SYSTEMATIC REVIEW

Eye-Tracking Technology in Science Education: A Systematic Review

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Abstract: *Eye-tracking technology is increasingly used in science education research, but its benefits and potential insights remain debated. This review explores its value and limitations through an analysis of its applications in the field. We reviewed 103 eye-tracking studies published between 2014 and 2025 to examine research areas and topics, instrument usage, participant demographics, interpretations of eye-movement indicators, and data processing methods. Results indicate that: (1) Eye-tracking has consistently attracted attention in science education over the past decade, with findings published in cognitive psychology, science education, and educational technology journals;(2) The three most studied topics are Classroom Contexts and Learner Characteristics, Students' Conceptions and Conceptual Change, and Teaching;(3) Participants were predominantly higher education students, with most studies involving fewer than 120 participants, and the largest subset involving 30-50 participants;(4) Tobii, SR Research, and SMI are the most frequently used eye-tracker brands;(5) The division of AOIs mainly depends on research objectives and experimental tasks, with most based on functional attributes;(6) Eye-movement indicators fall into three categories: cognitive processing, attention distribution, and search strategies. Fixation count, total fixation time, and fixation duration are the most commonly used; (7) All studies used descriptive statistics, with some also incorporating emerging methods like complex network and entropy analysis.*

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Introduction

AS AN ADVANCED tool, eye-tracking technology has been used in science education research to explore learners' cognitive processes, the optimization of Teaching content, and educational evaluation (Lai et al., 2013).Eye-tracking technology is widely regarded as a video-based monitoring method, at the core of which is the acquisition of positional information by analyzing eye-tracking video images (Klein & Ettinger, 2019).This technology employs an infrared light-emitting diode (LED) to irradiate the pupil and records pupil dynamics with an infrared camera, thus achieving real-time tracking of individual fixation points (Klein & Ettinger, 2019). Eye-tracking methods are based on the eye-mind hypothesis, which posits that what is fixated upon is what is processed (Just & Carpenter, 1980).This approach has been developed to study information processing mechanisms and various cognitive processes (Holmqvist et al., 2011).In eye-tracking studies, researchers use eye-tracking measures to indicate learners' or users' visual attention or cognitive load during a task (Rayner, 2009).

Recent advances in eye-tracking technology have provided new perspectives for science education research. Eye-tracking technology captures students' cognitive activities during science learning by recording indicators such as fixation points and saccade paths(Hahn & Klein, 2022; Van Gog & Jarodzka, 2013; Was et al., 2016).A recent review on the application of eye-tracking technology in science education was published in 2016(Was et al., 2016)， In this paper, 15 studies were analysed and summarized, highlighting the application of eye-tracking technology in science education in Taiwan, with a focus on the design of science learning materials, multimedia presentations, real classroom settings, and problem solving. However, this review has certain limitations. Its focus on Taiwan-specific studies limits the generalizability of its findings to broader educational contexts. Tothova et al. analysed the characteristics, themes, and methods used in the application of eye-tracking in science textbook research (Tóthová & Rusek, 2021b)，Chen et al. summarized the trends, material characteristics, primary eye-movement indicators, and research topics in eye-tracking studies related to scientific reading (Chen et al., 2023). Their review primarily focuses on textbook-related studies, which may not fully capture the diverse applications of eye-tracking technology in science education, such as in interactive learning environments or experimental settings. Yang et al. reviewed the research topics in science learning supported by digital environments with eye-tracking technology, and proposed teaching suggestions for digital environments (Yang et al., 2018), Hahn et al. reviewed the subject areas and implementation methods of applying eye-tracking in physics education research (Hahn & Klein, 2022), while Muna et al. reviewed research on measuring metacognitive skills in students' chemistry learning using eye-tracking. While these reviews provide valuable insights into different aspects of eye-tracking applications in science education, they also exhibit certain limitations in terms of scope, methodology, and critical evaluation of the effectiveness of eye-tracking in assessing and enhancing science learning. Therefore, this study aims to address these gaps by providing a comprehensive and critical synthesis of recent developments in the use of eye-tracking technology in science education, highlighting methodological considerations, emerging trends, and implications for future research.

While eye-tracking's potential in studying cognitive processes, evaluating scientific texts, and teaching is increasingly acknowledged, relevant reviews are lacking. The scope and application of eye-tracking in science education are significant. Key questions include: What research topics use eye-tracking in science education? How is it implemented? How can data be interpreted? No systematic evaluation exists. Thus, a comprehensive analysis of eye-tracking in science education is essential to deepen understanding and guide future research directions.

Research Questions

To critically assess eye-tracking technology in science education, this study establishes three research questions.

- RQ1: What research topics are currently explored through eye-tracking in science education?
- RQ2: How is the eye-tracking method applied, considering participant characteristics, device selection, and AOI design?
- RQ3: How can eye-tracking data in science education be interpreted, focusing on common indicators and data processing methods?

