
111+	11

As for sample size, neuroscience research in science education is primarily conducted with small to medium samples. It has been found that the most commonly used sample size is 11–30 participants (f = 30). This is followed by the ranges of 31–50 participants (f = 26) and 51–70 participants (f = 17). Studies conducted with larger sample sizes, however, appear to be limited in number.

Conclusion, Discussion, and Recommendations

Bibliometric (288 articles) and content analysis (105 articles) of studies integrating science education and neuroscience reveal that interest in the subject emerged in the early 1990s. The growth of this field was initially slow and steady, but it has experienced rapid growth, particularly in the last decade, and has been shaped by emerging methodological approaches. While research integrating science education and neuroscience appears to have emerged later when compared to research integrating mathematics education and neuroscience (Leikin et al., 2025), there is an observed increasing trend in the number of neuroscience studies in science education. The significant increase in research output can be attributed to advances in neuroimaging techniques and eye tracking technologies, policy support, the growing availability of relevant devices, and the field's increasing interdisciplinary importance.

The geographic distribution of research outputs indicates that the USA and Taiwan are the leading countries with the highest output and citation impact. In a study by Xu et al. (2022) on neuroscience in education, the USA was also identified as the most productive and influential country. Similar results were observed in a recent systematic review of eye tracking in science education; the USA was identified as the leading country in terms of academic productivity (Tóthová & Rusek, 2025). Italy, meanwhile, stands out for its high citation impact in science education and neuroscience research, despite fewer publications. An analysis of international collaboration shows that the USA and Taiwan are closely collaborating, while collaboration networks involving other countries are limited. Therefore, it can be said that fostering scientific communication and more inclusive collaborations among different countries, facilitating the sharing of expertise and infrastructure as well as interaction, and overcoming the theoretical, methodological, and technical challenges that may arise during the application of neuroscience techniques will be of great importance.

Bibliometric findings regarding publication patterns indicate that the "Journal of Chemical Education" and "Computers & Education" are the most productive journals in the field and also have the highest citation counts. However, it has been determined that research integrating neuroscience to examine science learning is not limited to disciplinary journals but is also published in journals focused on educational technology and neuropedagogy.

This indicates that the field exhibits an interdisciplinary structure. In this context, strengthening interdisciplinary approaches to support the development of future research in neuroscience in science education and actively encouraging science education journals to promote such work through special issues and thematic series dedicated to this topic will make significant contributions to enriching the field.

As for the authors, Yu-Cin Jian, Meng-Jung Tsai, and Fang-Ying Yang stand out as the most prolific authors. The author with the most citations is Richard E. Mayer, who has made significant contributions to the field's development. These findings enable researchers in the field to identify potential collaboration partners, establish research communities, make more informed journal selection decisions, and streamline their publication strategies. The co-authorship network of researchers collaborating on studies at the intersection of science education and neuroscience is represented by a limited set of individuals. This indicates that interdisciplinary interaction in this field remains limited to a relatively small group of researchers. To gain a more comprehensive, both theoretical and practical, understanding of neurocognitive research in science education, greater collaboration among researchers in neurocognition and science education is needed. The most frequently cited document is the study by Makransky et al. (2019). Among the most frequently cited studies, there is a notable presence of those that use eye tracking.

With regard to the evolution of keywords, it has been observed that there is a high degree of keyword overlap between adjacent periods. Research fields are not entirely independent of one another during the evolutionary process; rather, they interact. In these developmental processes, eye tracking technology has emerged as a key research tool for analyzing cognitive processes. In addition, an analysis of the author’s keyword network has revealed various trends related to the identified time periods. During the initial period, studies focused largely on the theoretical foundations of neuroscience and its pedagogical integration into science education. Furthermore, eye tracking methods were incorporated into the field of research during this period to study science learning processes. In the second period, thematic diversity increased, and research shifted toward topics such as models, knowledge, and conceptual change. Research during this period indicated that the theme of eye tracking/eye movements remained prominent and emerged as a central theme. Studies conducted during this period integrated neurocognitive data with fundamental issues in science education, including support for conceptual change, correction of misconceptions, knowledge construction, and instructional design models. In the latest phase, the thematic focus has shifted toward teacher education and pedagogical transformation, subject-specific science learning processes, technology-enhanced learning environments such as virtual and augmented reality, the development of more effective learning strategies, the facilitation of students’ understanding of scientific concepts, and the development of new insights into learning processes. In recent years, the themes of emotion and comprehension have emerged as a significant research focus in neuroscience for science education, actively shaping current research agendas.

A content analysis of research integrating science education with neuroscience has also revealed various methodological approaches and the use of different tools. The results indicate that the field is primarily shaped by eye tracking and EEG, with these two technologies occupying a central position, while the adoption of other tools remains limited. Eye tracking research, in particular, reached its peak in 2022. Future research focused on developing methodological approaches that integrate fNIRS, EEG, fMRI, and eye tracking devices may provide valuable insights for more precise analysis and a deeper understanding of students’ cognitive processes, as well as for developing more effective educational strategies grounded in neuroscientific evidence.

This study reveals a striking pattern regarding participant profiles: University students appear to be the most frequently selected group in these studies because they are more easily accessible to researchers. Another possible explanation is that obtaining ethical approval is generally easier for this group. The preference for university students in research is consistent with trends observed in neurocognitive research on mathematics education (Leikin et al., 2025). However, young children and individuals in preschool and elementary school are underrepresented. This limited representation is thought to stem from the technical and organizational challenges associated with conducting research with these age groups. For this reason, there is a need for further research that addresses learning objectives and includes students from different educational levels to gain a more comprehensive understanding of the neurocognitive foundations underlying science learning and to enhance the generalizability of the findings.

In terms of research methodologies, quantitative designs predominated in these studies, and in most identified studies, sample sizes ranged from 1 to 50. This may be attributed to the research context, difficulties in accessing equipment and recruiting volunteer participants, the complexity of using this equipment, and the fact that it can be used with only one participant at a time. This is consistent with the findings of Ulusoy et al. (2025), who noted that the vast majority of studies in the field of neuroeducation were conducted with sample sizes ranging from 0 to 50.

In conclusion, neuroscience research in science education remains an emerging field. As advancements in eye tracking and neuroimaging technologies continue, their potential to reveal cognitive and neural mechanisms is expected to grow. In this regard, if researchers and educators closely monitor these developments and systematically integrate these technologies into science education research extending beyond the laboratory setting to the classroom, this will make significant contributions to the development of science teaching and learning practices and to enhancing ecological validity. Especially in this era of rapid digital transformation, closely monitoring the integration of technologies such as artificial intelligence and digital tools with neurocognitive approaches will play a significant role in shaping the future research agenda for the design and implementation of personalized, adaptive digital learning environments.

While the results of this study offer a comprehensive overview of the intellectual structure, evolution over time, and global research trends in studies that combine science education with neuroscience, certain limitations must be acknowledged. First, the bibliometric dataset was restricted to publications indexed in the WoS database, specifically within the SCI, SSCI, A&HCI, and ESCI categories. Future research could expand the analysis to include additional established databases to provide a comprehensive picture of the field and ensure its representativeness. Second, this study is limited to English-language articles, which may introduce linguistic and geographical biases. Future research could analyze studies published in other languages and across different document types (e.g., conference papers, book chapters, scientific reports). Finally, although the search strategy is based on a comprehensive set of keywords, the scope of the terms used to identify articles may be limited. To address this limitation, future studies could examine a broader range of literature by using different keyword strings and filters.

Scientific Ethics Declaration

* The author declares that the scientific, ethical, and legal responsibility of this article, published in the JESEH journal, belongs to the authors.

* The data used in this study were obtained from secondary bibliographic sources provided by WoS and did not involve any human participants or personal data. Therefore, this study does not require ethical committee approval. The principles of scientific research and publication ethics were strictly adhered to at every stage of the analysis process.

Conflict of Interest

* The author declares that there is no conflict of interest

Funding

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How Generative AI Supports Scientific Inquiry and Science Practices in Science Education: A Scoping Review of Empirical Studies

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Abstract

Generative artificial intelligence (GenAI) has rapidly entered science education, but its role in supporting scientific inquiry and science practices remains unclear. This scoping review mapped empirical studies on how GenAI has been used to support inquiry- and practice-oriented work in science education. Guided by JBI scoping review principles and PRISMA-ScR, the review used a reproducible open-data search route through OpenAlex and Crossref, supplemented by targeted manual discovery. Records published from 30 November 2022 onward were screened against predefined criteria, resulting in 14 included empirical journal articles. The reviewed studies clustered around three main pedagogical roles: learner-facing inquiry partners, teacher-facing design and co-design tools, and assessment or feedback agents. Investigation planning, explanation, and inquiry scaffolding were more common than data analysis, argumentation, and explicit epistemic reflection. Overall, the literature suggests that GenAI is currently used more often to structure, prompt, or evaluate inquiry than to support deeper disciplinary participation. Productive use depended heavily on teacher mediation, prompt quality, and learners' critical oversight. The review identifies both practical opportunities and persistent epistemic gaps for future research.

Introduction

Generative artificial intelligence (GenAI) has rapidly become a visible part of science education research and practice. Following the public release of ChatGPT on 30 November 2022, researchers increasingly began to examine how GenAI might support science teaching, learning, assessment, feedback, and teacher preparation. This rapid growth has made GenAI one of the most discussed emerging technologies in contemporary science education and has intensified questions about both its pedagogical value and its epistemic implications (Lee et al., 2026).

In science education, the significance of GenAI extends beyond technological novelty. The goals of science education are not limited to transmitting scientific concepts or improving short-term achievement. Science education also aims to engage learners in disciplinary ways of knowing and doing, including asking questions, planning investigations, analyzing data, constructing explanations, using models, evaluating evidence, and participating in argumentation. For this reason, the role of GenAI in science education should not be evaluated only in terms of whether it improves general learning outcomes. It should also be examined in relation to whether it meaningfully supports scientific inquiry and science practices.

This disciplinary lens matters because science education is especially sensitive to how knowledge is produced, justified, and communicated. In many educational contexts, a tool may be judged primarily by whether it improves efficiency, access, or short-term performance. In science education, however, a tool must also be judged by whether it helps learners participate in the practices through which scientific knowledge is developed and critiqued. A response that is fluent or plausible is not necessarily evidence-based, and a lesson that appears inquiry-oriented is not necessarily strong in modeling, explanation, or argumentation. As a result, a review that remains at the level of general AI integration risks overlooking whether GenAI is aligned with the disciplinary core of science learning.

Recent review studies have advanced the field considerably. Broad reviews have already examined the role of artificial intelligence in science teaching and learning (Almasri, 2024), and more recent work has synthesized the general use of GenAI in science education (Cheung et al., 2025). Gunsaldi et al. (2025) reviewed the impact of GenAI applications on student learning outcomes in science education, while Duran and Dikmenli (2025) reviewed the use of artificial intelligence in biology education more broadly. Other recent reviews have also highlighted unresolved concerns related to disciplinary epistemic engagement, science identity, and the possibility that AI tools may support interest or content uptake more strongly than participation in scientific practices (Cheung, 2026; Lee et al., 2026).

These developments are important, but they also reveal a gap. Existing reviews tend to emphasize broad integration trends, student outcomes, or AI use across a wide range of educational goals. As a result, less attention has been paid to a more discipline-sensitive question: how GenAI is being used specifically to support scientific inquiry and science practices in science education. This gap matters because inquiry and practice are not peripheral features of science education. They are central to how science is learned, communicated, and justified in classrooms.

The emergence of inquiry-focused empirical work makes this gap timely to address. For example, Chang et al. (2026) showed that GenAI can be designed to provide feedback on students' epistemic understanding in scientific inquiry. Recent review work suggests that scientific practices, epistemic affect, and practice-oriented engagement remain underrepresented in the broader AI-science-education literature (Cheung, 2026). Recent field-level mapping has likewise pointed to continuing concerns around teacher preparedness, ethical decision making, and the challenge of integrating AI into science education without flattening disciplinary complexity (Lee et al., 2026). Taken together, these developments suggest that the field is now mature enough to benefit from a focused synthesis of how GenAI is positioned within the practice-oriented goals of science education, but still heterogeneous enough to warrant a scoping rather than effect-focused review approach.

