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ORIGINAL PAPER

Eye-tracking research in mathematics and statistics education: recent developments and future trends. A systematic literature review

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Abstract

Eye tracking is gaining significance in mathematics education research at a tremendous speed. For the discipline to grow, it is essential to monitor, structure, and synthesize the research in this rapidly evolving field, which calls for a systematic literature review. However, a comprehensive and systematic review does not exist for the research for the past five years. This is a profound gap considering the dynamics of the field, which is fueled by technological advancements in hard- and software and the increasing usability and availability of eye-tracking systems. The aim of this paper is to provide a comprehensive and systematic literature review on eye-tracking research in mathematics and statistics education published in the past five years. Using a systematic database search, we identified and reviewed 116 eye-tracking studies published between 2019 and the first quarter of 2024. We found that the studies addressed a wide range of topics in all relevant curriculum content areas as well as a multitude of phenomena, including teacher-student interaction and digital learning. Interestingly, the studies increasingly involved school students, partially in authentic classroom settings. We also found that the majority of the papers referred to a theoretical framework or made assumptions about the (domain-specific) interpretation of eye movements explicit. As a further important trend, probably still in its infancy, we observed the use of AI techniques for data analysis purposes, which allows for qualitative insights despite bigger numbers of participants. Our paper provides an overview and detailed insights into trends, of which many have not been visible in earlier review studies.

1 Introduction

Eye tracking is the technique of measuring eye positions and eye movements and of capturing where an individual looks at. Eye tracking has been developed over more than a hundred years, yet, only in recent decades non-invasive camera-based eye-tracking systems have been developed, which today are easier to use and more available than ever before (Holmqvist et al., 2011; Stuart, 2022). The technological developments in eye-tracking systems provide the basis for the use of eye-tracking research in the education sciences, and eye-tracking techniques are still improving dramatically "due to the increased speed of computer processors and improved computer vision techniques" (Duchowski, 2017, p. vii). It was in the recent decades that eye tracking has been employed by—among others—psychologists, neurobiologists, and clinicians (Pouget, 2019). Also, in mathematics education, there has been growing interest in eye-tracking research, with a notable increase of studies in mathematics education using eye tracking in recent years (Lilienthal & Schindler, 2019; Strohmaier et al., 2020) and new possibilities offered through fast-developing technologies, which goes along with a high dynamic.

Whenever a topic and according interest are evolving at high speed, it is challenging to monitor and trace the emerging developments. For individual researchers and for the discipline as a whole, such monitoring, sorting, and systematizing, as well as the identification of research directions and trends, is beneficial and even inevitable—for overviewing the landscape of (here: new technology-related) research, for the corpus of research to grow substantially and to gain maturity, and for advancing the discipline accordingly. Systematic review studies are an important tool for providing such comprehensive research overviews: They help synthesize and structure previous research in the field and identify research directions and trends (Kaiser & Schukajlow, 2024). For the field of eye-tracking research in mathemat-

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ics education, this is highly important since both mathematics education research as well as eye-tracking research are rapidly evolving fields of research (Duchowski, 2017; Kaiser & Schukajlow, 2024; Strohmaier et al., 2020).

For eye-tracking research in mathematics and statistics education, such comprehensive reviews do not exist for studies published later than 2018. A systematic and comprehensive review of eye-tracking research in mathematics education reviewing research published up to 2018 has been provided by Strohmaier et al. (2020). They found, for example, that the number of published eye-tracking studies in mathematics education was notably increasing between 2006 and 2014, and that it stayed on a plateau of approx. 20 studies per year from 2014 to 2018. Some even earlier review studies, which were less comprehensive, provided further insights (see Lai et al., 2013; Lilienthal & Schindler, 2019; Mock et al., 2016; Perttula, 2017). However, what is missing today is a systematic and comprehensive literature review on eye-tracking research in mathematics education published since 2019. Also, such a review study should look deeper into the topics that it addresses: Since, for example, the discourse about theoretical underpinnings has increased in recent years, it should be investigated in a more nuanced way what theoretical bases or assumptions of eye movement interpretation are being used. Further, future trends have not been investigated systematically so far. Such a literature review is needed to systematize and summarize the state-of-the-art in the rapidly evolving and technology-affine field of eye-tracking research in mathematics education.

The aim of this paper is to provide a systematic and comprehensive literature review on eye-tracking research in mathematics and statistics education published in the past five years (precisely from 2019 until the first quarter of 2024, when we started this literature review). Our review looks into *general study characteristics*, such as numbers of studies and participants, into *eye-tracking related characteristics*, such as the used technology and its properties (devices, framerate, accuracy), and into *the content and contributions* of the studies, which includes the mathematical topics, phenomena under investigation, and possible future trends.

2 Eye tracking: a brief background

The aim of this section is to set the stage for the literature review provided in this paper: to clarify important terms and provide foundations for the research topic and interest of this paper.

The eye and how eye tracking works Why do researchers look at eye movements after all? Simply put, what the eyes look at indicates what the individual is paying attention to

Fig. 1 Illustration of area of foveal vision: A thumbnail in arm length' distance

(Duchowski, 2017, p. 3ff). However, where individuals direct their attention is not necessarily voluntary: Visual attention may be guided voluntarily by the individual's goals and intentions, while also certain stimuli, which for example stand out, may cause where individuals direct their attention in an involuntary process (Goldstein & Brockmole, 2016, p. 127). However, why do the eyes move towards what humans pay attention to? The human eye has a small spot at the retina at the back of the eye, which is called fovea: This is the part of the retina where individuals can see objects in high resolution—and it covers only about 2° of the whole visual field of approx. 200°, which is approx. the size of a thumbnail in the distance of an arm length (Holmqvist et al., 2011, p. 21; Fletcher et al., 2022, p. 15, Fig. 1). So, in order to see an object sharply, i.e., in high resolution, individuals need to move their eyes to match their gaze with the object of attention—and this is a fact that eye-tracking techniques use. They measure eye movements to detect the gaze location of the individual.

What do eye movements stand for or indicate? The aim of researchers in mathematics education is mostly not to investigate the physical movement of the eye itself. Mathematics education researchers rather intend to use eye tracking to inquire into the learning and teaching of mathematics: They use eye tracking and draw inferences from what students or teachers look at to how they solve problems, about their understanding, their thinking, their interaction, or else. Yet, in simplified terms, looking is not thinking; researchers in mathematics education mostly do not intend to investigate how individuals look. There are different theoretical perspectives of what eye movements stand for—which may be considered background theories about the conceptualizations of eye movements in mathematics education (see Schindler et al., 2025). Often, researchers in mathematics education use the conceptualization that eye movements indicate an individual's attention, precisely their overt attention (e.g., Carrasco, 2011; Duchowski, 2017), while for covert attention, "attention is deployed to relevant locations without accompanying eye movements" (Carrasco, 2011,

p. 1486). Correspondingly, eye-tracking systems can only track eye movements and indicate overt attention, while they cannot capture covert visual attention (Duchowski, 2017, p. 13). When interpreting eye-tracking data, authors often reference the so-called eye-mind assumption or eye-mind hypothesis (Just & Carpenter, 1980; Schindler & Lilienthal, 2019). The eye-mind hypothesis states that eye movements are closely related to cognitive processes. Just and Carpenter formulated, "the eye-mind assumption, is that the eye remains fixated on a word as long as the word is being processed" (Just & Carpenter, 1980, p. 330), which conveys that this assumption originally stems from the use of reading research. While the eye-mind hypothesis has been useful, especially in reading research, it has its limitations and cannot easily be transferred to mathematics education. Schindler and Lilienthal (2019) along with subsequent studies have illustrated that in mathematics education contexts (here: geometry learning), the interpretation of eye movements is not straightforward. Researchers cannot assume the eye-mind hypothesis to hold irrespective of the subdomain of the study. Schindler and Lilienthal's study highlighted the need of a refined interpretation of eye-tracking data in mathematics education, especially through taking into account domain-specific information.

3 Aim of this paper and research questions

The aim of this paper is to provide a comprehensive and systematic literature review on eye-tracking research in mathematics and statistics education published in the past five years. We pursue the following research questions, which address (I) *descriptive general study characteristics*, (II) *eye-tracking related characteristics*, and (III) the *contents and contributions* of the eye-tracking studies.

Regarding (I), the study characteristics, we ask *1) How many studies were published, in what journals, with how many students, and at what grade levels?*

Regarding (II), the eye-tracking related characteristics, we ask *2.1) What eye-tracking systems were used* (*what kinds of devices, by what manufacturers, at what framerates*) *and how high was the reported eye-tracking accuracy of the systems? 2.2) What eye-tracking data and eye-tracking data representations were used in the studies and how are the data analyzed? and 2.3) What data sources were used in addition to eye-tracking data in the studies?* Referring to the question what theoretical stance on eye movement interpretation the studies have (see above), we ask: *2.4) What theoretical bases or assumptions about eye movements and their interpretation did the studies refer to?*

Regarding (III), the contents and contributions of the eye-tracking studies, we ask *3.1) What mathematical content areas and what mathematical topics were addressed in the eye-tracking studies in mathematics education?* Besides these mathematical topics, many eye-tracking studies in mathematics education also focus on additional, non-mathematical topics: pedagogical, psychological, or didactical phenomena, such as mathematical or learning difficulties, affective aspects, or use of representations, which was also indicated in Strohmaier et al. (2020). Therefore, we additionally ask *3.2) What phenomena were in focus in the eye-tracking studies in mathematics education?* Finally, we ask: *3.3) What future trends can be predicted for eye-tracking research in mathematics education?*

4 Methods

Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, we conducted a systematic literature review with three steps (Fig. 2): *the identification step*, in which we conducted a search procedure in data bases and further sources as detailed below; *the screening step*, in which we defined and applied inclusion and exclusion criteria; and *the analysis step*, in which we analyzed and categorized the papers with respect to our research questions.