Methods

Literature Retrieval Strategy

In this study, the Web of Science (WOS) and Scopus databases were selected to search for relevant studies included in this review. WOS covers high-quality, high-impact journals across multiple disciplines, including science education and educational technology, while Scopus is the largest database for citations and abstracts, reflecting the most common research sources in science education.

This research employs a keyword search strategy to gather relevant literature. Based on the research questions, the search phrase comprises three groups of search terms. The first group includes keywords related to eye-

Table 1. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
The study is within the field of science education.	Studies in other fields, such as medicine.
The study is an original empirical research.	Non-empirical studies, such as reviews.
Participants are students in university, secondary, or primary school.	Participants in other educational stages or professionals.
The study’s objective is related to students or science learning.	Other objectives, such as testing the usability of devices.
The study solely uses eye-tracking technology to collect eye-movement data.	Studies that do not use eye-tracking technology or use additional technologies like EEG or fNIRS.

Tracking (“eye gaze” OR “eye movement” OR “eye tracking” OR “eye-based gaze tracking” OR “eye gaze tracking” OR “visual attention”)..The second group adds keywords related to science or specific science disciplines(STEM OR Science OR Biology OR Chemistry OR Geology OR Physics).The third group includes keywords related to education(learning OR teaching OR education OR instruction).These three sets of keywords are combined using the Boolean operator AND.

To ensure the inclusion of quality and up-to-date research, the literature search was limited to studies published as articles in peer-reviewed journals indexed by the aforementioned databases between 2014 and 2025, and restricted to publications in English.

Screening Criteria and Process

This study followed the standard methodology for systematic literature reviews, using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework as a reference. After identifying the databases and search terms, the abstracts and full texts of the retrieved articles were thoroughly reviewed. The following criteria were applied in the selection process, from the initial search to the identification of the target literature, as outlined in **Table 1**.

The search for this study was conducted on March 22, 2025. In the initial search, a total of 2,980 articles were retrieved from Web of Science (WOS) and 542 articles from Scopus, with 282 duplicate articles removed, resulting in a total of 3,240 unique articles. After screening the titles and abstracts based on the established criteria, 3,106 articles were excluded. To further confirm the eligibility of the remaining studies, the full texts of the 135 remaining articles were reviewed, and 32 articles that did not meet the screening requirements were excluded. Ultimately, a total of 103 articles were included in the study. **Figure 1** illustrates the selection process and methodology used.

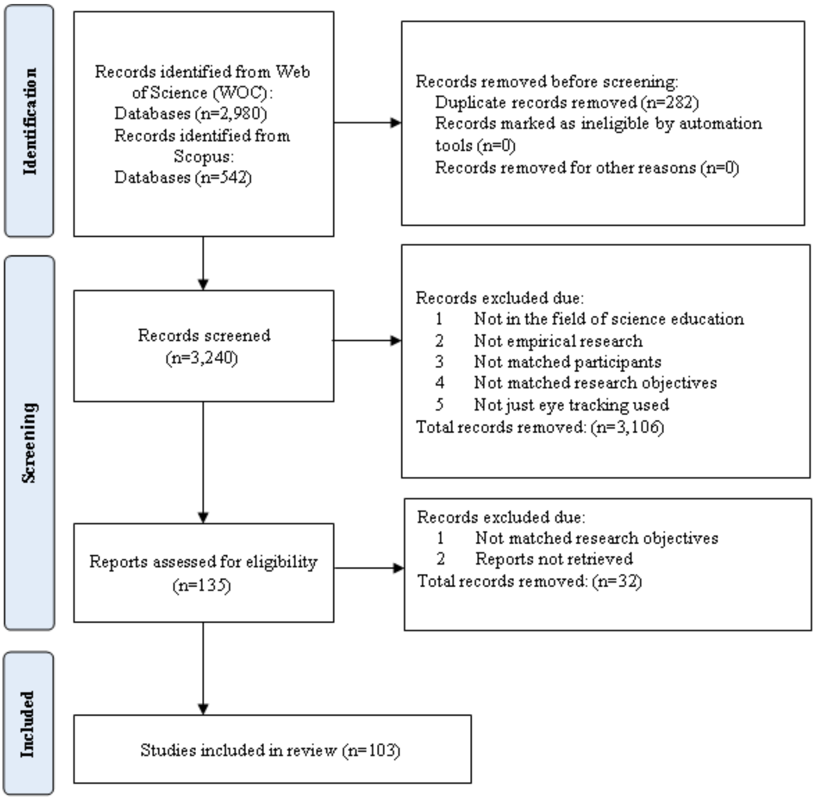

Figure 1. Article Selection Process PRISMA Program.

Coding Procedure

After the selection process, the content analysis method was employed to classify the articles and effectively address the research questions. Two researchers independently classified the papers, achieving a consensus rate of 0.90. Any differences in classification were discussed and resolved through mutual agreement. The frequency of each category was calculated for further analysis. The coding rules were based on the research questions.