The present review is intended to make that contribution. Rather than treating GenAI as a generic educational technology, it maps how GenAI is being embedded in inquiry-oriented tasks, science-practice routines, and pedagogical designs that are distinctive to science education. In doing so, it shifts the analytical focus from simple adoption or outcome claims to a more discipline-sensitive set of questions: what kinds of scientific work GenAI is being asked to support, what roles are assigned to it in that work, and where the emerging empirical literature still falls short.

Accordingly, this scoping review examined the following questions:

1. In what contexts has generative AI been used in science education?
2. Which dimensions of scientific inquiry and science practices are most frequently supported by generative AI?
3. What pedagogical roles are assigned to generative AI in the reviewed studies?
4. What cognitive, epistemic, affective, and assessment-related outcomes are reported?
5. What limitations, risks, and research gaps are highlighted in the literature?

Method

This study adopted a scoping review design to map the emerging empirical literature on the use of generative artificial intelligence in science education. A scoping review was appropriate because the literature has grown rapidly since late 2022, remains conceptually heterogeneous, and includes a wide range of educational purposes, study designs, and science-learning contexts. The review was guided by JBI scoping review principles (Peters et al., 2020; Peters et al., 2021) and structured in line with the PRISMA Extension for Scoping Reviews (PRISMA-ScR) (Tricco et al., 2018).

The review focused on English-language empirical journal articles published from 30 November 2022 onward. This starting point was selected because the public release of ChatGPT marked a major shift in the visibility and educational uptake of generative AI tools. The search was conducted through a reproducible open-data route rather than a subscription-database route. Specifically, records were identified through the OpenAlex works API and the Crossref works API, supplemented by targeted manual discovery through publisher pages and science-education journal searches. It should therefore be understood as an open-data scoping search rather than as a Scopus, Web of Science, and ERIC review.

The search strategy combined three concept groups: generative AI terms, science education terms, and inquiry- or practice-related terms. Across the scripted search process, six query clusters were used: core inquiry, core practices, argumentation and explanation, assessment support, lesson design, and laboratory support. Shared search limits included publication date from 30 November 2022 onward, English language, and journal-article formats where the source API supported such filtering. The scripted search produced 900 raw records, which were deduplicated to 684 candidate records. A high-confidence prescreen then reduced this pool to 58 records for closer inspection. In parallel, 20 additional candidate records were identified through targeted manual discovery. These two routes were later merged and deduplicated at the retained-record stage.

Studies were included if they were peer-reviewed empirical journal articles written in English; situated in science education contexts such as general science, biology, chemistry, physics, environmental science, or science teacher education; examined a generative AI tool, large language model, or AI chatbot; and addressed scientific inquiry, science practices, or closely related disciplinary processes such as explanation, modeling, evidence evaluation, investigation design, or data interpretation. Studies were excluded if they were editorials, conceptual papers, commentaries, conference abstracts, dissertations, or non-peer-reviewed texts. Studies were also excluded if they focused on AI in a broad sense without a clear generative-AI component, if they were not situated in science education, or if they addressed AI literacy without linking the work to science learning, inquiry, or science practices.

Screening proceeded in two stages. First, titles and abstracts were screened against the predetermined criteria. Of the 58 high-confidence open-data records, 40 were excluded and 18 were retained for closer review. Of the 20 manually discovered candidate records, 13 were excluded and 7 were retained. This yielded 25 retained records before cross-source deduplication. After merging these records, 19 unique priority records remained for closer eligibility review. Second, full-text articles were consulted for these 19 records in order to make final inclusion decisions and extract study characteristics. This process resulted in 14 included studies and 5 excluded studies in the final working corpus. Table 1 summarizes the PRISMA-style flow used in this review.

Table 1. PRISMA-style study selection flow summary

Stage	Count	Notes
Raw records identified through OpenAlex and Crossref	900	Scripted open-data retrieval across six query clusters
Deduplicated open-data candidate records	684	Initial deduplication at the metadata level
High-confidence open-data records advanced for screening	58	Prescreened for closer title/abstract review
Additional manually discovered candidate records	20	Identified through targeted journal and publisher discovery
Open-data records excluded at title/abstract screening	40	Removed for lack of science-education, GenAI, or inquiry/practice fit
Open-data records retained for closer review	18	Advanced to eligibility review
Manual candidate records excluded at screening	13	Removed for insufficient inquiry/science-practice centering
Manual candidate records retained for closer review	7	Advanced to eligibility review
Retained records before cross-source deduplication	25	Combined open-data and manual routes
Cross-source duplicates removed	6	Duplicates identified after merging retained sets
Unique full-text or closer-eligibility records assessed	19	Priority corpus for final decision making
Records excluded at closer eligibility review	5	Excluded for insufficient centering on inquiry or science practices
Final included empirical studies	14	Studies included in the thematic synthesis

Data from included studies were charted using a structured extraction form. The charting categories included bibliographic details, science domain, educational level, setting, participant group, GenAI tool, pedagogical role of GenAI, targeted inquiry or science practice, task design, reported outcomes, and reported risks or limitations. Particular attention was given to whether GenAI was positioned as a tutor, co-inquirer, feedback provider, assessment tool, lesson-design assistant, or content-generation aid, and to which inquiry or practice dimensions were most clearly supported. When study fit was uncertain, records were carried forward to closer eligibility review rather than being excluded prematurely.

The extracted data were synthesized using descriptive mapping and qualitative thematic analysis. Descriptive synthesis was used to summarize publication timing, disciplinary spread, educational levels, and types of GenAI tools. Thematic synthesis was then used to identify recurring pedagogical roles, the science practices most often emphasized, reported outcomes, and persistent boundary conditions such as teacher mediation, prompting quality, and epistemic risk. In line with common scoping review practice, the purpose of the review was to map the shape of the literature rather than to conduct a formal quality appraisal for effect estimation.

Results

Overview of Included Studies

Fourteen empirical studies met the inclusion criteria. The publication pattern was strongly concentrated in the most recent years: one study was published in 2023, two in 2024, eight in 2025, and three in early 2026. This distribution suggests that inquiry- and practice-oriented work on GenAI in science education is still a very recent literature, with most of the empirical base emerging after the first wave of broad commentary on ChatGPT in education.

The included studies spanned elementary, middle school, secondary/high-school, teacher-education, and undergraduate contexts. Most were anchored in school-level learning environments, while three were situated in undergraduate settings and several others focused on teacher-facing design or assessment work. This spread is helpful because it shows that GenAI-supported inquiry is not confined to a single age group or science domain. At the same time, it also highlights that the field is still fragmented: the reviewed studies differ substantially in educational level, task design, participant type, and outcome focus. Sample sizes ranged from small exploratory cohorts and interview-based studies to a larger performance dataset of 517 student responses in physics feedback research.

Disciplinarily, physics-related settings formed the clearest cluster, especially in guided inquiry, experiment design, density-concept instruction, and automated feedback. Biology and environmental science were also visible through lesson planning, laboratory assistance, and causal-modeling work. The remaining studies addressed chemistry/computational modeling, socioscientific inquiry, general science teacher integration, science inquiry assessment, and K-12 science-assessment critique. This pattern suggests that GenAI has already entered multiple corners of science education, but not yet in a balanced way across science domains or practice types.

Most studies examined general-purpose LLMs or LLM/chatbot variants, especially ChatGPT and closely related GPT-based tools. Thirteen of the 14 included studies relied on an LLM-family system, while only one study used a rule-based and AI-chatbot hybrid. One study emphasized a multimodal LLM, and one centered an open-source local model for physics feedback. Human guidance was explicit in 13 of the 14 studies, whereas prompt transparency was clearly reported in only 8 studies. This means that the field is simultaneously highly dependent on human orchestration and still inconsistent in documenting how GenAI was actually prompted and pedagogically configured. Table 2 presents the study identifiers used throughout the thematic synthesis.

Pedagogical Roles Assigned to GenAI

Three broad pedagogical role clusters were visible across the corpus. The first cluster consisted of six learner-facing inquiry-partner studies. In these studies, chatbots or LLMs supported guided inquiry, information search and justification, computational modeling, open-ended experiment design, causal modeling, or laboratory questioning (Chang et al., 2023; Stadler et al., 2024; Haraldsrud & Odden, 2025; Min et al., 2025; Nguyen et al., 2025; Doğru & Faulconer, 2026). In this role, GenAI was usually positioned as a scaffold around scientific work rather than as an autonomous replacement for student reasoning. The strongest examples involved bounded participation in specific tasks such as formulating inquiry steps, exploring alternative model structures, or asking laboratory questions during an ongoing activity.

The second cluster consisted of five teacher-facing design or co-design studies. In these studies, teachers or researchers used GenAI to generate, revise, or evaluate inquiry-oriented lesson plans and lesson-study materials (Adeyele & Ramnarain, 2024; Kahraman & Kıyıcı, 2025; Großmann et al., 2025; Cheng, 2025; Kim, 2026). Here the main attraction of GenAI was speed, idea generation, adaptation to curricular goals, and support for planning inquiry-oriented instruction. However, this cluster also showed that inquiry alignment was uneven. AI-generated plans often looked promising at the surface level but still required substantial pedagogical revision to sustain curiosity, coherence, procedural inquiry, or epistemic focus. In other words, design efficiency was easier to obtain than reliable inquiry quality.

The third cluster consisted of three assessment and feedback studies. This cluster included critique of science assessments for NGSS alignment, automated feedback on student physics responses, and scoring with dialogic feedback for scientific inquiry instruments (Nguyen & Hayward, 2025; Meyer et al., 2025; Chang et al., 2026). Compared with some of the broader inquiry uses, this cluster appeared comparatively mature and operational, especially in cases where the task structure and scoring criteria were clearly defined. These studies suggest that GenAI may currently be most defensible in bounded evaluative tasks where outputs can be checked against rubric-like expectations or human ratings.

Table 2. Characteristics of included studies

Study ID	Study	Level	Domain	GenAI tool	Pedagogical role	Main task focus
C002	Chang et al. (2023)	Elementary gifted education	Physics/sound transmission	Inquirybot	Guided-inquiry facilitator	Guided inquiry on sound transmission
C003	Stadler et al. (2024)	Undergraduate	Socioscientific inquiry	ChatGPT 3.5	Information source and reasoning partner	Inquiry on nanoparticles in sunscreen and justified recommendations
C005	Adeyele and Ramnarain (2024)	Secondary education	Science education	ChatGPT	Inquiry-support planning and integration aid	Teacher perspectives on ChatGPT within 5E inquiry-based learning
C007	Nguyen and Hayward (2025)	K-12	Science assessment	GPT-4 Vision or MLLM	Assessment tool and feedback provider	Critique of science assessments for NGSS-aligned sense-making
C008	Meyer et al. (2025)	High school	Physics	OpenChat 3.6; GPT-4o subset	Automated feedback provider	Feedback generation for short written physics responses
C009	Haraldsrud and Odden (2025)	Undergraduate	Chemistry/computational modeling	ChatGPT-4.0	Modeling scaffold and reasoning partner	Computational chemistry modeling task
C012	Kahraman and Kıyıcı (2025)	Middle school	Science	ChatGPT	Lesson-planning assistant	Inquiry-based lesson-plan generation
C013	Min et al. (2025)	Middle school	Physics	Generative AI assistant	Co-inquirer and tutor	Open-ended experiment design
C014	Großmann et al. (2025)	Secondary education	Biology	ChatGPT-4o	Lesson-planning assistant	Inquiry-based biology lesson-plan generation
C015	Cheng (2025)	Grade 7	Density concept	ChatGPT	Lesson-study support and co-designer	Density lesson-study implementation
C016	Kim (2026)	Teacher education	Environmental science agency	Large language model AI	Lesson-design assistant and co-designer	Environmental-science-agency lesson design
C017	Nguyen et al. (2025)	High school	Environmental science	LLM-based chatbots	Causal-modeling support and co-inquiry partner	Climate-change causal modeling
C018	Doğru and Faulconer (2026)	Undergraduate	Biology	ChatGPT	Virtual teaching assistant	Laboratory question answering on enzyme activity
C019	Chang et al. (2026)	Elementary school	Science inquiry	ChatGPT-4o	Assessment and dialogic feedback partner	Scoring and feedback on a scientific inquiry instrument

Taken together, these three clusters show that the pedagogical role of GenAI in science education is not singular. It shifts depending on whether the goal is to help learners move through a scientific task, help teachers prepare inquiry-oriented instruction, or help educators evaluate scientific work. What unifies the clusters is that GenAI is rarely treated as an independent instructional actor. Across roles, it functions more often as a support infrastructure that extends planning, prompting, annotation, or feedback.