4.1 Identification step: search procedure

The search covered the period from January 2019 to March 2024, which is when our systematic review process started. We included four sources of data: three databases (*Web of Science*, *PsycInfo*, *ERIC*) and conference proceedings of one conference. As for the latter, we included full papers published in the *Psychology of Mathematics Education Conference* (*PME*)—for three reasons: First, full PME papers, called Research Reports, have a length of eight pages, which provides sufficient space to present studies in a level of detail that is necessary for our review. Second, the PME is a high-quality conference with a rigorous peer review process, which was important to ensure the papers included in this systematic review are of high quality. Third, we follow Strohmaier et al. (2020) who also included PME papers in their review study for similar reasons as in our review study. The PME proceedings were covered from 2019 to 2023, since the 2024 proceedings were not published by March 2024.

As for the databases, in using *Web of Science* and *PsycInfo* we followed other systematic literature reviews in mathematics education (e.g., Reuter & Schindler, 2023) to include high-level journal publications. Additionally, we incorporated *ERIC* as a database, since it contains several journals from Williams and Leatham's (2017) list of top 20 journals in mathematics education based on citations that are not covered by *Web of Science* or *PsycInfo*.

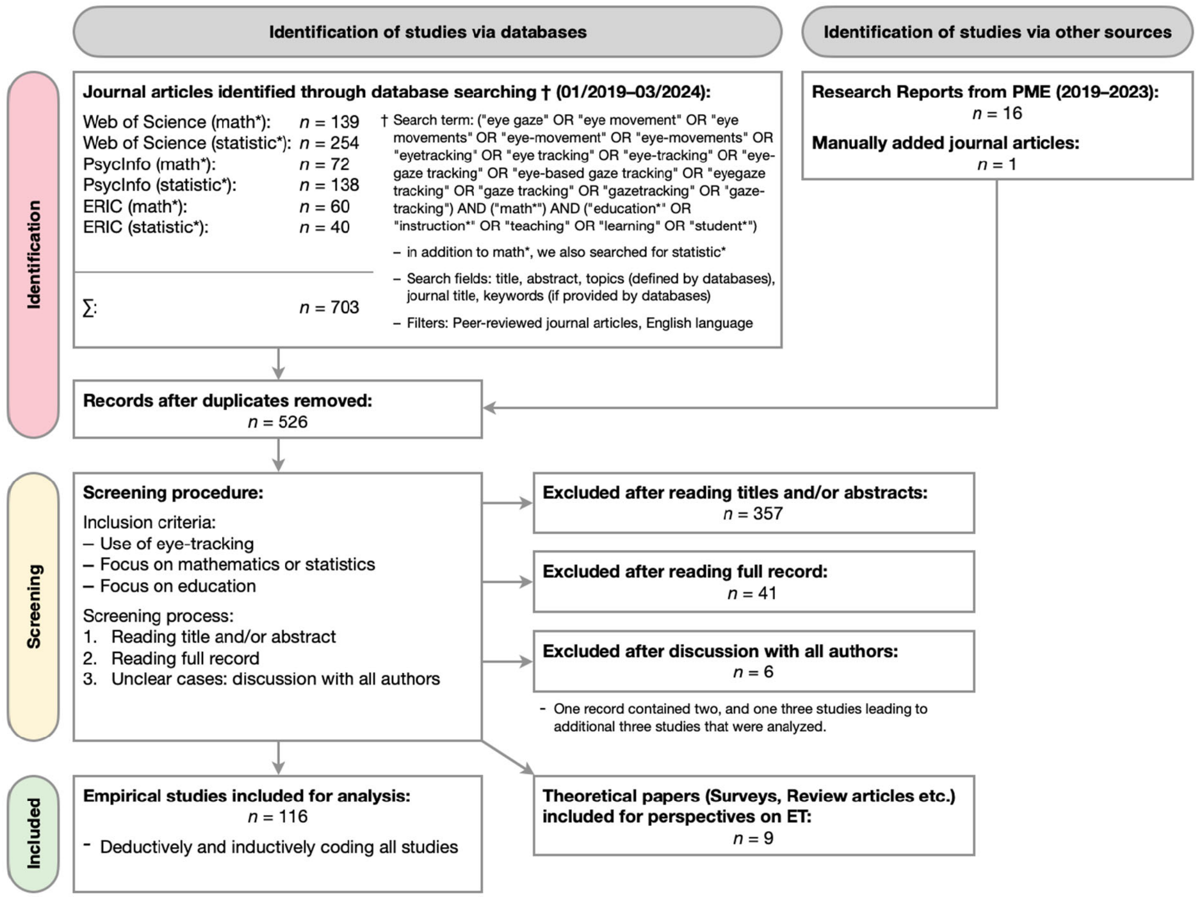

Fig. 2 PRISMA Flow Diagram showing the selection process

When searching for articles in the databases, we used Boolean operators to combine various search terms, similar to Hahn and Klein (2022). The search string was: ("eye gaze" OR "eye movement" OR "eye movements" OR "eye-movement" OR "eye-movements" OR "eyetracking" OR "eye tracking" OR "eye-tracking" OR "eye-gaze tracking" OR "eye-based gaze tracking" OR "eyegaze tracking" OR "gaze tracking" OR "gazetracking" OR "gaze-tracking") AND ("math*") AND ("education*" OR "instruction*" OR "teaching" OR "learning" OR "student*"). The first part of the search string includes a set of terms used synonymously for eye-tracking. The second part of the search string considers "math*" as the main topic. We ran a separate search with "statistic*" to include studies related to statistics that often do not use the term math* in title, abstract, or keywords.[1] The third part of the search string includes terms within the educational context. The Boolean operators "OR" and "AND" were used to combine the different categories (eye-tracking, mathematics or statistics, education) to ensure that only studies relevant to all three areas were captured. This search was conducted across the title, abstract, topics (defined by databases), journal title, or keywords (if provided by databases), and filtered for peer-reviewed journal articles in English. We identified 703 journal papers in total. After removing duplicate papers, 509 papers remained for screening. We added one journal paper manually (Boels et al., 2023), since it matched the search criteria and should have been found in the *ERIC* database search, while it was not—presumably due to a technical error or delay in the *ERIC* database.

Since PME proceedings are not included in the databases, we manually searched for the terms "eye" and "gaze" in the title or abstract of the Research Reports to find papers matching our inclusion criteria. We included 16 PME Research Reports.

4.2 Screening step: inclusion criteria

To find the papers relevant to our research questions, we specified inclusion criteria. Although the Boolean opera-

[1] While topics such as geometry are considered a subdomain of mathematics, statistics education is often regarded a discipline on its own (e.g., Ben-Zvi & Garfield, 2008), even though it originally arose from mathematics education and other disciplines. Thus, not all papers in statistics education refer to mathematics in their title, abstract, or keywords.

tor string was constructed to ensure the inclusion of studies from all three categories (eye-tracking, mathematics or statistics, and education), the screening process revealed that some studies did not meet all these criteria. Consequently, we added these aspects as inclusion criteria to ensure relevance of the studies regarding the research questions:

(A) *Use of Eye Tracking:* Only studies that collected and analyzed eye-tracking data were included. Studies that, for example, analyzed images taken from the front during the experiment to infer where the individuals looked at were not included.

(B) *Focus on Mathematics or Statistics:* Only studies focusing on mathematics or statistics were included. Studies that investigated, for example, dyslexia were not included.

(C) *Focus on Education:* Only studies focusing on education were included. This covers studies within the spectrum of students' learning of mathematics or statistics in or before school, mathematics or statistics in university courses, pre-service or in-service teachers teaching mathematics or statistics, or adults' learning of mathematics out of school.

The screening process followed three steps, each leading to the exclusion of several studies:

1. *Initial Screening:* Titles and/or abstracts of the 509 records were screened based on the inclusion criteria: use of eye tracking, focus on mathematics or statistics, and focus on education. This initial screening resulted in the exclusion of 357 papers.
2. *Full-Text Reading:* After the initial screening, full texts were read, which resulted in 41 papers being excluded.
3. *Final Discussion:* Difficult cases (studies where the inclusion was unclear) were discussed among all authors to reach a consensus. This led to the exclusion of 6 papers.

The screening process resulted in 113 papers included in this review.[2] Since one of these papers contained three eye-tracking studies, and another paper contained two eye-tracking studies, and since we analyzed these studies separately, in total 116 studies meeting all inclusion criteria were included in the final analysis.

4.3 Analysis step

The following steps outline how the 116 studies were analyzed to pursue the eight research questions.

1) Descriptive information. When analyzing the *sample size*, we focused on the number of participants for which eye-tracking data were collected, which is not always the same as the total sample size of the studies. For categorizing *grade levels*, we used categories commonly used in mathematics education and expanded these categories, which led to ten categories (see results section and *Supplementary Information* (*SI*) *2)*. These categories are used in a deductive coding process. Multiple coding was allowed when, for example, first-graders and university students took part in a study. We used the reported grades of the studies. If the grade was not reported, we used the reported age for orientation. Unclear cases were discussed among the authors and clarified to reach a consensus.

2.1) Eye-tracking systems. In coding the kinds of devices, we followed Holmqvist et al. (2011) in distinguishing static devices (also called screen-based or desktop systems) and head-mounted devices (mostly glasses or other mobile systems). Additionally, we analyzed the eye-tracking accuracy of the studies, i.e., the average angular offset between the measured gaze position and the true gaze position, which is an important component of the quality of eye-tracking data (Holmqvist et al., 2011).