First, with respect to RQ1, publication trends (i.e., the year of publication for the 101 studies) and research topics were analysed. In this study, the classification scheme developed by Tsai and Wen (based on the National Association for Research in Science Teaching (NARST) conference) was adopted (Lee et al., 2009; Tsai & Lydia Wen, 2005). This scheme includes the following nine categories: (1) Teacher education; (2) Teaching; (3) Learning–changes in students' ideas and concepts (learning concepts); (4) Learning–classroom context and learner characteristics (learning context); (5)

Objectives and policies, curriculum, assessment and evaluation (objectives, policies and curriculum); (6) Cultural, social, and gender issues; (7) The nature of history, philosophy, epistemology, and science (NOS); (8) Educational technology; (9) Informal learning. Subcategories and detailed descriptions of typical topics for each category can be found in prior research. Since a single study may involve multiple topics, the research topics were coded in a repetitive manner.

Second, RQ2 covers three categories: participant characteristics (e.g., number, education level), eye-tracking devices (e.g., manufacturer, sampling method), and area of interest (AOI). AOI refers to the spatial regions in visual stimulus materials where key elements are located, as defined by the specific research problem (Orquin et al., 2016). AOIs are spatial regions in visual stimuli where key elements are located, serving as basic units for eye movement data collection. In this study, AOIs are categorized into functional attribute (e.g., title, source), content form (e.g., pictures vs. text), and presentation position (e.g., sentences vs. paragraphs, top-left corner for images).

Finally, RQ3 involves the interpretation of eye movements and the processing of eye movement data. Eye movement indicators are categorized into three groups: attention allocation indicators, cognitive processing indicators, and search strategy indicators. Attention allocation indicators reflect the distribution of an individual's attention across different visual elements. Cognitive processing indicators capture the cognitive activities involved in visual information processing, while search strategy indicators reveal the strategies and methods used by individuals during visual search tasks. Based on these categories, the relevant eye movement indicators were coded and quantified. Additionally, the processing methods of eye movement data were also coded, including data processing techniques from fields such as statistics and information science.

Results

RQ1：What research topics are currently being applied to eye-tracking in science education?

Publication Trend

The publication dates of the reviewed literature were recorded in this study. **Figure 2** illustrates the annual publication trends of eye-tracking technology in the field of science education research over the decade from 2014 to 2023. It is important to note that the search concluded in March 2025, and the number of publications for the most recent year (2025) was 1. These 2025

Figure 2. Number of articles published per year.

Table 2. Research Topics in Science Education Covered by the Analysed Articles.

Topic	Frequency
Learning – Classroom Context and Learner Characteristics (Learning – Context)	54
Learning – Students' Conceptions and Conceptual Change (Learning – Concepts)	38
Teaching	26
Educational Technology	21
Informal Learning	5
Cultural, Social, and Gender Issues	4
History, Philosophy, Epistemology, and Nature of Science (NOS)	1
Teacher Education	0
Objectives and Policies, Curriculum, Assessment, and Evaluation (Objectives, Policies, and Curriculum)	0

Note: Studies may be assigned to multiple categories.

publications are not presented in the chart to avoid confusion, as the year has not yet ended.

According to the observed trend, the number of studies related to eye-tracking technology in science education research has increased in waves. Notably, more than 10 articles were published each year from 2019 to 2022, but only seven were published in 2023.

Research Topics

Table 2 provides an overview of the science education research topics covered in the 103 articles analyzed in this study. A brief summary of these categories is presented below.

In science education, eye-tracking research primarily focuses on classroom context and learner characteristics, followed by student conceptions and conceptual change. This study centers on elementary, secondary, and university students, excluding those focused on teachers. Notably, eye-tracking has not been applied to studies on teacher education, objectives and policies, or curriculum assessment in science education.

Learning – Classroom Context and Learner Characteristics (Learning – Context)

Fifty-two studies included in this review focused on learning contexts, making this the largest subject category for eye-tracking technology in science education research. Within this category, the research is grouped into seven subcategories: individual differences, learning methods, reasoning, learning environments, cooperative learning, learning motivation, and the emotional dimension of scientific learning. The first subcategory, individual differences, comprised 21 studies that examined differences between participant groups, such as experts versus novices or participants from different classes, in terms of eye-tracking during science reading or scientific problem solving(Lee, 2023; Teo & Peh, 2023).The second subcategory, learning methods, included 16 studies that used eye-tracking to analyze how participants learned science (Chen & She, 2020).The third subcategory, reasoning, encompassed five studies focusing on participants' reasoning processes. These studies used eye-tracking to explore how metacognitive support could improve evidence-based scientific reasoning in college students(Tsai et al., 2019) or to examine the relationship between visual attention distribution and scientific reasoning performance when students read conflicting scientific information(Yang, 2017).The fourth subcategory, learning environments, comprised five studies that investigated participants' eye-tracking in specific learning settings (Sun et al., 2024).Additionally, two studies analyzed eye-tracking in cooperative learning(Lämsä et al., 2022; Liu et al., 2021). Two other studies focused on learning motivation, using eye-tracking to analyze participants' self-efficacy(Wang et al., 2022)and learning interest (Catrysse et al., 2022).Only one study explored students' emotions during science learning, investigating the impact of emotional induction on scientific text processing and comprehension based on eye-tracking evidence.