Science Practices Supported and Underrepresented

The coding pattern suggested that the literature currently emphasizes some science-practice dimensions much more than others. Investigation planning appeared most often, with 7 of the 14 studies explicitly supporting tasks such as experiment design, lesson planning for inquiry, or planning of science learning sequences. Explanations and information evaluation or communication each appeared in 6 studies, while asking questions and modeling appeared in 4 studies each. In contrast, explicit support for data analysis was identified in only 2 studies, computational or mathematical thinking in only 2 studies, and argumentation in only 1 study. Table 3 shows this imbalance clearly.

This distribution is important because it indicates where GenAI is currently entering inquiry work. The reviewed tools were more often used at the front end of inquiry, where learners or teachers need help generating options, organizing a task, or drafting explanations, than at the back end, where stronger evidence interpretation, justification, and argumentative scrutiny are required. Even when information evaluation or communication was present, it was often embedded in guided prompting or critique tasks rather than in extended disciplinary discourse. As a result, the corpus gives a stronger picture of GenAI as a starter, organizer, or explainer than as a sustained partner in evidence-based scientific reasoning.

The cross-cutting codes point in a similar direction. Inquiry scaffolding was present in 10 studies and teacher mediation in 9 studies, indicating that much of the literature treats GenAI as support infrastructure around inquiry rather than as a stand-alone disciplinary agent. Feedback on practice appeared in only 4 studies, and explicit epistemic-understanding work was rare, appearing clearly in only 2 studies, even though epistemic engagement is central to practice-oriented science learning. Prompt transparency was reported in only 8 studies, which suggests that the reporting quality of GenAI use remains uneven and that the literature is not yet consistently documenting one of the main determinants of model performance.

Table 3. Science-practice and cross-cutting theme frequencies

Code or theme	n	Study IDs	Interpretation
Investigation planning	7	C002, C005, C012, C013, C014, C016, C018	The strongest practice emphasis in the corpus; GenAI is often used to structure inquiry design and lesson planning.
Explanations	6	C002, C003, C005, C008, C015, C017	Explanation support appears frequently, especially in guided inquiry, feedback, and causal reasoning tasks.
Information evaluation and communication	6	C003, C005, C007, C009, C016, C017	GenAI is regularly positioned as a tool for evaluating, critiquing, or communicating science information.
Asking questions	4	C002, C005, C014, C018	Question-focused support appears mainly in inquiry facilitation and laboratory assistance.
Modeling	4	C009, C014, C015, C017	Modeling appears in chemistry, biology lesson planning, lesson study, and environmental causal reasoning.
Data analysis	2	C013, C018	Data-analysis support is present but clearly underrepresented.
Argumentation	1	C003	Explicit argumentation work is rare in the current empirical base.
Inquiry scaffolding	10	C002, C005, C009, C012, C013, C014, C015, C016, C017, C018	The dominant cross-cutting pattern is scaffolding rather than autonomous disciplinary participation.
Teacher mediation	9	C002, C005, C007, C009, C012, C014, C015, C016, C017	Most studies still rely on strong human oversight and pedagogical revision.
Feedback on practice	4	C007, C008, C013, C019	Feedback-centered use cases are important but narrower than inquiry-scaffolding use cases.
Explicit epistemic understanding	2	C014, C019	Explicit epistemic work remains limited despite its relevance to science education.
Prompt transparency reported	8	C002, C003, C007, C008, C009, C012, C014, C019	Reporting quality is uneven; only part of the literature clearly describes prompt design.

Taken together, these patterns suggest that the current literature is stronger on initiating or structuring inquiry than on sustaining deeper forms of evidence-based disciplinary work. The empirical base shows more attention to planning, explanation, feedback, and communication than to argumentation, data interpretation, or explicit epistemic reflection. In practical terms, the current research emphasis is on making inquiry easier to start and manage, not yet on showing that GenAI can reliably deepen the quality of science-practice participation.

One plausible interpretation of this imbalance is that the currently dominant GenAI use cases map more easily onto front-end inquiry tasks than onto back-end disciplinary tasks. Planning, drafting explanations, or generating initial options are comparatively easier to scaffold with fluent language output, whereas sustained data interpretation, argumentation, and epistemic critique place greater demands on accuracy, multi-step reasoning, and resistance to plausible but weak justifications. Although the present corpus does not allow a causal claim about model architecture, the distribution of studies suggests that researchers may be gravitating toward practice dimensions that are easier to operationalize with current tools and lower-risk to implement in classrooms.

Reported Outcomes, Risks, and Research Gaps

The reported outcomes were mixed but informative. Across the corpus, cognitive or learning-related outcomes were reported in 9 studies, teacher- or design-oriented outcomes in 10 studies, assessment-related outcomes in 6 studies, epistemic outcomes in 5 studies, and affective outcomes in 4 studies. These categories overlapped, but their distribution still suggests that the literature is presently more comfortable reporting practical design and task-performance consequences than documenting deeper epistemic or identity-related change.

Several studies described productive uses of GenAI for inquiry-related support, including guided inquiry facilitation (Chang et al., 2023), improvement of density-concept learning through lesson-study integration (Cheng, 2025), support for causal modeling in environmental science contexts (Nguyen et al., 2025), and stronger support for open-ended experiment design in middle school physics (Min et al., 2025). Assessment-oriented studies also showed practical promise. Meyer et al. (2025), for example, reported that an open-source LLM achieved 0.84 classification accuracy and produced suitable feedback in 69% of cases on physics tasks, suggesting that school-controlled automated feedback may be feasible in at least some bounded domains. Chang et al. (2026) similarly suggested that dialogic AI-supported scoring and feedback can be useful in inquiry-instrument contexts when paired with human benchmarking.

At the same time, several studies identified important limitations. Stadler et al. (2024) found that LLM use reduced mental effort while also weakening the depth and quality of students' scientific justification. Haraldsrud and Odden (2025) similarly showed that productive use depended on students maintaining control over the modeling process rather than outsourcing reasoning to the AI. Teacher-facing lesson-planning studies revealed another recurring problem: GenAI could generate lesson plans that looked inquiry-oriented on the surface but drifted toward content transmission or inconsistent inquiry coherence when examined more closely (Kahraman & Kıyıcı, 2025; Großmann et al., 2025). These findings indicate that apparent fluency and convenience do not automatically translate into stronger science-practice engagement.

The risk pattern was also revealing. Implementation constraints were mentioned in all 14 studies, making them the most universal challenge in the corpus. Concerns linked to ethics, privacy, trust, or safety appeared in 8 studies, and issues related to epistemic authority or uncritical acceptance of AI output appeared in 7 studies. Accuracy concerns were raised in 5 studies, overreliance in 3 studies, and explicit hallucination or bias/fairness concerns in 2 studies each. This pattern suggests that the main barriers in this literature are not limited to classic "wrong answer" problems. More pervasive concerns involve how GenAI shapes authority, judgment, classroom responsibility, and the quality of participation in scientific work.

Across the included studies, productive outcomes were most credible when four conditions were present: a bounded task, explicit human oversight, reasonably transparent prompting, and criteria that allowed the AI output to be checked or revised. Where these conditions were absent, the literature more often reported drift, superficial inquiry alignment, or reduced quality of justification. Overall, the current empirical base suggests that GenAI is most established as a support layer for inquiry preparation, feedback, and design work. Evidence remains thinner for claims that GenAI already supports richer disciplinary engagement in data analysis, argumentation, and explicit epistemic reasoning. This imbalance marks an important gap for future science education research.

Discussion

The findings of this review suggest that the current GenAI literature in science education is developing along a narrower pathway than broad technology narratives often imply. Across the included studies, GenAI was most often used to support inquiry preparation, task structuring, lesson design, assessment feedback, or bounded forms of scientific reasoning. In other words, the literature currently positions GenAI more as a support layer around inquiry than as a robust facilitator of full disciplinary participation. This matters because science education is not defined only by efficient access to information or faster instructional planning. It is also defined by the quality of students' engagement with evidence, explanation, modeling, argumentation, and epistemic judgment. When the corpus is read through that lens, the empirical base appears promising but still uneven.

This interpretation helps clarify the contribution of the present review in relation to prior syntheses. Earlier reviews have already shown that AI and GenAI are becoming visible across science teaching and learning contexts (Almasri, 2024; Cheung et al., 2025), and JESEH has already published focused reviews on student learning outcomes and biology education (Duran & Dikmenli, 2025; Gunsaldi et al., 2025). However, those review lines do not fully answer a more discipline-sensitive question: whether GenAI is supporting the central practices through which science is learned and justified. The present review suggests that the answer is only partial. The literature is stronger on inquiry-adjacent support functions such as planning, feedback, and guided prompting than on richer practice participation such as argumentation, data interpretation, and explicit epistemic reflection. This pattern is also consistent with recent concerns that AI tools may support engagement or efficiency more readily than deeper disciplinary epistemic work (Cheung, 2026; Lee et al., 2026).

One useful way to interpret the corpus is to think of GenAI as infrastructural rather than transformational. In most included studies, the technology helped organize, annotate, draft, score, or suggest next steps. That is not trivial support; in some cases it clearly reduced workload, accelerated lesson design, or made feedback more available. Yet these functions are different from demonstrating that GenAI can deepen how learners weigh evidence, justify claims, challenge assumptions, or participate in scientific argumentation. The review therefore points to a field that is discovering where GenAI can be inserted into science-education workflows but is still far from proving that those insertions reliably strengthen the disciplinary core of science learning.

One of the clearest implications concerns teacher mediation. Even in studies that reported productive outcomes, GenAI rarely functioned well as an independent pedagogical actor. Inquiry chatbots required teacher monitoring when interactions broke down (Chang et al., 2023). Lesson-planning studies showed that AI-generated materials often needed substantial pedagogical revision before they could genuinely support inquiry (Kahraman & Kıyıcı, 2025; Großmann et al., 2025). Modeling and inquiry studies similarly indicated that productive use depended on whether learners retained control over the reasoning process rather than outsourcing key decisions to the model (Haraldsrud & Odden, 2025; Stadler et al., 2024). Taken together, these findings suggest that teacher judgment and instructional design remain central. The pedagogical question is therefore not whether GenAI can replace inquiry teaching, but under what conditions it can be orchestrated in ways that preserve scientific agency, scrutiny, and evidence-based reasoning.

This point has direct implications for science teacher education and professional development. If GenAI is to be used responsibly in science classrooms, teachers will need more than generic prompt-writing skills. They will also need practice-sensitive evaluative expertise: the ability to judge whether an AI-generated explanation supports conceptual sense-making, whether an inquiry plan genuinely preserves opportunities for investigation and revision, whether a chatbot response invites evidence-based reasoning rather than shortcut acceptance, and whether feedback aligns with disciplinary goals rather than only surface correctness. The teacher-facing studies in this corpus therefore imply that prompt literacy should be coupled with disciplinary and pedagogical review literacy. In pre-service teacher education, this could be translated into structured lesson-analysis tasks in which teacher candidates critique AI-generated science materials for inquiry coherence, epistemic quality, and alignment with science practices before adapting them for classroom use.