2.2) Eye-tracking data and representations. We looked into what eye-tracking data or representations are analyzed in the studies. This may be fixation measures, but also eye-tracking videos, or gaze heat maps. We used a mixed deductive-inductive approach: We started from categories such as fixations and saccades (see Holmqvist et al., 2011) and inductively extended our category system (including, e.g., pupil dilation, gaze plots). Many studies systematically analyzed visualizations, including gaze-overlaid videos, heat maps, or gaze plots, and we coded such visualizations as *data or data representation* if they were explicitly analyzed in the study, rather than used for illustrative purposes.

2.3) Data sources (*in addition to eye-tracking*). We first inductively searched all papers for what data sources (e.g., interview data, standardized tests, written products) they used in addition to eye-tracking data and listed them. In a further step, we summarized this collection and grouped similar data sources together (e.g., concurrent thinking aloud data), leading to a category system. This category system (see *SI 3*) was then used for final categorization of the data sources used in the studies.

2.4) Theoretical bases or assumptions. We used Nilsson et al. (2018) as orientation and coded theoretical bases or assumptions "whenever they were mentioned in the articles with both a statement and a reference" (p. 367). For example, Sprenger and Benz (2020) stated "The analysis of data generated with eye tracking was based on the eye-mind hypothesis, which goes back to Just and Carpenter (1980)" (p. 759). This was coded as "eye-mind hypothesis".

3.1) Mathematical contents. For our deductive analysis, we used the content areas used in the Principles and Standards for School Mathematics (NCTM, 2000), which include *Numbers and Operations*, *Algebra*, *Geometry*, *Measurement*, and *Data Analysis and Probability*. We expanded these categories by the category *Functions and Calculus*,

[2]Please note that a reference list with all papers included in this review can be found in *Supplementary Information 1*.

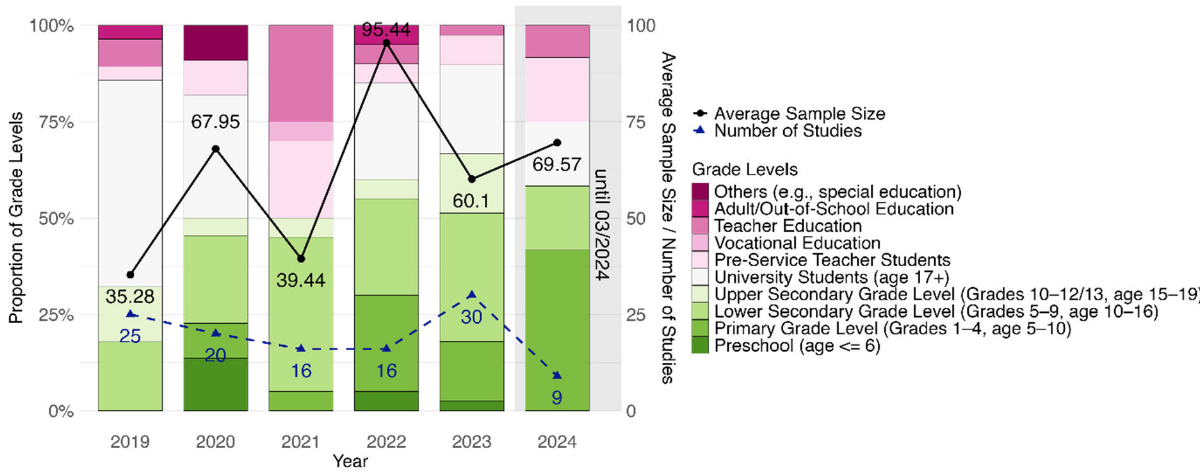

Fig. 3 Descriptive information about the eye-tracking studies. Proportion of eye-tracking studies in mathematics education for each grade level per year (left y-axis), average sample size per year and number of studies per year (right y-axis). For 2024, only studies published until the end of March are included

which is considered part of *Algebra* in NCTM (2000). Studies that did not clearly indicate a mathematical content were coded as “Unspecified”. Within each content area, we then inductively categorized subcategories based on their emergence in the papers (e.g., number line estimation within *Numbers and Operations*).

3.2) Phenomena. We coded phenomena inductively by screening the title and the aim and/or research questions of the papers. As phenomena, we understood didactical, pedagogical, or psychological topics that were in the focus of the study, for example affective aspects. We first coded on paper level (e.g., motivation, interest and feelings, mathematical anxiety) and then grouped the codes into broader categories (e.g., affective aspects). We then synthesized the findings for selected topics to illustrate what contributions eye tracking can offer to the landscape of mathematics education research.

3.3) Future trends. We used Artificial Intelligence (AI), in particular the Large Language Model (LLM) ChatGPT 4o to analyze future trends focusing on the discussions/conclusion sections of the 113 papers in our review. In short, we used the following procedure: As context, we first uploaded the discussion/conclusion sections in batches of 10 randomly selected papers into a new context and queried ChatGPT with the prompt “What future trends in eye-tracking research in mathematics education can be derived from the discussion in this paper? Future trends are expected developments in the field. Please refer explicitly to the paper for each trend.” We used a new chat, i.e., deleted previous contents, for each batch. This resulted in 12 lists of trends, with headings, summaries, and references to the respective papers. We then aimed to condense these trends into categories or clusters, by prompting the following: “Below are 12 summaries of discussions of 10 journal articles each on future trends in eye-tracking research in mathematics education. Develop categories within the 12 summaries by synthesizing future trends that appear multiple times. For each future trend, indicate how frequently it occurred and give the respective references.” This resulted in a list of ten future trend hypotheses, with a summary and two to five bullet points, each with examples and references. We (the authors) reviewed these trend category hypotheses, evaluated, and modified them: We split one trend category candidate into two, since the bullet points comprised two different aspects, while we took out two trend category candidates, where the examples and references did not match with the heading. For the other suggested trend categories, we polished the suggested wording of the headings so that they conveyed better the content and were easy to understand. This resulted in a list of nine future trends (see Sect. 5.3.3).

5 Results

5.1 Descriptive information about the eye-tracking studies

Number of studies From 2019 to 2022, the number of studies per year hovered around 20 (see Fig. 3). The number of studies decreased slightly from 25 in 2019 to 16 in 2022 while the number of studies increased significantly in 2023, with 31 studies published.

Journals Regarding journals publishing eye-tracking studies between 2019 and the first quarter of 2024, at least four eye-tracking papers were published in the following journals: *Educational Studies in Mathematics* (*ESM*) (7 studies), *Frontiers in Education* (6 studies), *ZDM – Mathematics*

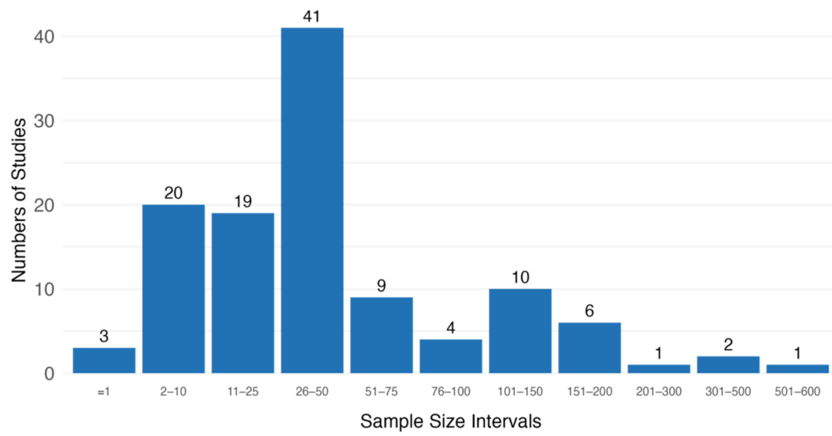

Fig. 4 Distribution of sample sizes

Education (5 studies), *International Journal of Science and Mathematics Education* (*IJSME*) (4 studies), *Physical Review Physics Education Research* (4 studies).

Grade levels We identified the trend that in recent years eye-tracking studies are increasingly involving participants from earlier grade levels. In 2019, most of the studies involved university students (one study with pre-service teachers and 15 with other university students). Since 2020, the number of studies examining students at and before school has increased. Notably, in 2020, three studies examined preschool participants (and two examined primary school students). This trend of focusing more on school students continued, reaching a peak in 2023, with 27 studies conducted with school students (seven with primary school students, 14 with lower secondary students, and six with upper secondary students). In 2024, up to March, this trend appears stable.

Sample size The average sample size of eye-tracking studies fluctuated over the years, yet indicates an upward trend that may become more pronounced in the coming years (Fig. 3). Figure 4 shows the distribution of sample sizes across defined intervals, showing that most often, studies had up to 50 participants.

5.2 Eye-tracking related characteristics of the studies

5.2.1 Eye-tracking systems and eye-tracking accuracy

All eye-tracking devices used in the studies are video-based. The majority of the studies (around 70%) used static eye-tracking devices—a trend that is relatively stable over time (Fig. 5). Of all static eye-tracking devices, around 4% were "built-in" (i.e., permanently incorporated into a monitor) and around 96% were "add-on" (i.e., flexible use with different monitors). Of the specific static eye-tracking devices

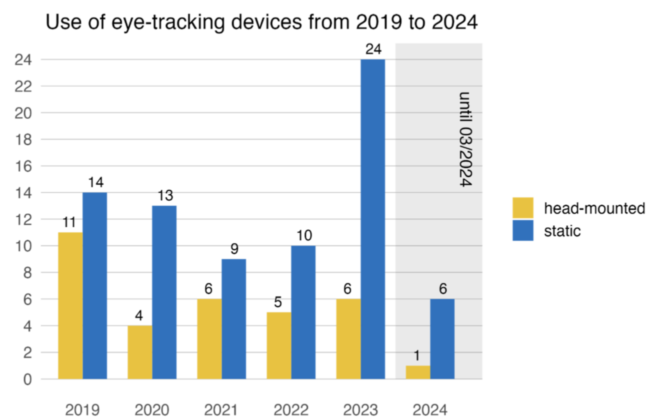

Fig. 5 Number of eye-tracking devices used from 2019 to 2024

that can in principle be used without a screen (e.g., the Tobii Spectrum), all were all used with a screen in the studies considered in this review. Of all studies using head-mounted eye-tracking devices (30%), around 82% used glasses, where illumination and eye camera are mounted into a pair of glasses. Tobii Pro Glasses 2 were used most often. Interestingly, one research group in mathematics education used self-made eye-tracking glasses, leading to a new eye-tracking glasses manufacturer (SeeTrue Technologies). Eight studies (i.e., around 7%) did not or only partially report, which eye-tracking devices they used.