Learning – Students' Concepts and Conceptual Changes (Learning – Concepts)

The close link between scientific concept learning and visual perception makes eye-tracking an appropriate research method for analyzing students' perceptions and learning patterns. Studies on learning concepts accounted for

38 of the studies in this review. Among these, the primary focus is on students' eye movements during the process of comprehension. Specifically, 34 studies explored students' understanding methods, including their comprehension of scientific terms(Yun, 2021), scientific problem solving(Ibrahim & Ding, 2021; Tóthová & Rusek, 2021a), scientific demonstrations(Cheng & Yang, 2022), and scientific experiments (Martinez et al., 2021).Additionally, three studies used eye-tracking technology to analyse students' conceptual development during the learning process(Rau et al., 2015).One study also addressed learners' conceptual changes, using eye-tracking technology to investigate students' visual attention during the Force Concept Inventory (FCI).

Teaching

There are 26 studies on science teaching, primarily focusing on three categories: knowledge representation, instructional behavior and strategies, and instructional knowledge and instructional content knowledge. Thirteen studies analysed participants' eye movements under various teaching behaviors and strategies. Additionally, 12 studies investigated students' learning performance and eye movements in different forms of knowledge representation. Only one study focused on instructional knowledge and instructional content knowledge, analyzing the difficulty of reading scientific texts and the impact of manual operation on science learning using eye-tracking (Jian, 2022).

Educational Technology

Twenty studies examined the use of educational technology in science education using eye-tracking technology. Within this category, the research is divided into four subcategories: learning and assessment involving the use of technology, video, integration of technology and teaching, and interactive multimedia. Eleven studies focused on learning and assessment using technology, such as using computers for scientific simulation experiments (Jian et al., 2024), physics-based game-based learning(Wang et al., 2022), and computer-based assessment of physics concepts(Chen et al., 2014). Four studies explored participants' eye movements during video-based learning. Three studies investigated the integration of technology and instruction, utilizing intelligent tutoring systems (ITSs) based on eye trackers to explore which concepts and learning processes are effective in specific domains(Rau et al., 2015).In addition, four studies examined interactive multimedia technologies, including virtual laboratories and online collaboration platforms(Lämsä et al., 2022).

Informal Learning

Five studies used eye-tracking to analyse informal learning. Research in this category focuses on science learning in informal settings. For example, some studies analysed participants' eye movements to explore and evaluate the mediating function of a Science Center gallery(Teo et al., 2024).Other studies explored the use of digital platforms to enhance informal learning and interaction(Magnussen et al., 2017). In science museum environments, mobile eye-tracking was employed to collect accurate data on learners' visual attention and interaction within real-world settings(Hsieh et al., 2022).One study in a zoo setting used eye-tracking technology to find that interpretive markers were the primary focus of attention for biology undergraduates (Heim & Holt, 2022).

Cultural, Social, and Gender Issues

Four studies examined cultural, social, and gender issues using eye-tracking techniques. These studies fall into two main subcategories: multiculturalism and bilingualism, and gender issues. Three studies focused on multiculturalism and bilingualism, investigating topics such as English as a Second Language (ESL) learners' processing of a multi-representation science article (Jaafar & Thang, 2020), the distribution of visual attention among English as a Foreign Language (EFL) learners when reading English science texts (Hung et al., 2020), and the impact of science reading comprehension levels on science learning in rural South Africa(Stott & Beelders, 2019)。In addition, one study analysed the impact of gender differences on reading scientific texts among college students, finding that female students paid more attention to data descriptions and charts, while male students focused more on facts and scientific explanations (Yang et al., 2016).

History, Philosophy, Epistemology, and Nature of Science

Only one study in this category examined the impact of scientific epistemological beliefs on students' reading of scientific texts. The study found that these beliefs primarily influence visual attention and cognitive effort during reading, with different dimensions of scientific epistemological beliefs correlating with various cognitive activities (Yang et al., 2016).

How the eye-tracking method is implemented, considering participant characteristics, the selection of eye-tracking devices, and the design of areas of interest (AOIs)?