The findings also suggest that not all GenAI use cases are equally mature. Assessment and feedback tasks appeared relatively strong in the corpus, especially when the target task was bounded, criteria were explicit, and outputs could be checked against established expectations. In contrast, more open-ended uses such as inquiry-oriented lesson planning or broad information-seeking during socioscientific inquiry showed greater instability. This distinction has practical importance for science educators. Near-term adoption may be more defensible in constrained tasks such as feedback generation, assessment critique, or structured questioning support, whereas open-ended inquiry uses may require more cautious implementation, stronger prompts, clearer pedagogical framing, and closer human review. The issue is not simply technical accuracy. It is also whether the AI-supported activity preserves the epistemic aims of science education.

The review also points to a methodological maturity problem in the field. Most included studies were exploratory, qualitative, design-based, document-analytic, or short-term implementation studies. Only a small subset used comparative designs, larger performance datasets, or benchmark-style evaluation against human ratings. This is understandable in a fast-moving area, but it limits the kinds of claims that can presently be made. We know more about where GenAI is being tried and what immediate affordances or tensions appear than about how GenAI changes classroom inquiry over time, how stable those effects are across contexts, or whether gains in efficiency come at the cost of disciplinary depth.

Several directions for future research follow from this pattern. First, more work is needed on science practices that remain underrepresented in the current corpus, especially argumentation, data analysis, evidence interpretation, and explicit epistemic reflection. Second, the field would benefit from more classroom-based longitudinal studies that move beyond short pilots, document how prompts are designed, and show how teachers mediate AI use over time. Third, future studies should more clearly report prompt structures, human guidance, and revision procedures so that GenAI-supported activities can be interpreted and replicated more responsibly. A useful next step would be the adoption of a simple prompt-reporting framework that captures the model used, prompt purpose, prompt wording or structure, revision steps, human oversight, and any output-filtering procedures. Fourth, there is a need for stronger attention to equity, transparency, and trust, particularly in settings such as laboratory work, environmental education, and assessment where the consequences of inaccurate or opaque output may be pedagogically significant. Finally, comparative work should examine not only whether GenAI improves performance, but also whether it changes the quality of disciplinary participation in science.

The review also has important limitations. Most importantly, the search in this project was conducted through OpenAlex, Crossref, and targeted manual discovery rather than through a full subscription-database search in Scopus, Web of Science, and ERIC. This route was reproducible and sufficient for building a focused scoping corpus, but it may not have included all eligible studies indexed in subscription databases. The corpus was also relatively small and heterogeneous, spanning different educational levels, science domains, task types, and methodological designs. In addition, the review focused on English-language journal articles and did not include conference papers, dissertations, or other literature. Finally, as a scoping review, the purpose of the study was to map the evidence base rather than to conduct a formal methodological quality appraisal or effect-size synthesis. The findings should therefore be interpreted as a structured map of an emerging field rather than as a definitive estimate of what GenAI does in science education.

Conclusion

This scoping review mapped how generative AI has been used to support scientific inquiry and science practices in science education across 14 empirical studies published from late 2022 to early 2026. The review shows that GenAI is most commonly positioned as an inquiry scaffold, design aid, or assessment-and-feedback support rather than as a fully developed partner for deeper disciplinary reasoning. Investigation planning, explanation, and inquiry scaffolding were more visible in the literature than argumentation, data analysis, and explicit epistemic work.

Overall, the literature suggests that GenAI has genuine potential in science education, but that its most defensible uses currently lie in bounded and well-mediated tasks. The field has not yet produced strong evidence that GenAI consistently supports the full range of science practices at the depth science education requires. For this reason, future research should move beyond general claims of usefulness and examine more closely how GenAI shapes disciplinary participation, epistemic agency, and the quality of inquiry in science classrooms.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in JESEH journal belongs to the author.

* This study reviewed published literature and did not directly involve human participants. Therefore, ethics committee approval was not required.

Generative AI Disclosure

* Generative AI tools were used in a limited editorial capacity during the preparation of this manuscript, primarily to support English-language clarity, grammar, sentence flow, and readability. The author remained fully responsible for the intellectual content, interpretation, organization, and final wording of the manuscript, and carefully reviewed and revised all AI-assisted suggestions before submission.

Conflict of Interest

* The author declares no conflict of interest.

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The Effect of Flipped Learning Used in Text-Based Coding Education on Students' Computational Thinking Skills and Attitudes: A Mixed Methods Study

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Abstract

This study aims to examine the effectiveness of the flipped learning (FL) model, an innovative teaching approach in coding education. The research investigates whether implementing text-based coding education using the FL model creates a significant difference in middle school students' self-efficacy perceptions regarding computational thinking skills and their attitudes toward coding compared to traditional teaching. Designed using an explanatory sequential mixed-methods approach, the study employed a quasi-experimental design. The study group consisted of a total of 60 students enrolled in the 6th grade of a private middle school, divided into an experimental (n=30) and a control (n=30) group. During the eight-week process, the experimental group learned the Small Basic programming language according to the flipped learning (FL) model, while the control group received traditional instruction. Quantitative data were collected using the CTSPSS and CEAS scales, while qualitative data were collected through semi-structured interviews with selected students from the experimental group. The findings showed that the experimental group obtained significantly higher scores than the control group on both scales. Qualitative findings also revealed that students came to class prepared thanks to flipped learning (FL), were able to learn at their own pace, and developed positive attitudes towards coding. In conclusion, it was determined that the flipped learning (FL) model is an effective strategy in text-based coding instruction.

Introduction

The 21st century is defined as a period that prioritizes skills such as processing, analyzing, restructuring information, and producing creative solutions rather than merely accessing information. At the center of this set of skills lies computational thinking, a systematic problem-solving approach inspired by the fundamental principles of computer science (Wing, 2006). Computational thinking encompasses mental processes such as understanding complex problems, breaking solutions into algorithmic steps, recognizing patterns, abstraction, and data analysis (Shute et al., 2017; Wing, 2006). One of the most effective tools for developing these skills is coding education. Coding not only involves teaching a programming language but also supports the development of higher-order skills such as logical reasoning, critical thinking, creativity, and problem solving (Grover & Pea, 2018).

The global trend in coding education is toward making this discipline a fundamental part of basic education. Countries such as Estonia, the United Kingdom, and Finland have integrated coding into their curricula from an early age (Bocconi et al., 2016). In Türkiye, the Ministry of National Education (MoNE) has included algorithm and coding instruction at the primary education level within the scope of the Information Technologies and Software course since 2018. Although block-based visual tools such as Scratch are generally used at the initial stage of education, transitioning to text-based programming languages (e.g., Small Basic, Python, JavaScript) is inevitable for acquiring real programming skills and developing abstract thinking capacity (Weintrop et al., 2016). However, due to factors such as the rigidity of syntax rules, the lack of immediate visual feedback, and the inadequacy of error messages, text-based coding can be demotivating and challenging for students, thereby increasing cognitive load during the learning process (Bers, 2018).

It is precisely at this point that there is a need to overcome such difficulties by restructuring the learning process. The flipped learning model is one of the approaches that has most prominently addressed this issue in recent years. This model proposes that the theoretical knowledge transmission traditionally conducted in the classroom be carried out by students in their own time and space through digital materials such as videos, animations, and interactive simulations, while class time is allocated to active learning activities such as discussion, problem solving, project development, and teacher-guided practice (Bergmann & Sams, 2023; Bishop & Verleger, 2013). By offering students opportunities to control their own learning pace, repeat content as much as needed, and engage in deeper interaction in the classroom, this model holds great potential, especially in practice-oriented fields such as coding where individual differences are pronounced (Lo & Hew, 2017).

The literature includes numerous studies demonstrating the positive effects of flipped learning on general academic achievement, motivation, and student engagement (Zainuddin & Halili, 2016). Previous studies examining flipped learning in technology-supported environments reported improvements in student achievement, engagement, and learning motivation (Zainuddin & Halili, 2016; Zheng et al., 2020). However, most of these studies have focused on block-based coding or have measured only academic achievement quantitatively. Research that applies flipped learning in text-based coding education and simultaneously examines both cognitive (computational thinking skills) and affective (attitude, self-efficacy) dimensions in depth using mixed methods is quite limited (Lo & Hew, 2020). Although numerous studies have reported positive effects of flipped learning on student engagement and academic achievement, some research has found limited or non-significant differences between flipped learning and traditional teaching methods depending on contextual factors such as instructional design, duration of implementation, and student characteristics (Erdem, 2018; Lo & Hew, 2017). There is a particular need for comprehensive studies conducted with middle school students that shed light on the Turkish context.

Aiming to fill this gap, the present study addresses the following main research problems:
"Is there a statistically significant difference in the computational thinking skills and attitudes toward coding of middle school students who receive text-based coding education conducted according to the flipped learning approach compared to those who receive traditional instruction conducted according to the existing curriculum?" and "What are the experiences of middle school students regarding text-based coding education implemented through the flipped learning approach, their perceptions of this process, the difficulties they encounter, and the effects of this instructional model on their computational thinking skills and attitudes toward coding?"

Within the framework of this problem, the sub-problems are as follows:

1. Is there a statistically significant difference between the computational thinking skills scores of middle school students in the experimental group receiving text-based coding education based on the flipped learning approach and those in the control group receiving education based on the traditional curriculum?
2. Is there a statistically significant difference between the attitudes toward coding of middle school students in the experimental group receiving text-based coding education based on the flipped learning approach and those in the control group receiving education based on the traditional curriculum?
3. What are the views of the students in the experimental group regarding the implemented flipped learning model?

Purpose of the Study

In today's education systems, individuals are expected not only to access information but also to process, analyze, restructure, and use this information effectively, as well as to engage in creative problem-solving processes. In this context, computational thinking skills and coding education have become fundamental components of 21st-century learning skills (Brennan & Resnick, 2012; Wing, 2006). Coding not only involves software development but also encompasses cognitive processes such as algorithmic thinking, systematic analysis, abstraction, and modeling. Therefore, introducing students especially at the secondary education level to these skills at an early age is of great importance in enabling them to adapt to the demands of the modern era (Grover & Pea, 2013).

In recent years, there has been a noticeable increase in the use of innovative educational approaches that go beyond the limits of traditional teaching practices. One such approach is the flipped learning model, which encourages students to come to class prepared in advance while allowing class time to be devoted more to higher order cognitive processes such as practice, analysis, and production (Bergmann & Sams, 2023). The flipped learning approach places students at the center of the learning process by providing differentiated content tailored to individual learning pace and needs, and by enabling students to manage their own learning processes (Zainuddin & Halili, 2016). Especially in technology-supported learning environments, the implementation of the flipped model has been shown to positively affect students' academic achievement.

The flipped learning approach involves students engaging in knowledge-based activities outside the classroom through videos, presentations, or digital documents, while class time is focused on activities such as group work, project development, and problem solving (Abeysekera & Dawson, 2015). This approach can enable students to experience more active and productive learning processes, particularly in practice-oriented disciplines such as coding education. Within the scope of coding education, the use of text-based programming languages (e.g., Python, JavaScript) contributes to the development of students' skills such as algorithmic thinking, debugging, and the use of conditional statements (Weintrop et al., 2016).

In this regard, the main purpose of this study is to examine the effects of implementing text-based coding education with middle school students within the framework of the flipped learning model on their computational thinking skills and attitudes toward coding. The study aims to compare the effectiveness of the flipped learning approach with that of existing instructional practices and to reveal the contribution of this model to coding education.

In particular, computational thinking skills enable students to acquire higher-order cognitive skills such as analytical thinking, data analysis, algorithm development, problem solving, and debugging (Shute et al., 2017). However, the development of these skills is possible not only through theoretical instruction but also through constructivist, student-centered, and practice-based learning approaches. In this sense, the flipped learning approach supports the development of computational thinking by providing students with opportunities to access theoretical knowledge outside the classroom and to engage in active practices under teacher guidance during class time.