The reported sampling rates ranged between 25 Hz and 2000 Hz (see Fig. 6), while 20% of the studies did not report sampling rates.

Around 65% of the studies in our review did not report the accuracy of the eye-tracking data. Around 9% of the studies reported a general accuracy of the device as reported by the manufacturer under ideal conditions. However, ideal and actual eye-tracking accuracy can differ immensely, especially since many eye-tracking studies address school students and accuracy if often lower for children than for

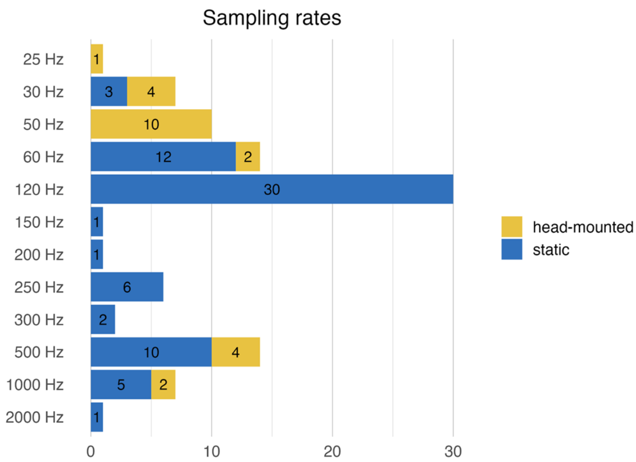

Fig. 6 Eye tracker sampling rates of the studies for static and head-mounted systems (numbers of studies)

adults.[3] This means that in 74% of the cases, it is not clear how accurate the eye-tracking data in the particular study were. However, 26% of the studies reported eye-tracking accuracy: either a threshold or an average accuracy. Approximately 9% of the studies reported an accuracy-threshold (e.g., 1°) necessary for data inclusion (sometimes without specifying the exact accuracy), while 17% reported an average accuracy. The values ranged between 0.15° and 1.5°, which is often considerably higher (worse) than the accuracy reported by the manufacturer under ideal conditions.

5.2.2 Eye-tracking data and data representations

In the inductive analysis of data and data representations, we found eight main categories: three data representations displaying trajectory data or gaze distributions, which were predominantly analyzed qualitatively, namely (1) gaze plots, (2) eye-tracking videos, and (3) heatmaps. In addition, many studies used (4) fixation measures and/or (5) saccadic measures (e.g., numbers or durations of fixations, or the number or length of saccades). Also, (6) AOIs were used—partially in combination with fixation measures, partially otherwise, for example, when transitions between AOIs, the order of visited AOIs, or the hit ratio on AOIs was analyzed. Finally, some studies looked into features of the eye apart from foveal vision, i.e., (7) pupil dilation and (8) blinks, which have the potential to offer additional insights (e.g., with respect to cognitive load or affective variables), yet pose high demands for among others research settings and data analysis (see Discussion section). As can be seen in Fig. 7, the group of fixation/saccadic measures together with AOIs was predominantly used, with 74, 27, and 61 studies each. However, also representations that lend themselves to more qualitative analyses, such as eye-tracking videos, heatmaps, and gaze plots are also used notably (33, 16, and 11 times respectively), while pupil dilation and blinks are used in twelve cases in total.

A similar picture shows with regard to the analyses conducted: In 88 studies (76%), quantitative statistical analyses were conducted and in 53 studies (46%), qualitative interpretative analyses were conducted (while double coding was possible, when studies used both kinds of analyses). Notably, 14 studies out of 116 used machine learning for their analyses, which accordingly was used in 12% of the studies, which may hint at a future trend (see also Sect. 5.3.3).

5.2.3 Data sources in addition to eye tracking

In our inductive analyses, we found nine kinds of data sources that were used in addition to eye-tracking data (Fig. 8). *(1) Thinking aloud interviews* ($n = 18$) were conducted either in a *(a) concurrent* way (where the verbalization of thoughts takes place *during* the work on a task, $n = 11$), or in a *(b) retrospective* way (with a verbalization of thoughts *after* the work on a task, $n = 6$)). In *(2) Stimulated Recall Interviews* ($n = 16$), participants were asked to describe and explain their thoughts using either *(a)* their own *eye-tracking data* ($n = 14$) or *(b) other data* ($n = 2$; e.g., classroom video recordings) as stimuli. *(3) Interviews* ($n = 4$) took place before or after the data collection (e.g., qualitative diagnostic interviews addressing mathematical difficulties). *(4) Observations* of *groups of participants or whole classes* ($n = 12$) involved, for example, observations of collaborative learning situations. *(5) Product collection and analysis* ($n = 9$) analyzed detailed written works or drawings by participants, while *(6) Participants' work on tasks* ($n = 73$) focused either *(a)* on participants' *answers* to tasks in the eye-tracking data collection ($n = 56$) or *(b)* on their *response times* ($n = 17$). *(7) Tests* were conducted in addition to the eye-tracking experiments ($n = 38$; e.g., standardized mathematics or reading tests). *(8) Questionnaires* were used, for example, to assess personal attitudes or perceptions ($n = 23$; e.g., task difficulty or response confidence). *(9) Online measures* comprised data that were gathered online, while the participants worked on tasks. This involved, for example, smartpen or mouse click data, motion tracking data, or other physiological data such as EEG/MRI or heart rate data. A table presenting the eye-tracking related characteristics and the corresponding studies can be found in *SI 4*.

With 73 studies, students' work on the tasks, especially their answers, were used most often as additional data source in eye-tracking studies. Also, tests were used in 38 studies,

[3] For example, the average accuracy in a study by Boels et al. (2023) with upper secondary school students was 1.16° with an eye-tracking system which, according to the manufacturer, has an accuracy of 0.4° under ideal conditions.

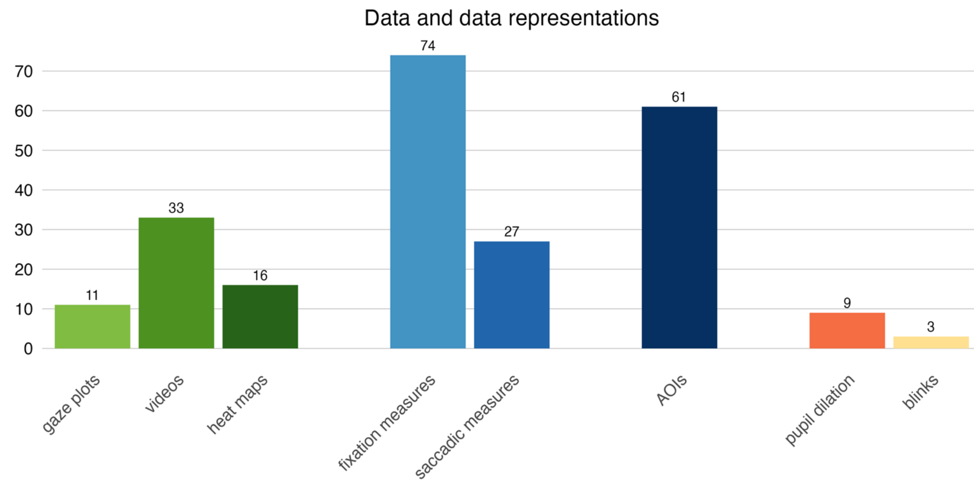

Fig. 7 Data und data representations used in the eye-tracking studies (numbers of studies)

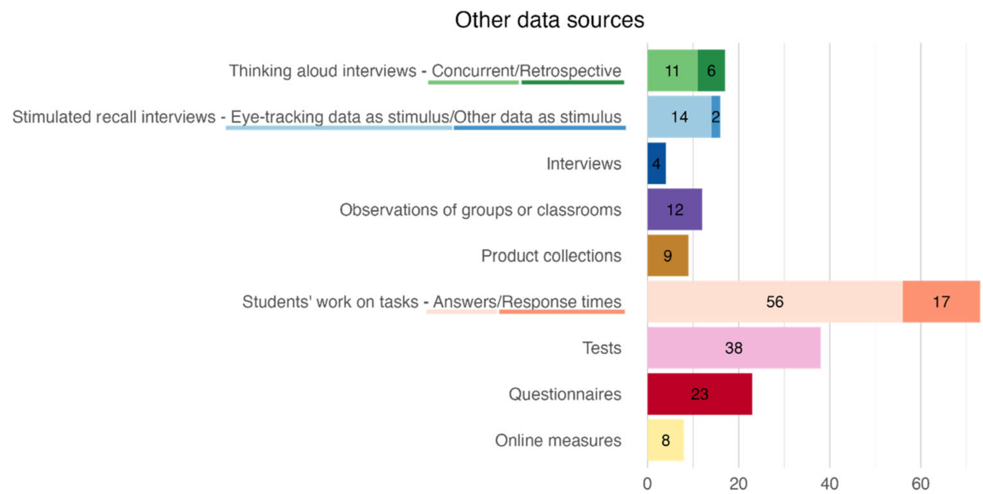

Fig. 8 Data sources used in addition to eye-tracking data (numbers of studies)

often to create groups of students or for inclusion of students or to investigate group differences. Data from interviews, i.e., *stimulated recall interviews* and *thinking aloud interviews*, were repeatedly used for qualitative analyses together with the eye-tracking data.