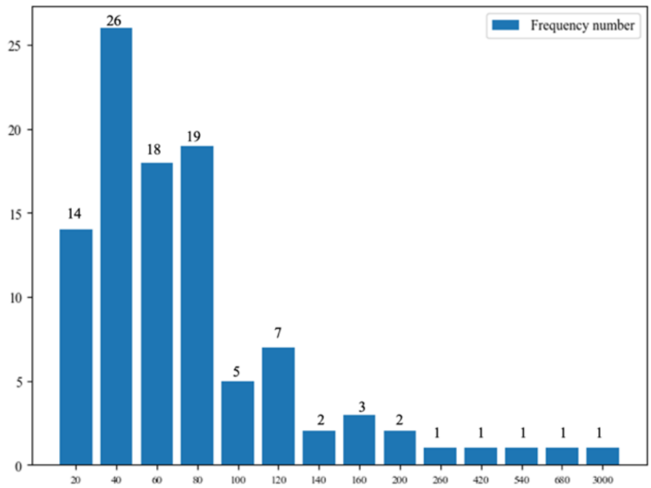

Figure 3. Number of Studies within Different Participant Range.

Participant Characteristics

All studies in this review tested participants individually, with 105 experiments across 103 studies. Among them, 56.9% involved higher education participants, 25.3% included secondary education, and 17.8% focused on primary education. Three studies included participants from multiple levels, indicating a focus on college students, followed by middle school students, in eye-tracking research in science education.

All studies reported specific numbers of participants, with a total sample size of 10,490 participants. The distribution of participants across the studies is presented in **Figure 3**.

As seen in **Figure 3**, 85 studies (83.5%) involved fewer than 120 participants. Among these, 26 studies (25.2%) had approximately 40 participants, making this the most common participant range. There were 25 studies (24.3%) with more than 120 participants. Notably, when the number of participants exceeded 200, only one study fell into each interval.

Eye Movement Equipment

Two studies in this review did not specify the eye-tracking devices used, and three studies used two different eye trackers. In total, 12 different eye-tracking device manufacturers were involved, with 36 devices used across the studies. **Table 3** lists the 12 device manufacturers identified in the reviewed studies.

Table 3. Manufacturers, Countries, and Numbers of Eye-Tracking Devices.

Eye-tracking Manufacturer	Frequency	Percentage
Tobii	46	44.7%
SR Research	23	22.3%
SMI	16	15.5%
Seeing Machines	7	6.8%
Pupil Labs	2	1.9%
Ergoneers GmbH	2	1.9%
LC Technology	2	1.9%
GazePoint Technologies	2	1.9%
Eye Tribe	1	1.0%
Applied Science Laboratories (ASL)	1	1.0%
Copenhagen IT University :ITU Gaze Tracker 2.1b	1	1.0%
National Taiwan Normal University:EyeNTNU-120	1	1.0%

The manufacturer with the highest usage was Tobii, accounting for 44.7% of the devices, followed by SR Research at 22.3%, and SMI at 15.5%. Seeing Machines was used in seven studies (6.8%). It is noteworthy that two studies used eye-tracking systems developed by universities: the ITU Gaze Tracker 2.1b from the University of Copenhagen and the EyeNTNU-120 from Taiwan Normal University.

The 36 types of eye trackers covered in this review are generally classified into two categories. The first category is static screen eye trackers, where stimuli are typically presented on a computer monitor, and 65 studies used this type of eye tracker. Examples include the Tobii X3-120, SMI RED250, and Seeing Machines faceLAB. The second category is head-mounted devices, which were used in 35 studies. These include eye trackers connected to head-mounted devices, such as the SMI iView Hi-Speed and EyeLink 1000 Plus, as well as eye-tracking glasses, such as Tobii Pro Glasses 3, SMI ETG2W, and Ergoneers Dikablis from GmbH. Notably, 12 studies used eye-tracking glasses, allowing participants to move freely and capture eye movement data across multiple areas of interest (AOIs), facilitating strong interaction.

Division of Areas of Interest (AOI)

The classification of AOI in the reviewed literature, along with its corresponding proportions, is presented in **Table 4**.

The classification of AOI based on functional attributes is the most common approach, with 49.5% of the studies using this method. The second most common approach is division based on content form, accounting for 34.0%. Division according to the presentation position was used in 16.5% of the studies.

Table 4. Division of Areas of Interest (AOI).

AOI Division	Frequency	Percentage
Functional attributes	51	49.5%
Content form	35	34.0%
Presentation position	17	16.5%

Table 5. Connotation And Frequency of Eye Movement Indicators.