In addition, attitudes toward coding encompass students' interest in coding courses, their motivation, and their perceptions of self efficacy. Developing positive attitudes toward coding increases students' active participation in the learning process and ensures the permanence of learning outcomes (Abdüsselam & Uzoğlu, 2022). Examining whether text-based coding education supported by the flipped learning model positively affects students' attitudes is important in terms of the quality of educational programs.

Significance of Study

With the advancement of technology, many innovations have emerged in our lives. These technological developments have brought about changes in all fields, including education. The basic skills expected of learners in education are no longer the same as before. In a constantly developing and changing world, individuals are expected to possess skills such as algorithmic thinking and problem analysis (Scot, 2018). Computational thinking is one of these skills.

Computational thinking is generally defined as a systematic problem-solving process involving abstraction, algorithmic reasoning, pattern recognition, and logical thinking skills (Wing, 2006; Grover & Pea, 2013). Computational thinking is defined as a multidimensional construct including algorithmic reasoning, problem solving, abstraction, and collaborative processes (Shute et al., 2017; Weintrop et al., 2016). Computational thinking essentially refers to a systematic approach to the problem-solving process. These skills involve identifying solution steps, organizing them systematically, decomposing complex problems into manageable parts, and evaluating possible solutions through algorithmic reasoning (Shute et al., 2017; Weintrop et al., 2016). Computational thinking skills are directly related to coding, as algorithmic thinking forms the basis of coding.

One of the most important contributions of coding education to students is its support for the development of computational thinking skills. Research has shown that learning programming also significantly enhances mathematical thinking capacity (Taylor et al., 2010). The methods and models used in coding education are of great importance. One of the models that can be used in coding education, which has become increasingly widespread in recent years, is the flipped learning model. When middle school students receive text-based coding education for the first time, they often experience difficulties in understanding the subject. This is because text-based coding education can be more challenging for students due to its more abstract and complex structure compared to visual programming tools. Considering this situation, it can be suggested that the flipped learning model may be used as an effective approach to help students grasp the fundamental logic of text-based coding, increase the permanence of learning, and transfer the knowledge they acquire. Through digital learning environments, the flipped learning model offers students opportunities for flexible learning by allowing access to instructional content independent of time and place while supporting self-paced learning processes (Abeysekera & Dawson, 2015; Lo & Hew, 2017).

The findings of this study are expected to provide practical contributions to educational practices as well as to form a theoretical basis for future research in this field. In addition, this study contributes to the literature by examining flipped learning within a text-based programming environment and by analyzing both cognitive and affective outcomes simultaneously through a mixed-methods approach.

Method

Research Model

This study was designed using an explanatory sequential mixed methods design, in which quantitative and qualitative data collection and analysis techniques are used together in a sequential manner (Creswell & Creswell, 2017). In this design, quantitative data are first collected and analyzed; subsequently, qualitative data are gathered in order to explain and interpret the quantitative findings in greater depth. In the quantitative phase, a quasi experimental design specifically, a nonequivalent pretest–posttest control group model was employed to conduct causal comparisons. This model is frequently used in educational research to examine the effects of an intervention while preserving the natural structure of classroom settings (Büyüköztürk, 2002).

Table 1. Experimental design

Groups	Pre-test	Intervention	Post-test
Experimental	CTSPSS CEAS	Flipped Learning Model	CTSPSS CEAS Interview
Control	CTSPSS CEAS	Existing Curriculum	CTSPSS CEAS
CTSPSS: Computational Thinking Skills Self-Perception Scale			
CEAS: Coding Education Attitude Scale			

Study Group

The study group consists of 6th-grade students enrolled in a private middle school located in Nevşehir during the fall semester of the 2024–2025 academic year. In sample selection, convenience sampling, one of the non-probability sampling methods, was used due to ease of implementation and accessibility (Etikan et al., 2016). The study group comprises a total of 60 students selected from different classes within the same school that have similar socioeconomic and academic profiles. The assignment of the groups as experimental or control groups was carried out impartially. Accordingly, 30 students constituted the experimental group and 30 students constituted the control group.

Data Collection Instruments

Quantitative Data Collection Instruments

Computational Thinking Skills Self-Efficacy Perception Scale (CTSPSS): This scale, used to measure students' self-efficacy beliefs regarding computational thinking skills, consists of 36 items and 5 sub-dimensions (e.g., algorithmic thinking, problem solving, abstraction). It has a 3-point Likert-type response format ("Yes = 3," "Partly = 2," "No = 1"). In the original scale development study, the Cronbach's alpha internal consistency coefficient was reported as .943. Within the scope of the present thesis study, the Cronbach's alpha (α) value was calculated by the researcher as 0.853.

Coding Education Attitude Scale (CEAS): This scale, developed by Karaman and Filiz (2019) to determine students' attitudes toward coding courses, consists of two dimensions general positive attitude (28 items) and general negative attitude (13 items) and a total of 41 items. It is rated on a 5 point Likert scale ranging from "Strongly Disagree = 1" to "Strongly Agree = 5." Negative attitude items are reverse-coded when calculating the total score. The reliability coefficient reported in the original study is .94. In this thesis study, the Cronbach's alpha (α) value was calculated by the researcher as 0.951.

Qualitative Data Collection Instrument

Semi-Structured Interview Form: To collect qualitative data, five open-ended questions prepared in line with expert opinions were used. These questions were directed to five volunteer students selected from the experimental group after the completion of the 8-week experimental implementation, in order to obtain in-depth data. In this way, it became possible to obtain a richer perspective on the research topic and to evaluate different viewpoints. In addition, collecting the opinions of different individuals on the same topic contributed to providing solutions to the research problem (Yıldırım & Şimşek, 2021). The interviews were conducted on a voluntary basis in the computer laboratory where the instruction was implemented.

The interview questions included in the semi-structured interview form are presented below:
1. What is text-based coding? Can you explain it?
2. What is the flipped learning model? Can you explain it?
3. Did you experience any difficulties during the implementation of the flipped learning model? If yes, what were they?
4. Do you think that teaching text-based coding through the flipped learning model was beneficial for you? Can you explain?
5. Do you think that the flipped learning model should be used in every unit of this course? Can you explain?

The interview transcripts obtained were analyzed using the thematic analysis method in accordance with qualitative data analysis procedures. To increase the reliability of the codes, the coders (the researcher and the supervising teacher) independently examined the codes, and the final version was agreed upon through joint evaluation. Thus, students' perceptions of text-based coding and the flipped learning model, the difficulties they experienced, the skills they gained, and their suggestions were systematically categorized. The findings obtained during the analysis process were presented under themes in a manner that supports the qualitative aspect of the study, and direct quotations from students were included to enhance the credibility of the findings (Miles & Huberman, 1994).

Implementation Process

The implementation process of the study lasted for 8 weeks. Prior to the implementation, the necessary ethics committee approval (Niğde Ömer Halisdemir University, Decision No: 2024/07-27), permissions from the Ministry of National Education, and approval from the school administration were obtained; voluntary participation consent was secured from students and their parents. Within the scope of the 6th-grade "Information Technologies and Software" curriculum, weekly lesson plans covering the topics of Algorithms and Small Basic were prepared in order to support students' development in algorithmic thinking and text-based coding.

Table 2. Weekly lesson plan schedule

Week 1	Information was provided about algorithms, the fundamentals of algorithms, and their purposes of use
Week 2	Information was provided about decision and conditional structures in algorithms. Simple algorithm examples were also presented.
Week 3	The Small Basic program was introduced, and its installation was explained. Information was provided on the concepts of TextWindow, BackgroundColor, ForegroundColor, Write, and WriteLine.
Week 4	The Small Basic application and its components were used. Information was provided on Arithmetic Operators, Comparison Operators, and Logical Operators.
Week 5	The topic was integrated with prior learning. Information was provided on TextWindow, Variables, the Math class, Power, Max, Min, SquareRoot, Round, and Remainder, and related examples were implemented.
Week 6	The topic was integrated with prior learning. Information was provided on the Read and ReadNumber commands, and related examples were implemented.
Week 7	Information was provided on If–Else conditional structures, the Clock object, and its methods, and related examples were implemented.
Week 8	Information was provided on the For loop, While loop, and the GraphicsWindow class, and related examples were implemented.

Week 1: Information was provided about algorithms, the fundamentals of algorithms, and their purposes of use. In the first week, a pre-test was administered to the students. Subsequently, the topics of what an algorithm is, the purposes of using algorithms, and how algorithms are constructed were covered. Algorithms are considered fundamental components of computational thinking and support students in developing systematic approaches to

solving problems (Wing, 2006; Cormen et al., 2009). In computer science, algorithms are the building blocks of problem solving and form the foundation of programming languages. Algorithms are used in many fields ranging from daily life to artificial intelligence, thereby promoting structured thinking (Knuth, 1997).

Week 2: Information was provided about decision and conditional structures in algorithms. Simple algorithm examples were also presented. In the second week, decision and conditional structures in algorithms were introduced, and simple examples were included. The flexibility and functionality of algorithms largely depend on decision and conditional structures. Through these structures, programs can branch in different directions depending on specific conditions. For example, control statements such as "if…else" are commonly used to implement such conditional branching. In addition, flowcharts can be used for visualization to facilitate a better understanding of these concepts (Cormen et al., 2009).

Week 3: The Small Basic program was introduced, and step-by-step instructions were provided on how to download and install the program on a computer. Subsequently, basic commands and concepts such as TextWindow, BackgroundColor, ForegroundColor, Write, and WriteLine were emphasized. In the practical activities, students performed simple text output examples by setting background and text colors of their own choice.

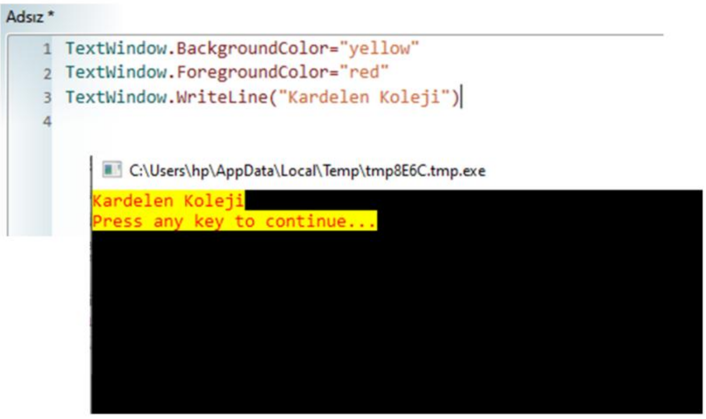

Figure 1. Study on the concepts of TextWindow, BackgroundColor, ForegroundColor, Write, and WriteLine

Week 4: The Small Basic application and its components were used. Information was provided about Arithmetic Operators, Comparison Operators, and Logical Operators.
The basic operators supported by Small Basic were explained. These operators are used to perform mathematical and logical operations. Arithmetic Operators include +, −, *, and /. Comparison Operators include =, <, >, <=, and >=. Logical Operators include And, Or, and Not.