5.2.4 Theoretical bases or assumptions about eye movements and their interpretation

In our inductive analysis, we found a variety of theoretical bases or assumptions about eye movements and their interpretation that the papers referred to (see Fig. 9). Ninety-three out of 116 studies (i.e., ca. 82%) referred to theoretical bases or assumptions about eye movements and their interpretation. Many papers referred to the *eye-mind hypothesis* ($n=28$; Just & Carpenter, 1980) or implied that eye movements represent *cognitive processes* ($n=31$), both reflecting a more or less cognitivist perspective. Notably, 41 papers referred to *visual attention*, and among them, several papers referred to more specific theoretical assumptions about attention, for example, *overt attention* ($n=2$; Carrasco, 2011; Posner, 1980) or *bottom-up or top-down visual attention* ($n=4$; see Gegenfurtner et al., 2011). The studies also refer to *expert attention* ($n=6$; Gegenfurtner et al., 2011), implying that experts attend to stimuli in a different way than novices; and to *scanpath theory* ($n=2$; Noton & Stark, 1971), which argues that attention is a top-down process and guided by individually stored images and by the scanpaths previously used to perceive objects.

Besides this, three papers referred to eye movements as indicating *intentions* and next actions (see Lukander et al., 2017). There was also a cluster of papers addressing *embodied cognition* or *eye movements as sensorimotor processes* ($n=7$), which assumes that “the human body is not a separate entity from the mind, but it is an intrinsic part of cognition (Lakoff & Nunez, 2000)” (Bicer & Bicer, 2023, p. 366).

In addition, nine papers addressed *cognitive load theory*, and one addressed *cognitive demand* as a phenomenon in mathematics learning, while one paper associated eye movements with *affective processes*: In particular, this paper investigated eye contact assuming that “eye contact transfers experiences of affiliation, positive attitude, and warmth to-

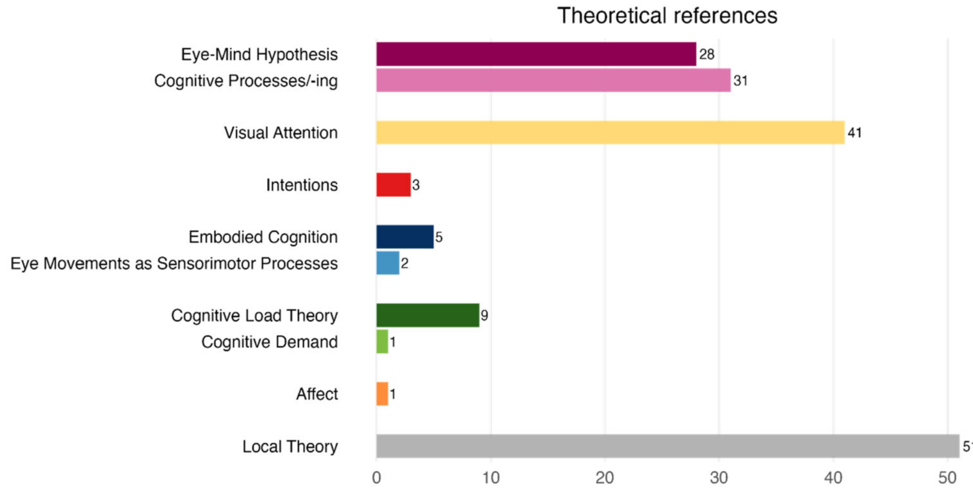

Fig. 9 Theoretical bases or assumptions referred to in the eye-tracking papers

wards the other person (Mehrabian, 1972)" (Haataja et al., 2019b, p. 11).

It is also interesting that many papers referred to local theories for the interpretation of eye movements ($n = 51$). These papers often described domain-specifically how eye movements can be interpreted in the subdomain of study, based on previous works and theorizations.

5.3 Content and contributions of the eye-tracking studies in mathematics education

5.3.1 Mathematical content areas

Figure 10 shows the number of eye-tracking studies in mathematics education for each content, distinguished for different grade levels.[4] A more comprehensive description of the studies in each content area and a table presenting all studies addressing these topics can be found in *SI 5*. The results of this categorization are summarized in the following.

Numbers and operations Most studies ($n = 40$) were conducted within the content area *of Numbers and Operations*. Eight topics were identified within *Numbers and Operations*: Enumeration and quantity recognition ($n = 14$), (basic) arithmetic operations ($n = 11$), arithmetic word problems ($n = 8$), number line estimation ($n = 4$), and rational numbers ($n = 3$).

Algebra Seventeen studies were conducted in the content area of *Algebra*. Within *Algebra*, we identified five topics: Integer sequences ($n = 5$), patterns ($n = 4$), equations ($n = 4$), vector fields ($n = 3$), graphs & matrices ($n = 1$).

[4]Please note that the numbers of studies in Fig. 10 differs slightly from the total number in the Table 2 in the SI, since Fig. 10 also breaks down by grade levels; and in some cases, multiple grade levels were investigated for one content.

Functions and calculus Fourteen studies were conducted in the content area of *Functions and Calculus*. To take account of the diversity of functions, we have differentiated between function types and categorized the following topics: Graph interpretation (various) ($n = 5$), graph interpretation (linear) ($n = 3$), trigonometry ($n = 3$), differentiation & integration ($n = 2$), parabolas ($n = 1$), relations ($n = 1$).

Geometry With 27 studies conducted, *Geometry* is the second most addressed content area. The studies are categorized in the following topics: Figures ($n = 14$), Steiner problem ($n = 8$), mental rotation ($n = 3$), solids ($n = 2$).

Measurement Twelve studies were conducted in the content area of *Measurement*. There are two topics in this content area: Word problem (various) ($n = 5$), and word problem (areas) ($n = 2$).

Probability and statistics Ten studies were conducted in the content area of *Probability and Statistics*. There are five topics: Histograms (data distribution) ($n = 6$), boxplots ($n = 1$), tree diagrams and tables ($n = 1$), bar graphs ($n = 1$), and data comparison (symbolic) ($n = 1$).

5.3.2 Phenomena

Our inductive analysis of didactical or pedagogical phenomena revealed a diverse set of phenomena. The appearance of phenomena in the papers is summarized in Fig. 11, while a textual description and Table 3 in the *SI 6* present in detail the phenomena, subcategories, and the studies that investigated them. We found that a large variety of phenomena were addressed, which indicates the richness of the contemporary eye-tracking studies in mathematics and statistics education and the potential that eye tracking offers to inquire into pedagogical and didactical phenomena. In the

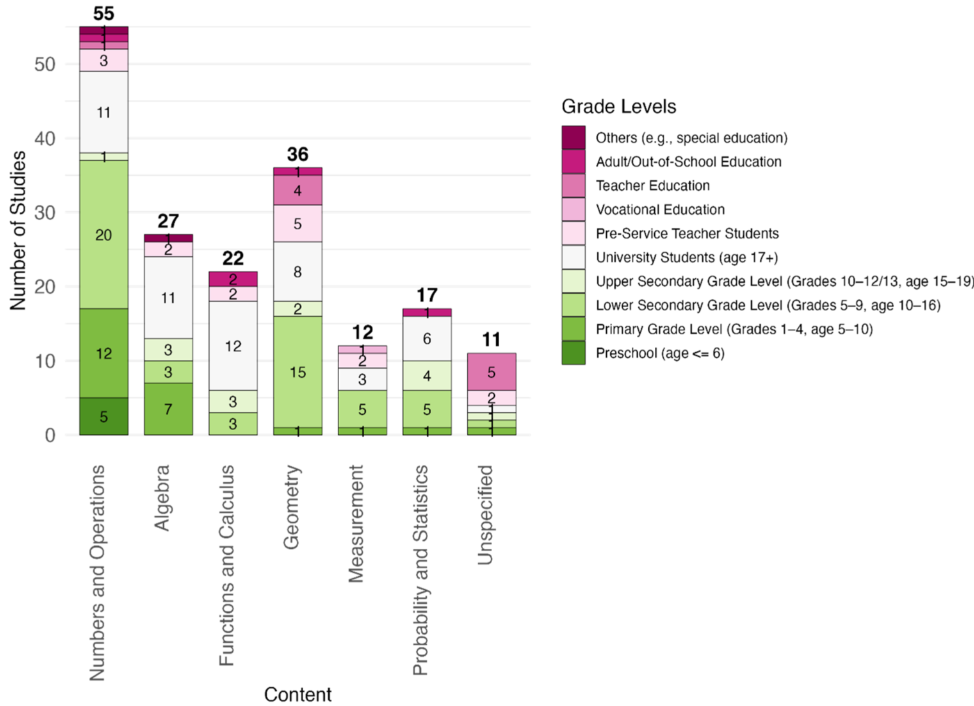

Fig. 10 Content areas: Numbers of studies, distinguished for different grade levels

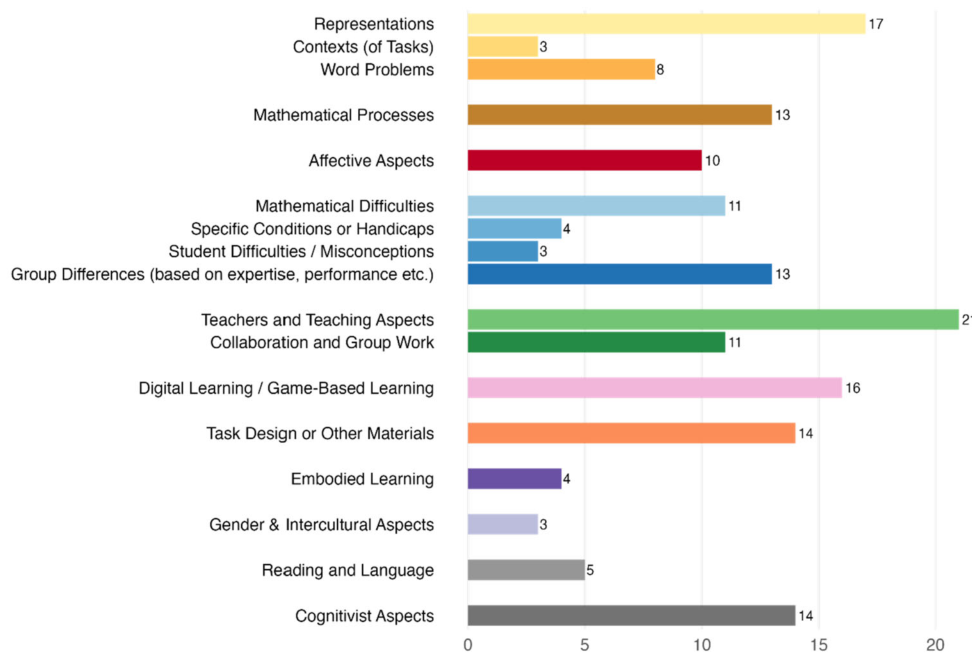

Fig. 11 Phenomena in focus in the eye-tracking studies

following, we will synthesize the findings and contributions of eye-tracking research for some of these phenomena.