Category	Eye movement indicators	Connotation	Frequency	Percentage
Attention allocation	Fixation Count	The number of times an observer's or research subject's gaze remains on a specific target or area is used to measure the degree of the observer's attention to the object.	62	60.2%
	Total Fixation Time	The total duration of an observer's gaze on a particular target or area provides insights into the depth of attention an individual devotes to a specific object during the observation process.	38	36.9%
	Fixation Time Percentage	The proportion of time spent looking at a particular area compared to the total observation time reflects the degree of attention allocated to different parts of an image, text, or scene.	25	24.3%
	Pupil Diameter	The size of the pupil opening can indicate cognitive engagement. When an individual focuses on a task or learning material, pupil dilation may occur, suggesting that their attention is highly engaged.	8	7.8%
	Fixation Point Order	When an individual observes a visual stimulus, the movement of their eyes and the position of the fixation point reveal their attention pattern during observation.	8	7.8%
Cognitive processing	Fixation Duration	The number of times an individual looks at a specific target within a given time reflects the concentration of their attention on the target.	60	58.3%
	average fixation duration	The average duration of an individual's gaze on a particular target reflects the depth of information processing and the cognitive load.	23	22.3%
	First Fixation Time	The average time an individual spends on their first fixation on a target reflects their initial attention to the information and the speed of cognitive processing.	18	17.5%
	Second Fixation Time	The interval between the end of the first gaze and the beginning of the second gaze reflects the cognitive processing involved when learners deal with complex visual information.	6	5.8%
	Regression Time	When learners encounter difficult or important information during reading or learning, they tend to return their gaze to parts of the text or image they have previously read.	4	3.9%
Search Strategy	Number of Fixation Transitions	The number of times an individual's eyes move from one fixation point to another while observing a visual stimulus reflects their visual exploration behavior and the frequency of attention shifts during the observation process.	22	21.4%
	Eye Movement Trace	The movement path of the eyes on a page or screen reveals the individual's cognitive strategy and visual attention allocation during observation.	18	17.5%
	Regression Count	The number of times an individual returns to a previously viewed visual stimulus indicates difficulties in comprehension, failed information extraction, or distractions requiring further attention.	17	16.5%
	AOI Transition Counts	The number of transitions between different areas of interest (AOIs) provides a detailed description of subjects' behavior patterns while processing visual information.	16	15.5%
	average saccade length	The average distance the eyes travel from one fixation point to the next during visual attention transfer is an indicator of reading efficiency and comprehension.	5	4.9%

Table 6. Eye Movement Measurements Across Different Study Topics.

Topic	Attention Allocation Indicators	Cognitive Processing Indicators	Search Strategy Indicators
Learning - Classroom Context and Learner Characteristics (Learning - Context)	47	36	22
Learning - Students’ Conceptions and Conceptual Changes (Learning - Conception)	31	34	23
Teaching	28	16	13
Educational Technology	21	18	11
Informal Learning	8	3	6
Cultural, Social, and Gender Issues	5	4	3
History, Philosophy, Epistemology, and Nature of Science	2	1	0
Total	142	112	78

Table 7. Statistical Methods and Times Of Eye Movement Data Processing.

Statistical method	Frequency	Percentage
Descriptive statistics	101	98.1%
Difference test	93	90.3%
Visual analysis	89	86.4%
Relation test	73	70.9%
Sequential analysis	52	50.5%
Cluster analysis	25	24.3%
Complex network	2	1.9%
Entropy analysis	2	1.9%

RQ3：How can eye-tracking data in science education be interpreted, including common eye movement indicators and data processing methods?

Interpretation of Eye Movement Indicators

The statistical analysis results of attention distribution index, cognitive processing index and search strategy index are shown in **Table 5**.

This study summarizes the main eye movement indicators involved in science education research. Fixation Count, Total Fixation Time, and Fixation Duration are the three most frequently used indicators. Under these three categories, the most commonly used eye movement indicators are Fixation Duration, Fixation Count, Number of Fixation Transitions, and Eye Movement Trace.

Table 6 shows the eye movement measurements across different study topics. The selection of all eye movement measurements is often driven by specific research questions, and different research topics may emphasize various types of measurements. Overall, attention allocation indicators were the most commonly used across all research topics. In studies related to Learning - Students' Conceptions and Conceptual Changes (Learning-Conception), there were more cognitive processing indicators than attention allocation indicators. For informal learning topics, search strategy indicators were more frequently used than cognitive processing indicators.

Eye Movement Data Processing

The 103 studies reviewed used methods including descriptive statistics, difference testing, visual analysis, relationship testing, sequence analysis, cluster analysis, complex network analysis, and entropy analysis. Descriptive statistics summarize eye movement data, difference testing uses t-tests and ANOVA, and visual analysis includes scan path maps and heat maps. Relationship testing applies correlation and regression, while sequence analysis examines event sequences. Cluster analysis groups eye movement patterns, complex network analysis models interactions, and entropy analysis assesses fixation distribution for insights into visual attention. **Table 7** lists these methods and their frequencies.

Except for two qualitative studies, all 101 studies used descriptive statistical methods. In second place was the difference test, used in 93 cases. Visual analysis ranked third, employed in 89 studies. This was followed by relationship testing, applied in 73 studies. About half (52) of the studies used sequential analysis. Additionally, cluster analysis was conducted in 25 studies, and two studies transformed eye-tracking data into a network model to analyse interactions and patterns between eye movement behaviors.

Discussion

RQ1：What research topics are currently being applied to eye-tracking in science education?