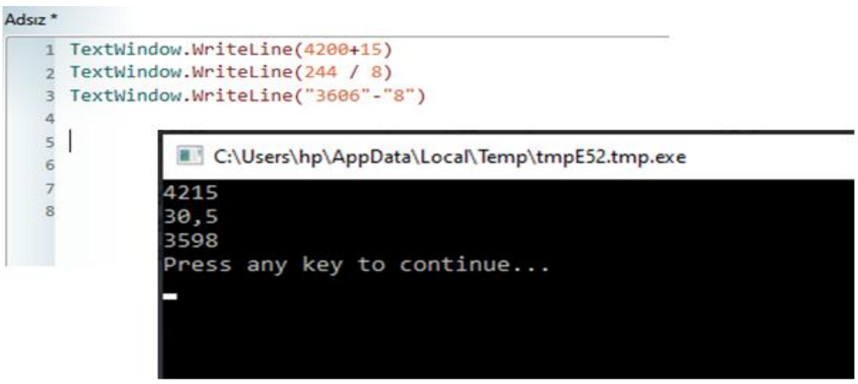

Figure 2. Operators activity

Week 5: The topic was integrated with prior learning. Information was provided on TextWindow, Variables, the Math class, Power, Max, Min, SquareRoot, Round, and Remainder, and related examples were implemented.
At this stage of the study, the Math class was integrated into the programming environment. Through this class, various mathematical operations were performed on defined variables, and calculation processes were carried out. In the programming domain, mathematical operations constitute one of the fundamental building blocks (Turing,

1936). The four basic arithmetic operations (addition, subtraction, multiplication, and division), which are standard in all programming languages, are indispensable components of algorithmic solutions (Arslan et al., 2022). The use of the Math class enables the implementation of more complex mathematical functions beyond these basic operations.

• Math.Power, Math.SquareRoot: Exponentiation and square root operations
• Math.Max, Math.Min: Finding the maximum and minimum values
• Math.Round, Math.Remainder: Rounding numbers and finding remainders

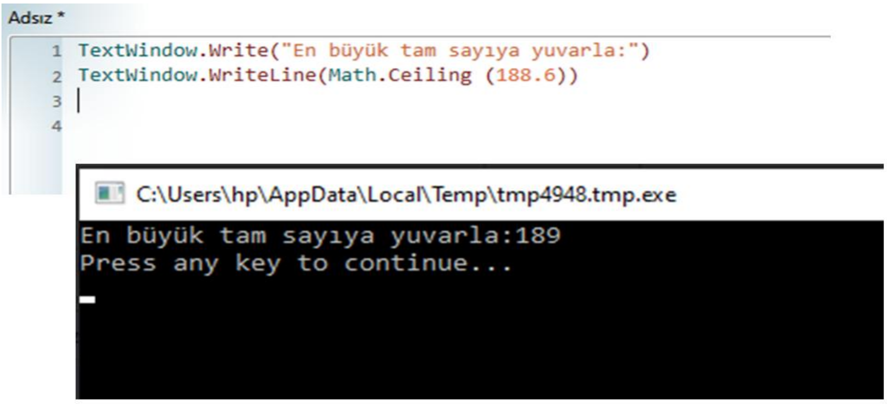

Figure 3. Math class usage activity

Week 6: The topic was integrated with prior learning. Information was provided on the Read and ReadNumber commands, and related examples were implemented. The topic of receiving user input through the Read and ReadNumber commands was covered. This initiates user interaction at a basic level and represents one of the fundamental steps in human–computer interaction. It is essential for a program to interact with the user.

Commands:
TextWindow.Read: Receiving textual input
TextWindow.ReadNumber**:** Receiving numerical input
During the lesson, students developed programs that receive input from the user, process this information, and display the output on the screen using these commands. In this way, the foundations of creating interactive applications in the programming process were established.

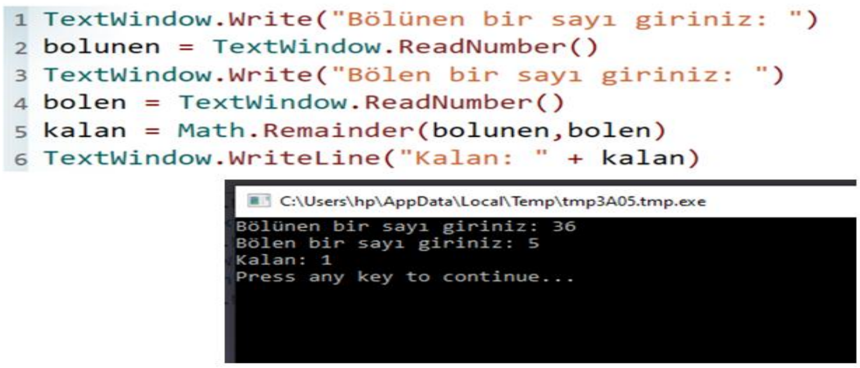

Figure 4. Read and ReadNumber commands activity

Week 7: Information was provided on If–Else conditional structures, the Clock object, and its methods, and related examples were implemented. In this week, advanced uses of If–Else structures were introduced together with the Clock object. Time-related programming structures contribute to students' understanding of dynamic systems and conditional decision-making processes in programming environments (Cormen et al., 2009). These programming structures provide software with dynamic flexibility and conditional decision-making capability. They allow different execution flows to be carried out depending on user inputs. Such decision mechanisms enable algorithms to produce different responses under varying conditions (Kandemir, 2018).

Commands: Clock.Hour, Clock.Minute, Clock. SecondTime control embedded within If–Else structures

Figure 5. If–Else commands activity

Week 8: Information was provided on the For loop, While loop, and the GraphicsWindow class, and related examples were implemented. For and While loops are used for repetitive operations. The GraphicsWindow class was used to demonstrate, through hands-on activities, how visual outputs can be created. These structures are employed to repeat specific operations or to continue processes until a certain condition is met (Demirkol, 2020). Loops enable repetitive tasks to be performed in a concise and efficient manner. The GraphicsWindow class is used for visualization and animation purposes.

Loop Structures:
For i = 1 To 10 While condition

GraphicsWindow Commands:
GraphicsWindow.DrawRectangle,
DrawLine, FillEllipse, SetPixel

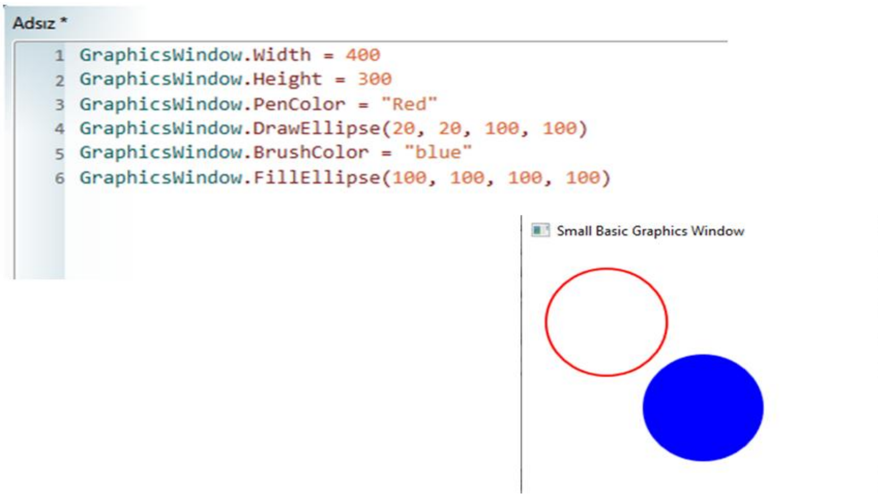

Figure 6. Visual output activity

Implementation Process in the Experimental Group

At the beginning of the study, the necessary institutional permissions were obtained in accordance with ethical principles, and the purpose, process, and methodology of the research were explained to the students in detail. During the eight-week experimental study, students reviewed and watched the lesson videos prepared by the teacher and uploaded to the Edpuzzle platform as part of the pre-class preparation phase. Within the scope of the study, students' use of the pre-class preparation videos was systematically monitored through the Edpuzzle platform. Through the teacher panel, the duration for which each student watched the video content was recorded and analyzed.

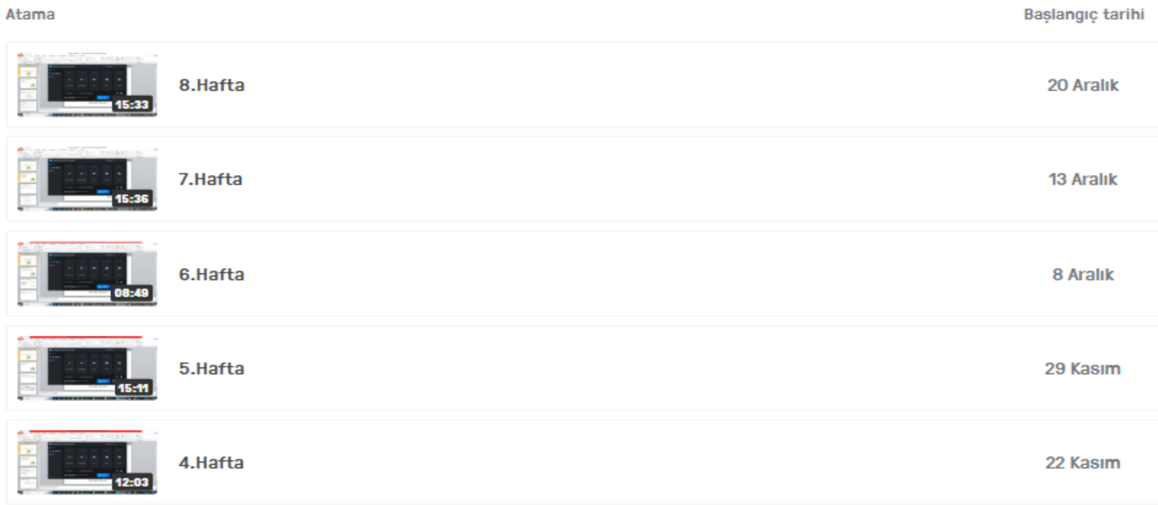

Figure 7. Date information of the lesson

Data Analysis

Quantitative Data Analysis

Data analysis is defined as the systematic application of appropriate statistical methods to transform the data collected during the research process into scientifically valid results (Büyüköztürk, 2002). The implementation phase of the study was conducted in a controlled manner during the 2024–2025 academic year. Before initiating the data analysis process, the normality of the score distributions obtained from the scales was examined using the Shapiro–Wilk test, since the number of participants in the study group was below 50. In the analysis of the data, descriptive statistics such as mean, median, mode, standard deviation, skewness, and kurtosis values were used. Skewness and kurtosis values were calculated for both scales in order to determine the type of comparison to be conducted. The results of the homogeneity and normality tests conducted to determine whether the CTSPSS and CEAS scores met the assumptions of parametric tests are presented in Table 3.

Table 3. Descriptive analysis of the scales

Scale	$\overline{X}$	sd	Median	Skewness	Kurtosis	Shapiro-Wilk	
						Statistic	p
CTSPSS	2.01065	.145294	2.02778	-.027	1.015	.958	.039*
CEAS	3.41748	.578524	3.18293	-.480	-.528	.870	.000*

*p<0.05 level

Normality analyses of the *Computational Thinking Skills Self-Efficacy Perception Scale* and the *Coding Education Attitude Scale (CEAS)* used in the study were evaluated based on skewness, kurtosis coefficients, and Shapiro–Wilk test statistics. For the computational thinking skills scale, the skewness value was found to be 0.027 and the kurtosis value was 1.015. These values fall within the ±1.5 range, indicating that the data are close to a normal distribution (Tabachnick & Fidell, 2013). However, the Shapiro–Wilk test result yielded p = .039, which is below the .05 significance level, indicating that the normality assumption was not statistically met. Nevertheless, it is known that the Shapiro–Wilk test may show excessive sensitivity to deviations from normality when the sample size is small (n < 50–100) (Ghasemi & Zahediasl, 2012). Therefore, considering the total sample of 60 participants consisting of 30 students in the experimental group and 30 students in the control group, minor deviations were not considered sufficient to preclude the use of parametric tests.

For the Coding Education Attitude Scale (CEAS), the skewness value was −0.480 and the kurtosis value was −0.528, both of which also fall within the ±1 range. However, the Shapiro–Wilk test result of p = .000 clearly indicates a violation of the normality assumption. This finding suggests that non-parametric tests may be safer when analyzing CEAS data. Nevertheless, the acceptable skewness and kurtosis values and the moderate sample size support the flexible use of parametric tests (Field, 2018). In conclusion, for both scales, it is recommended that decisions regarding the normality assumption be based on multiple criteria, including not only p values but also skewness–kurtosis values and sample size. Therefore, an independent samples t-test was used for comparative analyses in this study.