One phenomenon where eye tracking has much potential is the topic of *Teachers and Teaching Aspects*. The studies included in our review showed that eye tracking provided valuable insights into teacher/tutor-student interactions, teachers' support for, and assessment of students. Across these studies, a recurring insight is that eye tracking enables a detailed examination of how teachers allocate their visual attention during instructional interactions. This allocation is shaped by pedagogical intentions (Haataja, et al., 2019a; Haataja et al., 2019b; Haataja et al., 2021; Maatta et al., 2021), influenced by students' actions in learning processes of joint attention (Shvarts & Abrahamson, 2019), and varies depending on teaching experience (Kosel et al., 2021; Pouta et al., 2021; Schnitzler et al., 2020; Stahnke & Blömeke, 2021). Haataja et al. methodologically reflect that their "method of combining real-life gaze-tracking recordings with video and interview data enables [them] to reach a new level of validity in investigating the implementation of teachers' pedagogical principles and decisions in an authentic learning environment" (p. 12). Eye-tracking research has further contributed to the study of teacher noticing and classroom management, showing how teachers' gaze reflects their sensitivity to relevant classroom events and their ability to monitor multiple areas of student activity (Stahnke & Blömeke, 2021; Stahnke & Friesen, 2023). In the domain of assessment, eye-tracking research has shown that variations in teachers' knowledge and judgment accuracy are reflected in how efficiently and selectively they attend to students and task-relevant information (Schnitzler et al., 2020; Schreiter et al., 2021), whereas in the domain of individual support, visual attention has been proven to be linked to the quantity and quality of instructional responses provided to students (Chaudhuri et al., 2022).

Also, for *Digital and Game-Based Learning*, eye-tracking research has provided insights into the visual attention of learners. Studies in this research area collectively highlight how eye-tracking data can inform the design of adaptive, engaging, and effective game-based learning environments. It was shown that depending on what elements of incentive systems are visible in the environment, they influence learners' attention allocation on mathematical tasks, for example, when time pressure is visible (De Mooij et al., 2020), or when reward mechanisms appeal to learners without attracting much visual attention (Lomos et al., 2023). Eye-tracking research also provided new insights into how students interact with digital teaching and assessment materials. These insights can inform the design of multimedia instructional or assessment materials to influence students' attention, comprehension, and interactions in digital learning environments: Students' attention has been found to vary depending on the complexity of the tasks and their prior knowledge (Chen & Ho, 2022; Huh et al., 2019). Students' attention to the materials is further affected by the type of elements presented (e.g., dynamic and interactive) (Dyrvold & Bergvall, 2023) and by the design of the elements (Dirkx et al., 2021). Regarding the usability of digital learning systems, eye-tracking research has offered valuable insights to identify areas for improving interface design and tailoring digital learning tools to users' needs (Own et al., 2023; Wang et al., 2019).

5.3.3 Future trends

Based on the ChatGPT-supported analysis of future trends (for a detailed description see *SI 7*) from the discussion sections of the papers, we found nine meaningful future trends: *(1) Digitalized adaptive and real-time learning systems*, where eye tracking can be used to investigate or monitor the students' individual attention, their strategies, and give immediate feedback; *(2) AI for eye-tracking data analysis*, for example, using machine learning to partially automatically analyze, enhance, and advance the analysis of eye-tracking data; *(3) Investigation of teacher gaze and instructional practices*, focusing on aspects such as teacher gaze patterns and scaffolding interactions, teacher professional vision (expert attention or teacher noticing), and teacher training; *(4) Investigation of pupil dilation*, for example, to investigate visual complexity, cognitive load, or other variables; *(5) Identification and intervention for learning difficulties*, where eye tracking is used as a diagnostic tool to identify learning difficulties, and to provide targeted support; *(6) Collaboration and joint attention*, where eye tracking is used to analyze group work or joint attention, or where visual cues are used to support joint attention, or similar; *(7) Ecological validity and use of eye tracking in authentic settings*, for example, eye-tracking studies in authentic classroom settings; *(8) Integration of eye tracking with additional data sources*, for example, with think-aloud protocols, with video recordings, and verbal reports; *(9) Use of eye tracking in combination with other technologies*, for example, with biometric measurements, with behavioral logs, neurosciences techniques.

6 Discussion

The aim of this paper was to provide a comprehensive and systematic literature review on eye-tracking research in mathematics and statistics education published in the past five years. In addition to conducting descriptive analyses regarding study characteristics and eye-tracking characteristics of the included studies, we had an analytic approach in that we traced patterns, theoretical bases and assumptions, carved out phenomena, found relations, drew inferences, and predicted future trends.

Regarding (I), *the study characteristics*, we found that the *number of studies* per year from 2019 to March 2024 is—with approximately 20 a year—similar as found by Strohmaier et al. (2020) up to 2018. A slight decrease of studies from 2019 to 2022 might be likely due to the COVID-19 pandemic, which hindered the possibilities of conducting studies in schools worldwide, whereas an increase in 2023 may be due to the regained opportunities to collect data in schools and to the fact that first papers were published online for two eye-tracking focused special issues in *Educational Studies in Mathematics* (Schindler et al., 2025) and in *Frontiers in Education* (Rusek et al., 2024). We found an accumulation of eye-tracking studies in mathematics education in several journals, for example, in *ESM*, *Frontiers in Education*, *ZDM*, and *IJSME*. The accumulation may partially be due to the above-mentioned special issues. Notably, the list of journals differs from that found in the review of Strohmaier et al. (2020) which might be because in Strohmaier et al.'s study, search words such as "numerical cognition" lead more likely to the inclusion of more journal publications from the domain psychology. Also, it might reflect that more eye-tracking studies in mathematics and statistics education are being published, while before, the origin was more often in domains such as psychology. Regarding *grade levels*, as a key finding, we perceive a tendency of studies to increasingly involve school students. This is a positive trend since it is one fundamental aim of mathematics education research to investigate mathematics learning of school students and since using eye tracking to analyze school students' learning allows for more straightforward practical implications of eye-tracking research and its findings. This trend adds to the findings from Strohmaier et al. (2020), who reported that while most eye-tracking studies involved tertiary education participants (59%), a smaller proportion (28%) focused on primary or secondary school students. We found that during the past five years, most studies had a *sample size* of less than 50 participants, while only ten out of 116 studies had more than 150 participants. Future technological advancements, for example, AI and machine learning, could help to handle larger amounts of data and might influence the sample sizes of future eye-tracking studies in mathematics education—which is also indicated by the fact that those 14 studies, which used machine learning, had 100 participants on average (as compared to 59 participants for all included studies on average).

Regarding (II), the *eye-tracking related characteristics* of the studies, we perceived that no studies in our review used webcam eye-tracking systems yet. However, webcam eye tracking is already under development for the use in mathematics education (see Asghari et al., 2022), using domain information to address issues with eye-tracking quality and accuracy. Webcam eye tracking offers great potential for the future, since it is almost cost-neutral to end users such as schools (where often computers and webcams are available) and opens up a whole new world of eye-tracking applications in school practice. Regarding the *accuracy* of eye-tracking devices, we found that the majority of the studies did not report any eye-tracking accuracy, while some reported only the accuracy provided by the manufacturer under ideal conditions. However, the manufacturer accuracy can differ largely from the actual one—amounting to more than 1 cm difference on the (digital) task sheet, which can have a huge impact on the task design requirements and the domain-specific interpretation of eye-tracking data. We found that 17% of the studies reported the actual accuracy of the study and 9% reported a threshold, i.e., a minimum accuracy required for the participants to take part in the study. Taken together, these 26% are already more than the 12% found in the review study by Strohmaier et al. (2020). We believe that this increase may persist in future studies, that eye-tracking data interpretation may be discussed more carefully, and that studies will more often report the system's actual accuracy.

Despite these descriptive analyses, we inquired into how eye-tracking data are combined with *additional data sources* and, in our inductive approach, worked out a variety of combinations. This variety indicates the methodological richness of eye-tracking studies. We also perceived a trend in combining eye-tracking data with video-recorded observations of groups, or classrooms in studies about teaching or collaboration. We believe that this line of research has much potential and will be fueled in the future by easy-to-use eye-tracking glasses and increased technical possibilities for data evaluation in real-world settings (see also "Future Trends" below). Eye-tracking data are also frequently combined with interviews, thinking aloud interviews, or stimulated recall interviews: Here, often verbal data were analyzed and triangulated with eye-tracking data, which was especially beneficial for gaining detailed insights into students' work on tasks or mathematical processes. Another interesting trend is the additional use of online measures, which often involves additional technologies. We believe that the use of additional technologies in mathematics education research—apart from eye tracking—is still in its infancy, yet, it has great potential, which early overviews hint at (for motion tracking, see, e.g., Reuter & Schindler, 2023; see also "Future Trends" below).