In the past decade, the use of eye-tracking technology in science education research has fluctuated but generally increased, peaking in 2022 with 18 publications. This rise may be linked to the COVID-19 pandemic, as distance learning and online education grew more common.Eye-tracking technology enables researchers to better understand students' attention and engagement in online learning environments (Yang, 2017). In contrast, the number of studies in 2023 was relatively small, possibly due to the rise of alternative technologies such as EEG and NIR being applied in science and education research (Ido et al., 2021). In some study Settings, EEG and fNIRS provide richer cognitive measurements. Therefore, future research could further explore how these techniques can be combined to provide a more comprehensive cognitive analysis of learning.

The studies in this review span seven research topics, with inconsistent use of eye-tracking across them. Learning-classroom context and learner characteristics (learning-situation) are the most widely studied, reflecting general trends in science education research. In recent years, learning situations have been the primary focus in science education research (Lin et al.)， This may be because eye-tracking technology was initially used to observe and analyse how learners process information in a teaching environment and their eye movement patterns during this process (Tóthová & Rusek, 2021c). Within this research topic, individual differences among learners receive the most attention, with studies investigating differences in eye-tracking data between experts and novices, as well as participants at various academic levels. Eye-tracking technology can accurately capture learners' gaze points, gaze duration, and gaze sequences(Jian et al., 2024).Additionally, participants of different school ages and academic levels may employ distinct gaze strategies and paths in learning tasks. Eye-tracking technology provides an intuitive way to observe these differences, helping educators understand individual learning needs and design more targeted teaching strategies and resources (Anggraini et al., 2020).Secondly, in the topic of learning-students' concepts and conceptual changes (learning-concepts), eye tracking technology mainly focuses on the method of students' understanding, which is similar to the research conclusion of Lai et al. (Lai et al., 2013). Eye-tracking technology helps uncover implicit cognitive strategies and dynamic conceptual changes in understanding and problem-solving. Additionally, in the topic of teaching research, eye-tracking technology is used to assess learners' performance across different forms of representational knowledg(Susac et al., 2023), the impact of various teaching behaviors and strategies (Anggraini et al., 2020), and the varying difficulty of reading science texts and conducting hands-on experiments in science learning(Yang et al., 2016).Under the topic of educational technology research, eye trackers are primarily used to investigate students' scientific learning with technology, including science simulation experiments, gamified learning, virtual laboratories, and online collaboration. This shows that scientific learning is gaining attention in the context of digital inquiry. Eye-tracking technology provides valuable data for instructional design, learning assessment, and personalized education(Rau et al., 2015).In the topic of informal learning, eye trackers are used to explore participants' gaze duration and gaze behavior sequences in science centers and museums(Teo et al., 2024), helping evaluate and improve exhibits. Wearable eye trackers are particularly suitable for use in open spaces, allowing researchers to detect participants' visual attention in real-world environments. In the topic of cultural, social, and gender issues, eye trackers are used to examine how learners with different language backgrounds engage in science learning and how gender differences influence the reading of scientific texts (Yang et al., 2016).In the topic of the history, philosophy, epistemology, and nature of science, eye trackers are used to investigate the effect of scientific epistemological beliefs on visual attention during the reading of scientific texts (Yang et al., 2016). Future research could further explore the links between different research topics and explore how to build more comprehensive models of learning processes using multiple indicators.

How the eye-tracking method is implemented, considering participant characteristics, the selection of eye-tracking devices, and the design of areas of interest (AOIs)?

This study found that the number of participants in studies on the application of eye-tracking technology in science education was generally small, with 26 studies having participant numbers between 20 and 40, the largest range of studies. These 26 studies primarily used a combination of quantitative and qualitative research methods for data interpretation, possibly because eye-tracking devices are expensive and can only be used by one participant at a time. The results also showed that studies with participants from higher education had the largest number of participants, followed by secondary education, with the fewest participants from primary education. This may be because college students are the easiest to recruit, while involving primary and secondary school students is relatively more challenging. Moreover, primary school students often have limited attention spans and cognitive control skills, making it difficult for them to maintain focus for long periods, which can result in lower data quality in eye-tracking experiments. In contrast, middle school students typically have better attention control and can focus more effectively on experimental tasks (Lee, 2023; Teo & Peh, 2023).

Regarding the use of eye-tracking devices, the most commonly used brands for research in science education are Tobii, SR Research, and SMI, likely because these are leading brands in the field. This finding aligns with the conclusions of Strohmaier et al.. Among them, Tobii is particularly dominant, likely due to its user-friendly software, broad hardware adaptability, and strong institutional presence. Tobii’s extensive technical support and integration with major statistical analysis software, such as SPSS and MATLAB, further enhance its usability in academic research (Strohmaier et al., 2020). Additionally, two studies used independently developed eye-tracking systems—ITU Gaze Tracker 2.1b from the University of Copenhagen and EyeNTNU-120 from Taiwan Normal University. Higher education institutions may develop custom eye-tracking systems tailored to specific research or teaching needs, ensuring better adaptation to particular environments. However, they may not match commercial devices in terms of data accuracy, stability, and software support. Therefore, in the future, we can explore how to optimize these self-developed devices to make them more competitive. Notably, wearable eye-tracking devices do not require head stabilization and can accurately capture real-time eye movement within the environment (Chen et al., 2023; Jian, 2022).