Prior to the implementation, pre-test data were collected using the relevant scales. After the completion of the intervention, post-test data were obtained using the same scales. In this study conducted with 60 students, quantitative data were transferred to the SPSS for Windows 24.0 statistical software package, and analyses were carried out using this software. After data entry was completed, reverse-coded items in the scales were recoded.

Qualitative Data Analysis

In qualitative data analysis, methods such as thematic analysis, content analysis, or discourse analysis are used to achieve an in-depth understanding of the data. This process focuses on interpreting participants' experiences, behaviors, and social contexts (Creswell & Creswell, 2017). In this study, thematic analysis was adopted as the qualitative data analysis technique. Thematic analysis involves dividing data into meaningful units, classifying these units according to their content, and grouping similar content to form themes (Braun & Clarke, 2006). In this context, interview transcripts were carefully examined after the transcription process and structured within the framework of themes determined in line with the research questions. Meaningful statements were selected from the data, grouped according to similar content, sub-themes were created from these groups, and direct quotations from participants that strongly represented each sub-theme were included.

To ensure the reliability of coding in the thematic analysis process, coding was repeated at different times, and the relationships among data, codes, sub-themes, and themes were continuously reviewed throughout the analysis process. This approach enabled the meaningful organization and in-depth interpretation of interview data (Yıldırım & Şimşek, 2021). The findings obtained as a result of the analysis formed the basis for data interpretation. In this study, a semi-structured interview form was used with students. Semi-structured interviews are data collection tools used by researchers in qualitative studies to obtain in-depth information (Büyüköztürk et al., 2019).

Findings

Quantitative Findings

In this section, quantitative comparisons conducted for both groups are presented.

Table 4. Independent samples t-test analysis of the experimental and control groups based on CTSPSS and CEAS pre-test results

Scale	Group	n	$\overline{X}$	sd	df	t	p
CTSPSS	Experimental	30	2.02593	.139163	58	.812	.420
	Control	30	1.99537	.151985			
CEAS	Experimental	30	3.00569	.221853	58	1.604	.114
	Control	30	2.88862	.332434			

Table 5. Independent samples t-test analysis of the experimental and control groups based on CTSPSS and CEAS post-test results

Scale	Group	n	$\overline{X}$	sd	df	t	p
CTSPSS	Experimental	30	2.50185	.136655	58	15.026	.000*
	Control	30	1.97593	.134457			
CEAS	Experimental	30	3.93089	.192485	58	15.276	.000*
	Control	30	2.90407	.313850			

*p<0.05 level.

In the CTSPSS pre-test analysis, the mean score of the experimental group was determined as $\overline{X}$ = 2.03, while the mean score of the control group was $\overline{X}$ = 2.00; the results yielded t(58) = .812 and p = .420. Similarly, in the CEAS pre-test, the mean score of the experimental group was $\overline{X}$ = 3.01 and that of the control group was $\overline{X}$ = 2.89, with t(58) = 1.604 and p = .114. In both measurements, p values greater than .05 indicate that there was no statistically significant difference between the groups. The literature emphasizes that interpretations based solely on significance levels are insufficient and that sample size, homogeneity of variance, and effect size should be evaluated together (Cohen et al., 2018). In this study, considering that each group consisted of 30 participants, along with small t values and low mean differences, the findings support the conclusion that the groups were equivalent at baseline. Therefore, it can be stated that prior to the intervention, the experimental and control groups were statistically similar in terms of both self-efficacy perceptions related to computational thinking and attitudes toward coding. According to the CTSPSS post-test results, the mean score of the experimental group was calculated as $\bar{X}$ = 2.50185, while the mean score of the control group was $\bar{X}$ = 1.97593. The standard deviation values were .136655 and .134457, respectively, and the t-test results yielded t(58) = 15.026 with p = .000. This result indicates a highly statistically significant difference between the groups ($p < .001$).

Similarly, when the CEAS post-test scores were examined, the mean score of the experimental group was found to be $\bar{X}$ = 3.93089, whereas the mean score of the control group was $\bar{X}$ = 2.90407. The corresponding standard deviations were .192485 and .313850, and the analysis yielded t(58) = 15.276 with p = .000. This finding also demonstrates a statistically significant difference between the two groups in terms of attitudes toward coding. Considering the high t values and significance levels obtained for both scales ($p < .001$), it can be concluded that the text-based coding instruction implemented in the study had a significant and positive effect on the experimental group students' self-efficacy perceptions related to computational thinking as well as their attitudes toward coding. Within the scope of the study, in order to determine the progress of both groups throughout the process, changes in their mean scores were also compared within each group separately.

It should be noted that the reported values represent scale mean scores rather than raw total scores, which may lead to relatively small standard deviation values. Therefore, the high t values observed in the analyses should be interpreted together with effect size statistics.

In order to better interpret the magnitude of the observed differences, effect size values were calculated. Cohen's d was used to determine the practical significance of the flipped learning intervention. The effect size for computational thinking self-efficacy was found to be d = 3.89, while the effect size for attitudes toward coding was calculated as d = 3.95. According to Cohen (1988), effect size values of 0.20 indicate a small effect, 0.50 a medium effect, and 0.80 or above a large effect. Therefore, the obtained values indicate a very large effect size.

Table 6. Results of the t-test analysis comparing the experimental group's pre-test and post-test mean scores within the group

Group		n	$\bar{X}$	sd	df	t	p
Experimental	CTSPSS- pre-test CTSPSS- post-test	30 30	2.0259 2.5019	.13916 .13666	29	-11.707	.000*
Experimental	CEAS- pre-test CEAS- post-test	30 30	3.0057 3.9309	.22185 .19248	29	-13.065	.000*

* p<0.05 level

The findings indicate that students in the experimental group showed a significant improvement in both their computational thinking skills and their attitudes toward coding after the text-based coding instruction implemented through the flipped learning approach. The increase observed in the students' scores on the CTSPSS scale (t(29) = −11.707, $p < .001$) demonstrates that the applied instructional method supported the fundamental components of computational thinking, such as problem solving, algorithmic thinking, and logical reasoning. On the other hand, based on the data obtained from the CEAS scale, it was determined that there was also a statistically significant increase in students' attitudes toward coding (t(29) = −13.065, $p < .001$).

Table 7. Results of the t-test analysis comparing the control group's pre-test and post-test mean scores within the group

Group		n	$\bar{X}$	sd	df	t	p
Control	CTSPSS- pre-test CTSPSS- post-test	30 30	1.9954 1.9759	.15198 .13446	29	.590	.560
Control	CEAS- pre-test CEAS- post-test	30 30	2.8886 2.9041	.33243 .31385	29	-.578	.568

According to the analysis results obtained within the scope of the findings, no significant difference was found between the pre-test and post-test scores of the students in the control group. The mean pre-test score of the control group students on the CTSPSS scale was calculated as 1.9954, while the mean post-test score was 1.9759. The results of the paired-samples t-test revealed a value of t(29) = 0.590, p = .560, indicating that the existing instructional method did not have a statistically significant effect on computational thinking skills. Similarly, the mean pre-test score obtained from the CEAS scale was 2.8886, and the mean post-test score was 2.9041; this change was also not statistically significant ($t(29) = -0.578$, $p = .568$).

Qualitative Findings (Thematic Analysis)

As a result of the analysis of the data obtained from the interviews conducted with the students in the experimental group, the following themes were created based on thematic analysis.

1. Perceptions of Text-Based Coding
2. Characteristics of the Flipped Learning Model
3. Challenges Encountered
4. Contributions to the Learning Process
5. Views on Applicability

The themes that emerged as a result of the analyses were presented by supporting them with direct quotations and interpretations; thus, students' perceptions of text-based coding and the flipped learning model were revealed in detail. This process was conducted in accordance with qualitative research standards, thereby increasing the validity and reliability of the findings. At the end of this process, five main themes and sub-themes related to these themes were identified. The findings were supported by direct quotations from student opinions.

Theme 1: Perceptions of Text-Based Coding

Sub-Theme 1.1: Definitional Approaches
Most of the students defined text-based coding as the process of giving commands through writing.
"Text-based coding is a type of programming that we do by writing commands. For example, Small Basic is text-based programming." (S1)
"Text-based coding is explaining to the computer what it should do in written form." (S2)

Sub-Theme 1.2: Difficulty and Need for Attention
It was stated that text-based coding requires more attention and discipline compared to block-based coding. When an error is made, the program not running increased the students' need to be careful.
"Writing code with words requires a bit more attention." (S5)
"When it is written with words and symbols at every stage, if there is any mistake, the program we wrote does not work." (S3)

Sub-Theme 1.3: Perceived Value and Emotional Reactions
While some students found this type of programming enjoyable, others described it as difficult at first but instructive afterward.
"Everything is written with words, numbers, and symbols. Although it is difficult at first, it makes sense once you learn it." (S4)
"In this type of coding, codes are written line by line. Writing code with words requires a bit more attention. Even games can be made. After block-based coding, I felt like an engineer with this programming." (S5)

The findings obtained reveal that students are able to make sense of the concept of text-based coding not only in a definitional manner but also in functional and affective dimensions. Students defining text-based coding through written commands, symbols, and numbers; making comparisons with block-based coding and interpreting it at their own level; indicate that they have developed a basic cognitive awareness in this field. In addition, expressing their positive and negative experiences related to the process shows that students question the learning process and can perform self-evaluation. The strategies they developed in the face of difficulties encountered while writing code, increasing their attention, and performing error analyses demonstrate that text-based coding carries not only a technical but also a pedagogical value. As a result, when students' perceptions of text-based coding are examined, it can be said that this process contributes to their development both cognitively and affectively and is a learning tool that can be effectively used in educational environments.

Theme 2: Characteristics of the Flipped Learning Model

Sub-Theme 2.1: Change in the Learning Process

It was stated that with the flipped learning model, students come to class prepared, are more active in class, and can manage the process better.
"In the flipped learning model, we watch a video before the lesson and then do activities in class. Thanks to this method, instead of repeating the topic in class, the teacher does applications with us. When I learn the topic before the lesson, I become more active in class." (S1)
"In this model, we learn the topic at home and learn in more detail in class. I think this provided more permanent learning because we can communicate more with the teacher." (S2)

Sub-Theme 2.2: Student-Centeredness and Participation
The student-centered nature of the model and students directing the process were emphasized as positive features.
"I think the most important feature is that we direct the lesson, not the teacher. After watching the video at home, I had the opportunity to ask what I wondered about in class. I used to listen passively, but in this model I participate more." (S3)

Sub-Theme 2.3: Flexible Learning
The fact that videos can be paused and rewatched facilitated learning. "I didn't understand the flipped model at first, but later I got used to it. Especially being able to pause and watch the videos as much as I want is very good. It also became easier to have one-on-one interaction with the teacher in class. Therefore, it was more efficient." (S4)

The research findings reveal the effects of the flipped learning model on students' learning processes in a multidimensional manner. Participants stated that thanks to this model, they came to class prepared, engaged in more activities in class, and found opportunities for one-on-one interaction with the teacher. Students' ability to use video content in accordance with their individual learning pace personalizes the learning process and enables them to focus more deeply on the content. This situation increases motivation for learning and contributes to the creation of a student-centered learning environment. In addition, more efficient use of in-class time allows students to interact more effectively with both the teacher and others.

Theme 3: Challenges Encountered

Within the scope of the research, the challenges students encountered in the flipped learning process were grouped under four sub-themes. These themes reflect time management, technical and content-related difficulties experienced by students in the learning process, level differences in group work, and the absence of difficulties.