We also analyzed for all studies included in our review what *theoretical bases or assumptions regarding their conceptualization of eye movements* they used, which reflects the background theories about eye movements. We found the positive trend that 93 out of 116 studies (i.e., ca. 82%) explicitly refer to theoretical bases or assumptions about eye movements and their interpretation. In our inductive approach, we found that the variety of theories was much bigger than we anticipated based on previous review studies (e.g., Strohmaier et al., 2020). In our inductive analysis, we found that two major theoretical elements were cognitivist aspects (referring to the eye-mind hypothesis or cognitive processing) and visual attention. Scholars often even more specifically referred to designated assumptions, such as overt attention, bottom-up/top-down attention, or similar. Several of these theoretical strands were not found in previous reviews, such as theoretical references to intentions, to embodied cognition and sensorimotor processes, and affective aspects. This indicates the increasing theorization of eye movements in mathematics education research. One interesting and novel finding is that many papers used local and often domain-specific theories in the subdomain of their study for theorizing eye movements or for guidelines about their interpretation. The trends towards the use of domain-specific local theories is commendable and in line with Schindler and Lilienthal's (2019) study mentioned above that pointed at the need for a "domain-specific interpretation of eye-tracking data" (p. 123), since domain-specific theories "may reduce the inherent ambiguity and uncertainty that eye tracking data analysis has" (p. 123).

Taken together, our review unfolds a variety of theoretical references and may inspire researchers to look into alternatives or specifications of the two main strands (cognitive processing and visual attention)—possibly in combination with local theories. We believe that the matching of research topics and theoretical bases could be even increased further if scholars had a better overview of available theories: Also in this way, the overview that our review provides can contribute to theory development in eye-tracking research in mathematics education—and beyond.

Finally, we investigated (III), *the contents and contributions* of eye-tracking research in mathematics and statistics education. Regarding the *mathematical content areas and topics*, our analytic approach allowed us to see that eye-tracking studies since 2019 have addressed all NCTM content areas, with a variety of topics and with *Numbers and Operations* and *Geometry* addressed most often, while *Measurement* was addressed least often. Whereas Strohmaier et al. (2020) found that most studies addressed *Numbers and Operations*, we found that the content areas were more equally distributed, and we expect this trend to continue in the future. The detailed overview of the topics in each content area (see also *SI 5*) allows researchers to easily identify eye-tracking studies that investigate relevant topics.

We furthermore carved out *phenomena* under investigation in eye-tracking studies in an inductive way. The majority of phenomena were not found in previous review studies in mathematics education. Notably, we perceived a new trend that a large number of studies addressed *teachers and teaching aspects* in the mathematics classroom, including teacher-student interaction. A possible reason for the recency of this trend is that many of these studies do not use static, screen-based eye tracking, but use eye-tracking glasses in (relatively) natural settings in the classroom—which poses high demands on the data collection, analysis etc., but also offers great opportunities for a whole field of new findings through eye-tracking in natural classroom settings (see "Future trends" below). A synthesis of studies in this area showed that eye tracking is a powerful tool for capturing teacher-student interaction as well as teachers' support and assessment of students. Here, eye tracking can help inquiring into very sophisticated and subtle aspects of interactions in authentic learning environments in the mathematics classroom.

Also, notably, *digital learning and game-based learning* are a trend of topics in eye-tracking studies in mathematics education not found in previous review studies, which is likely to gain even greater significance in the future (see below). A synthesis of the contributions of these studies showed that eye tracking here can assist in showing where the students' attention is (when and for how long), and how their visual attention differs based on task complexity, different types of elements or interfaces etc., which can ultimately contribute to design and tailor digital learning systems in mathematics. These findings align with findings from physics education research, where a similar trend has been observed (see Hahn & Klein, 2022). Yet, we believe that the potential that eye tracking holds for investigating digitalized learning is far from being exploited. The few studies did, for example, not use eye tracking to inquire into students' understanding or learning processes in digital learning systems in mathematics.

We additionally identified nine key *future trends* based on a systematic analysis of all papers using AI. We then searched for connections between these trends, and we clustered them into four general future topics (Fig. 12): (1) digitalized learning and its analysis, (2) classroom studies, (3) eye-tracking data and beyond, as well as (4) AI for analysis of eye-tracking data. The first trend, "digitalized learning and its analysis", connects to the phenomenon of digital/game-based learning and we believe that this kind of application of eye tracking in mathematics education will gain even more significance in the future, including the support for students with difficulties in their mathematical learning. The future trend "classroom studies" addresses ecological validity, teacher-student interaction, and group work—a trend that is visible in the surveyed studies on teachers and teacher aspects and collaboration and group work. The two further future trends regarding eye-tracking data and the use of AI also resonate with our previous findings: We found a multitude of additional data sources used in combination with eye tracking data (see above). We also saw that pupil dilation was used in several studies. However, measuring pupil dilation is non-trivial (e.g., since pupil dilation is affected by the change of illumination of the computer monitor under different tasks) and may only be possible in restrictive settings, which might prevent a corresponding trend to unfold in mathematics education in the near future. However, we do expect the combination of eye tracking and other technologies to be very important in the future, which is also indicated by the use of "online measures" found in the studies in our review (e.g., smartpen data, motion tracking data, or physiological data such as EEG/MRI or heart rate data). Finally, as in many other fields, the use of AI for eye-tracking studies in mathematics education will very likely increase, which was already noticeable in our survey. AI can be used, for example, as analysis tool to deal with great amounts of eye-tracking data, or specifically with complex eye-tracking data from natural classroom settings, or to develop digitalized learning systems that use eye tracking as input for providing tailored support (see Schindler et al., 2026/forthcoming).

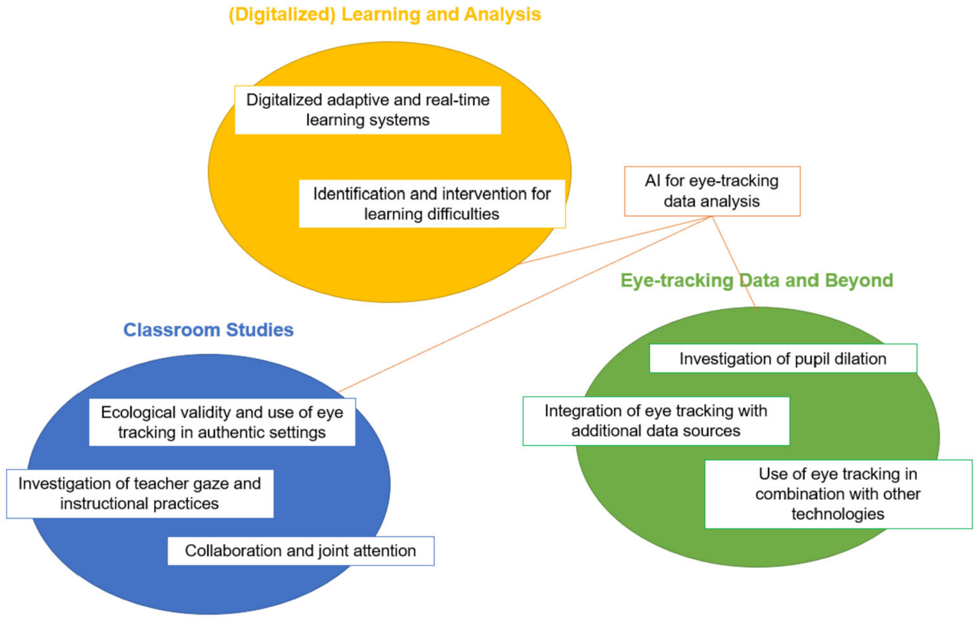

Fig. 12 Predicted future trends for eye-tracking research in mathematics education

7 Conclusion

This review paper describes the status and development of eye-tracking research over the last five years. It provided insights regarding characteristics of eye-tracking studies and traced patterns, theoretical bases and assumptions, carved out phenomena, found relations, drew inferences, and predicted future trends. It shows that eye-tracking in mathematics education is a rapidly developing field. AI is used increasingly often, and this trend will likely continue in the future. Also, the interpretation of eye movements is more extensively grounded in theory than before and domain-specific interpretations are now widely used. This should be pursued further in the future and not overshadowed by technological progress. Finally, we hope that this review will be a helpful source for current and future eye-tracking researchers in their endeavor to investigate mathematics learning.

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Declarations

Competing Interests The authors declare no competing interests.

References

Asghari, P., Schindler, M., & Lilienthal, A. J. (2022). Can eye tracking with pervasive webcams replace dedicated eye trackers? An experimental comparison of eye-tracking performance. In C. Stephanidis, M. Antona, S. Ntoa, & G. Salvendy (Eds.), *HCI international 2022, part I* (pp. 3–10). Springer.

Ben-Zvi, D., & Garfield, J. (2008). Introducing the emerging discipline of statistics education. *School Science and Mathematics*, *108*(8), 355–361. https://doi.org/10.1111/j.1949-8594.2008.tb17850.x.

Bicer, A. & Bicer, A. (2023). Understanding young students' mathematical creative thinking processes through eye-tracking-stimulated recall interview. *Mathematics Education Research Journal*, *35*, 361–399. https://doi.org/10.1007/s13394-022-00429-7

Boels, L., Lyford, A., Bakker, A., & Drijvers, P. (2023). Assessing students' interpretations of histograms before and after interpreting dotplots: A gaze-based machine learning analysis. *Frontline Learning Research*, *11*(2), 1–30. https://doi.org/10.14786/flr.v11i2.1139.