The most common AOI division is based on functional attributes, likely because many research tasks naturally have clear functional areas. Dividing AOIs based on functional attributes allows researchers to directly reflect participants' attention distribution and information processing while completing tasks (Skrabankova et al., 2020). One-third of the studies used content forms for AOI division,where AOIs were split between text and images or computer screens and physical areas. There are fewer studies that divide AOIs based on presentation position, which mainly involves studies on semantics and scientific terms. Overall, AOI division depends largely on the research objectives and experimental task design, which is consistent with the conclusions of Chen et al. (Chen et al., 2023).

How can eye-tracking data in science education be interpreted, including common eye movement indicators and data processing methods?

It was found that eye movement indicators reflecting attention distribution were used most frequently followed by information processing and search strategy indicators. This aligns with the conclusions of Lai et al (Lai et al., 2013).where eye movement indicators in the reviewed studies predominantly revealed real-time attention distribution. When applied to scientific learning research, eye-tracking technology is primarily used to illustrate the shifts in learners' attention, their level of understanding, and cognitive load, rather than to uncover basic cognitive mechanisms (Anggraini et al., 2020).

In studies related to learning-students' concepts and conceptual changes (learning-concepts), cognitive processing indicators were more prevalent than attention allocation indicators. Particularly in studies focused on students' understanding methods, such as comprehending scientific terms and arguments, cognitive processing indicators (e.g., gaze duration, average gaze duration, first gaze time) offer deeper insights into how students process information. For informal learning topics, search strategy indicators were more commonly used than cognitive processing indicators, which is reasonable since scientific learning in informal settings often requires more advanced analysis of spatial measures like fixation position and sequence to reach more accurate conclusions(Jung et al., 2018).

Regarding eye movement data analysis, all studies in this review employed descriptive statistics as a basis for further statistical analysis, such as difference testing and relationship testing. Over 90% of the studies utilized difference testing, likely to highlight variations in study variables before and after learning interventions (Chen et al., 2023) and to examine individual differences among participants. It is worth noting that emerging statistical methods were used to study participants' learning and decision-making processes. Complex network analysis helps researchers understand learners' visual search strategies and network structures when processing complex information, as well as how these strategies influence learning outcomes (Braun et al., 2022). Entropy analysis can be used to assess the stability and variability of learners' visual attention allocation when processing information, revealing changes in cognitive load when learners face tasks of varying difficulty or complexity (Jian et al., 2024). Traditional statistical methods, such as ANOVA, are mainly used to compare the overall differences in different experimental conditions, while complex network analysis and entropy analysis can reveal deeper patterns of eye movement behavior. These methods provide richer information about the learning process than traditional methods. However, the application of advanced data analysis methods is still limited, possibly because researchers need additional data processing power and computational resources. Future research could explore how to simplify the use of these methods to make them more widely available for science education research.

Limitation

Setting inclusion criteria for a systematic review requires balancing breadth and depth (Gough et al., 2017). This study focused on eye-tracking research in experimental settings related to students' science learning, which may limit the scope, as much science learning occurs in real-world contexts. Additionally, potential biases exist due to double coding; for instance, one study analyzed gender differences and epistemological beliefs, fitting two categories: cultural, social, and gender issues, and epistemology and nature of science (Yang et al., 2016). This suggests the coding framework is adaptable for double coding, though it may benefit from future refinement.

Conclusion

This systematic review offers new insights into using eye-tracking technology in science education, highlighting cognitive and thought processes. Eye-tracking technology makes it possible to obtain information that would otherwise be impossible to collect, and we suggest that future research on eye tracking technology in science education should focus on the following areas:

- Eye-tracking technology enables data collection otherwise unattainable, with a focus in science education on learning contexts and learner characteristics, particularly methodological approaches and individual differences in student understanding. However, historical, philosophical, and epistemological aspects of science are underexplored. Eye-tracking has also revealed significant visual attention differences across cultures and genders, valuable for designing inclusive, personalized science education.
- For experimental design, larger participant samples are essential in eye-tracking studies to enhance validity. Attention allocation metrics (e.g., fixation counts, gaze time) are vital in understanding the science learning process, but a broader range of metrics based on specific research topics is encouraged. Advanced analysis methods, including data mining using information theory and computer science, could yield new insights. Glasses-based eye trackers show promise for informal learning, especially in exhibit design at science centers, though equipment limitations remain (Teo et al., 2024).
- Eye-tracking primarily assesses attention shifts, comprehension, and cognitive load rather than core cognitive mechanisms (Anggraini et al., 2020). Future research should combine eye-tracking with EEG and near-infrared spectroscopy for multimodal data on student behavior and cognition. Integrating virtual reality (VR), augmented reality (AR), and intelligent systems like virtual labs could provide immersive, interactive learning experiences, advancing science education research.

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