Sub-Theme 3.1: Time management and lack of preparation
Some students stated that they could not allocate enough time to watch the videos that needed to be watched before the lesson. In particular, the intensity of other courses caused students to be unable to watch the videos on time and come to class unprepared.
"Sometimes I couldn't find time to watch the video at home. When my other courses are intense, I come to that day's lesson unprepared. This makes it difficult for me to fully understand the activities done in class." (S1)

Sub-Theme 3.2: Technical and content-related difficulties
They stated that technical problems such as slow internet connection negatively affected the video watching process. Especially the long loading time of long videos reduced students' motivation.
"I had difficulty watching the videos because my internet was sometimes slow. Especially in long videos, I had to wait a lot. This reduces my motivation." (S2)
"The videos sometimes progress very fast. I have to rewind the parts I don't understand, but still some topics remain incomplete. It is also difficult to ask the teacher everything in class because time is not enough." (S3)

Sub-Theme 3.3: Level differences in group work
Some of the students stated that differences in preparation levels among members in group work negatively affected the activities. Students who came to class after watching the video stated that when working with friends who had not watched it, disruptions occurred in the flow of activities.
"In class, sometimes there were disconnections in activities because some friends came at different levels. I have watched the video, but if others haven't, group work becomes difficult." (S4)

Sub-Theme 3.4: Student who did not experience difficulties
Some students stated that they did not experience any difficulties in the process, that they watched the videos before the lesson on time and actively participated in class activities.

"I did not experience any difficulties. I participated in the lesson by watching the videos on time." (S5)

These findings reveal that the applicability of the flipped learning model may not be at the same level for every student. Time management problems cause students to neglect their individual responsibilities and to benefit insufficiently from in-class activities. Technological problems, on the other hand, lead to loss of motivation and learning disruptions, especially in the process of accessing video content. In addition, differences in students' readiness levels create imbalance in interactive practices such as group work and may negatively affect the learning process. These findings show that for the flipped learning model to be applied effectively, not only instructional design but also students' individual support needs and environmental conditions should be taken into consideration. Therefore, in order to make this model sustainable and inclusive, it is of great importance to provide students with guidance on time management, technical support, and learning responsibility.

Theme 4: Contributions to the Learning Process

According to the research findings, the flipped learning model made positive contributions to students' learning processes from different perspectives.

Sub-Theme 4.1: Coming Prepared
Students stated that thanks to the videos they watched before the lesson, they came to class by learning the topic in advance. This situation contributed especially to a decrease in error rates during the application phase and to obtaining more efficiency from the lesson.
"Thanks to the videos, I understand the topic in advance and come to class prepared. This helped me make fewer mistakes while writing code." (S1)

Sub-Theme 4.2: Activity and Self-Confidence
Some students stated that with the flipped learning model, more time was allocated to the application part of the lesson, and this increased their self-confidence in coding. It was emphasized that text-based coding topics, which were previously perceived as difficult, were understood more easily thanks to seeing them in advance through videos and practicing them in class.
"Text-based coding normally seemed difficult to me, but with the flipped model, when I first watched the videos and then practiced in class, I understood the topic better. Now I feel more confident while writing code." (S2)
"I think the most important contribution is that we can do more activities in class. Thanks to this situation, we were able to speed up by making fewer mistakes while writing code." (S3)

Sub-Theme 4.3: Permanence
The ability to watch videos repeatedly helped students reinforce the topics and increase the permanence of learning.
"Since I could watch the videos several times, I understood the topic better. This increased the permanence of what I learned." (S4)

The research results reveal that the flipped learning model provides significant and multidimensional contributions in the process of text-based coding education. Students stated that thanks to this model, they were able to develop their coding skills more effectively and made fewer mistakes in in-class applications. The pre-learning process enabled students to come to class prepared; this allowed them to use in-class time more efficiently and understand complex commands more comfortably. In addition, the flipped learning approach reduced students' cognitive load and encouraged deeper learning; uncertainties experienced in the coding process were replaced by a more planned and secure learning process. The increase in self-confidence toward learning directly affected students' success in a field with low error tolerance such as text-based coding and enabled them to participate in the learning process more willingly. In this context, the flipped model stands out as an effective instructional strategy in courses that require technical knowledge such as coding education.

Theme 5: Views on Applicability

When students' views on the future applicability of the flipped learning model were examined, different perspectives emerged.

Sub-Theme 5.1: Partial implementation proposal

Some students stated that the flipped learning model does not need to be implemented in every unit and that it may be more beneficial especially in theoretically oriented topics.
"I think it can be applied in some units, but it is not necessary in all. For example, watching videos is useful in theoretical topics, but in practical units, direct in-class application may be more effective." (S1)
"I think if the topic is complex, video support would be good. But I don't think it is necessary for simple topics." (S4)

Sub-Theme 5.2: Defense of full applicability
Some students argued that the model should be used in all units. According to this view, having basic knowledge about the topic before the lesson makes the learning process in class more efficient.
"It can be applied in all units because having prior knowledge on every topic helps me understand better in class. It was especially very useful in topics such as coding and algorithms." (S2)
"Yes, it should be applied. Because thanks to this model, we learn both at home and in class." (S5)

Sub-Theme 5.3: Criticism of the model in terms of time
Some students think that implementing the flipped learning model in every unit may be inefficient in terms of time. It was stated that especially the weekly video watching duration was perceived as a waste of time by some students.
"No, it is not necessary in every unit. Also, I think watching videos every week is a waste of time." (S3)

The findings reveal that although the flipped learning model is an effective instructional strategy, applying it in the same way and in a rigid manner in all units may not always yield ideal results. While students emphasized that the model provides meaningful contributions especially in complex or application-based topics, they stated that this method may be inefficient in terms of time management in some simple or repetitive topics. This situation shows that the flipped learning approach should be planned flexibly and structured according to the characteristics of the subject. The frequency and form of the model's implementation should be adjusted by taking into account instructional objectives, content structure, and student needs. In this way, it will be possible both to benefit from the advantages offered by the model and to maintain student motivation and balance in the learning process. As a result, the flipped learning model should be implemented not with a single rigid pattern throughout the entire instructional process, but in a content-oriented, differentiated, and need-sensitive manner.

Discussion and Conclusion

The present study examined the effects of the flipped learning approach on middle school students' computational thinking skills and attitudes toward coding. The findings indicate that the implementation of the flipped learning model contributed positively to both cognitive and affective dimensions of learning. Improvements observed in computational thinking skills and attitudes toward coding suggest that instructional environments combining technological support with active learning experiences may facilitate multiple aspects of student development.

A significant increase was observed in computational thinking scores among students in the experimental group following the implementation process. This finding is consistent with Wing's (2006) conceptualization of computational thinking as a process involving problem-solving, abstraction, algorithmic reasoning, and logical thinking. Computational thinking has increasingly been viewed not only as a technical programming skill but also as a broader cognitive competency supporting systematic approaches to solving complex problems. Similarly, Grover and Pea (2013) emphasized that computational thinking develops through active participation in programming experiences and structured problem-solving processes. Shute et al. (2017) further argued that coding activities provide opportunities for learners to strengthen higher-order thinking skills by encouraging reasoning, analysis, and iterative problem solving.

The findings also revealed improvements in students' attitudes toward coding after the instructional intervention. Positive attitudes toward coding are associated with increased participation, stronger engagement, and sustained learning experiences (Abdüsselam & Uzoğlu, 2022; Kalelioğlu, 2015). One possible explanation for this outcome may be related to the structure of the flipped learning model itself. Allowing students to access learning materials before class may reduce uncertainty and increase learners' confidence during classroom activities. Students who have prior exposure to instructional content may participate more actively and approach coding tasks with greater self-confidence.

Qualitative findings provide additional support for this interpretation. Students frequently stated that they were able to review instructional videos whenever needed and experienced increased opportunities for interaction with the teacher during classroom activities. These experiences align with previous research suggesting that flipped learning transforms classroom sessions from content delivery settings into more interactive and student-centered environments (Bishop & Verleger, 2013; Zainuddin & Halili, 2016). Similarly, Lo and Hew (2017) reported that flipped learning environments may increase student participation and engagement by providing opportunities for more active classroom experiences.

The overall findings are also supported by findings from meta-analytic studies. Cheng et al. (2019) reported that flipped classroom practices generally have positive effects on student learning outcomes across different educational settings. Similarly, van Alten et al. (2019) found that learning outcomes improved particularly when classroom time in flipped environments was used for active learning and application activities. Zheng et al. (2020) additionally reported positive effects on both academic achievement and learning motivation. The consistency between these findings and the results of the present study strengthens the interpretation that flipped learning may represent an effective instructional approach for coding education.

Students' opinions regarding text-based coding also provide valuable insights. Participants described text-based coding as more abstract and demanding than block-based environments and indicated that greater attention and precision were required during programming activities. Similar findings have also been reported in studies emphasizing that novice learners may experience higher cognitive demands in text-based programming environments (Weintrop et al., 2016; Bers, 2018). Despite these challenges, students also reported improvements in conceptual understanding, reductions in coding errors, and increased confidence over time.

The distribution of cognitive demands across different stages of learning may help explain these findings. Rather than concentrating all learning processes within classroom sessions, students had opportunities to familiarize themselves with concepts before class and devote classroom time to guided practice and problem-solving activities. Particularly in coding education, where learners frequently encounter syntax errors and logical difficulties, teacher-supported classroom activities may contribute to deeper understanding and more meaningful learning experiences.

Although many studies report positive outcomes associated with flipped learning environments, findings in the literature are not entirely consistent. For example, Erdem (2018) did not identify significant differences between flipped and traditional instructional approaches. Such inconsistencies may stem from differences in implementation duration, participant characteristics, technological infrastructure, or instructional design. Therefore, the effectiveness of flipped learning should be interpreted within the context in which it is implemented rather than being considered universally effective.

Overall, the findings suggest that integrating text-based coding activities with a flipped learning environment contributes not only to the development of computational thinking skills but also to students' learning experiences and perceptions of coding. Considering the increasing importance of computational thinking and digital literacy skills in contemporary education, instructional environments that support both academic performance and learner engagement may provide important contributions to educational practice.

Recommendations

In line with the research findings, it has been concluded that the flipped learning model can be used as an effective instructional approach in coding education. In this context, it is recommended for educational practitioners that the flipped learning model be systematically integrated, especially into courses that include text-based programming content. It is important for teachers to support students' pre-class preparation by developing digital content (videos, online quizzes, interactive code editors, etc.), as this allows in-class time to be devoted to practice. In this way, students will be able to manage their individual learning processes and take an active role in classroom activities. The scope of in-service training programs should be expanded to enhance teachers' digital pedagogical competencies, and guidance should be provided to teachers on implementing the flipped learning model. In particular, content integrated with the flipped learning model should be developed for information technologies courses and made accessible to all teachers.

Strategic planning can be carried out to integrate the flipped learning model with innovative instructional approaches into the existing curriculum. Especially in practice-oriented courses such as information technologies, mathematics, science, and technology, the widespread adoption of these models will support students in developing both 21st-century skills and individual learning autonomy. Students' access to an appropriate home study environment aligned with this model directly affects its success. Families should be encouraged to take on supportive roles in this process and to monitor students' out-of-school learning activities.

For future research, it is recommended that longitudinal studies be conducted to test the applicability of the flipped learning model across different age groups and educational levels. The limitation of this study to a short-term (8-week) implementation provides limited data on long-term learning outcomes. In addition, multidimensional studies should be carried out to examine the effects of the flipped learning model not only on academic achievement but also on variables such as students' self-confidence, motivation, problem-solving strategies, and creative thinking skills. Considering the cognitive difficulties, syntactic errors, and conceptual misunderstandings that students encounter while coding, the impact of the flipped learning model in these areas should be analyzed in depth.

Finally, how the flipped learning model interacts when used together with other instructional methods (for example, project-based learning, collaborative learning) should also be investigated. Supporting coding education not only with individual learning but also with collaboration-based learning processes will enable students to develop skills in social learning environments as well. In this way, the flipped learning model can gain a structure that supports not only individual achievement but also a collective learning culture. In this context, newly developed instructional models are important in terms of strengthening the pedagogical foundations of digital transformation in education.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in JESEH journal belongs to the authors

Conflict of Interest

* The authors declare that they have no conflicts of interest

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