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*(13), 1484–1525. https://doi.org/10.1016/j.visres.2011.04.012.

Chaudhuri, S., Muhonen, H., Pakarinen, E., & Lerkkanen, M.K. (2022). Teachers' visual focus of attention in relation to students' basic academic skills and teachers' individual support for students: An eye-tracking study. *Learning and Individual Differences*, *98*, 102179. https://doi.org/10.1016/j.lindif.2022.102179.

Chen, Y.T. & Ho, M.C. (2022). Eye movement patterns differ while watching captioned videos of second language vs mathematics lessons. *Learning and Individual Differences*, *93*, 102106. https://doi.org/10.1016/j.lindif.2021.102106.

De Mooij, S.M., Kirkham, N.Z., Raijmakers, M.E., van der Maas, H.L., & Dumontheil, I. (2020). Should online math learning environments be tailored to individuals' cognitive profiles? *Journal of Experimental Child Psychology*, *191*, 104730. https://doi.org/10.1016/j.jecp.2019.104730.

Dirkx, K.J.H., Skuballa, I., Manastirean-Zijlstra, C.S., & Jarodzka, H. (2021). Designing computer-based tests: Design guidelines from multimedia learning studied with eye tracking. *Instructional Science: An International Journal of the Learning Sciences*, *49*, 589–605. https://doi.org/10.1007/s11251-021-09542-9.

Duchowski, A. (2017). *Eye tracking methodology: Theory and practice*. Springer.

Dyrvold, A. & Bergvall, I. (2023a). Computer-based assessment in mathematics: Issues about validity. *LUMAT: International Journal on Math, Science and Technology Education*, *11*(3), 49–76.

Fletcher, A., Dunne, S., & Butler, J. (2022). A brief history of eye movement research. In S. Stuart (Ed.), *Eye tracking: Background, methods, and applications* (pp. 15–29). Springer.

Gegenfurtner, A., Lehtinen, E., & Säljö, R. (2011). Expertise differences in the comprehension of visualizations: A meta-analysis of eye tracking research in professional domains. *Educational Psychology Review*, *23*(4), 523–552. https://doi.org/10.1007/s10648-011-9174-7.

Goldstein, E. B., & Brockmole, J. R. (2016). *Sensation and perception* (10th ed.). CENGAGE Learning.

Haataja, E., Garcia Moreno-Esteva, E., Salonen, V., Laine, A., Toivanen, M., & Hannula, M. S.. (2019a). Teacher's visual attention when scaffolding collaborative mathematical problem solving. *Teaching and Teacher Education*, *86*, 102877. https://doi.org/10.1007/s10648-020-09538-w.

Haataja, E., Toivanen, M., Laine, A., & Hannula, M.S. (2019b). Teacher-student eye contact during scaffolding collaborative mathematical problem-solving. *LUMAT: International Journal on Math, Science and Technology Education*, *7*(2), 9–26.

Haataja, E., Salonen, V., Laine, A., Toivanen, M., & Hannula, M.S. (2021). The relation between teacher-student eye contact and teachers' interpersonal behavior during group work: A multiple-person gaze-tracking case study in secondary mathematics education. *Educational Psychology Review*, *33*(1), 51–67. https://doi.org/10.1007/s10648-020-09538-w.

Hahn, L., & Klein, P. (2022). Eye tracking in physics education research: A systematic literature review. *Physical Review Physics Education Research*, *18*(1), 013102. https://doi.org/10.1103/PhysRevPhysEducRes.18.013102.

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & Van de Weijer, J. (2011). *Eye tracking: A comprehensive guide to methods and measures*. Oxford University Press.

Huh, D., Kim, J.H., & Jo, I.H. (2019). A novel method to monitoring changes in cognitive load in video-based learning. *Journal of Computer Assisted Learning*, *35*(6), 721–730. https://doi.org/10.1111/jcal.12378.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review*, *87*(4), 329–354. https://doi.org/10.1037/0033-295X.87.4.329.

Kaiser, G., & Schukajlow, S. (2024). Literature reviews in mathematics education and their significance to the field. *ZDM - Mathematics Education*, *56*(1), 1–3. https://doi.org/10.1007/s11858-023-01541-z.

Kosel, C., Holzberger, D., & Seidel, T. (2021). Identifying expert and novice visual scanpath patterns and their relationship to assessing learning-relevant student characteristics. *Frontiers in Education*, *5*, 612175. https://doi.org/10.3389/feduc.2020.612175.

Lai, M.-L., Tsai, M.-J., Yang, F.-Y., Hsu, C.-Y., Liu, T.-C., Lee, S. W.-Y., Lee, M.-H., Chiou, G. L., Liang, J.-C., & Tsai, C.-C. (2013). A review of using eye-tracking technology in exploring learning from 2000 to 2012. *Educational Research Review*, *10*, 90–115. https://doi.org/10.1016/j.edurev.2013.10.001.

Lakoff, G., & Núñez, R. (2000). *Where mathematics comes from*. Basic Books.

Lilienthal, A. J., & Schindler, M. (2019). Eye tracking research in mathematics education: A PME literature review. In M. Graven, H. Venkat, A. Essien, & P. Vale (Eds.), *Proceedings of the 43rd conference of the international group for the psychology of mathematics education* (Vol. 4, p. 62). PME.

Lomos, C., Seineke, U., Kesting, F., & Luyten, J.W. (2023). The design of incentive systems in digital game-based learning: How primary school children interact with it. *Education Sciences*, *13*(7), 668. https://doi.org/10.3390/educsci13070668.

Lukander, K., Toivanen, M., & Puolamäki, K. (2017). Inferring intent and action from gaze in naturalistic behavior: A review. *International Journal of Mobile Human Computer Interaction (IJMHCI)*, *9*(4), 41–57. https://doi.org/10.4018/IJMHCI.2017100104.

Määttä, O., McIntyre, N., Palomäki, J., Hannula, M.S., Scheinin, P., & Ihantola, P. (2021). Students in sight: Using mobile eye-tracking to investigate mathematics teachers' gaze behaviour during task instruction-giving. *Frontline Learning Research*, *9*(4), 92–115. https://doi.org/10.14786/flr.v9i4.965.

Mehrabian, A. (1972). *Nonverbal communication*. Routledge.

Mock, J., Huber, S., Klein, E., & Moeller, K. (2016). Insights into numerical cognition: Considering eye-fixations in number processing and arithmetic. *Psychological Research*, *80*, 334–359. https://doi.org/10.1007/s00426-015-0739-9.

NCTM (National Council of Teachers of Mathematics) (2000). *Principles and standards for school mathematics*. National Council of Teachers of Mathematics.

Nilsson, P., Schindler, M., & Bakker, A. (2018). The nature and use of theories in statistics education. In D. Ben-Zvi, K. Makar, & J. Garfield (Eds.), *International handbook of research in statistics education* (pp. 359–386). Springer.

Noton, D., & Stark, L. (1971). Scanpaths in saccadic eye movements while viewing and recognizing patterns. *Vision Research*, *11*(9), 929-IN8. https://doi.org/10.1016/0042-6989(71)90213-6.

Own, C.M., Cai, T., & Hung, C.Y. (2023). Exploring the potential of tangible and multitouch interfaces to promote learning among preschool children. *IEEE Transactions on Learning Technologies*, *16*(1), 66–77. https://doi.org/10.1109/TLT.2022.3170031.

Perttula, A. (2017). Eye tracking studies focusing on mathematics: A literature review. In L. Gómez Chova, A. López Martínez, & I. Candel Torres (Eds.), *Proceedings of the 11th international technology, education and development conference (INTED)* (pp. 2166–2173). IATED Academy.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25.

Pouget, P. (2019). Introduction to the study of eye movements. In C. Klein & U. Ettinger (Eds.), *Eye movement research: An introduction to its scientific foundations and applications* (pp. 3–10). Springer.

Pouta, M., Lehtinen, E., & Palonen, T. (2021). Student teachers' and experienced teachers' professional vision of students' understanding of the rational number concept. *Educational Psychology Review*, *33*, 109–128. https://doi.org/10.1007/s10648-020-09536-y.

Reuter, A. S., & Schindler, M. (2023). Motion capture systems and their use in educational research: Insights from a systematic literature review. *Education Sciences*, *13*(2), 167. https://doi.org/10.3390/educsci13020167.

Rusek, M., Klein, P., & Schindler, M. (2024). Eye tracking for STEM education research: New perspectives (editorial). *Frontiers in Education*. https://doi.org/10.3389/feduc.2024.1389962.

Schindler, M., & Lilienthal, A. J. (2019). Domain-specific interpretation of eye tracking data: Towards a refined use of the eye-mind hypothesis for the field of geometry. *Educational Studies in Mathematics*, *101*, 123–139. https://doi.org/10.1007/s10649-019-9878-z.

Schindler, M., Shvarts, A., & Lilienthal, A. J. (2025). Introduction to eye tracking in mathematics education: Interpretation, potential, and challenges. *Educational Studies in Mathematics*, *118*, 309–321. https://doi.org/10.1007/s10649-025-10393-1.

Schindler, M., Cevikbas, M., & Lilienthal, A. J. (2026). AI in mathematics education research: A systematic literature review exploring opportunities and navigating risks. *ZDM – Mathematics Education*.

Schnitzler, K., Holzberger, D., & Seidel, T. (2020). Connecting judgment process and accuracy of student teachers: Differences in observation and student engagement cues to assess student characteristics. *Frontiers in Education*, *5*, 602470. https://doi.org/10.3389/feduc.2020.602470.

Schreiter, S., Vogel, M., Rehm, M., & Dörfler, T. (2021). Through the eyes of prospective teachers: Judging task difficulties in the domain of fractions. In M. Inprasitha, N. Changsri, & N. Boonsena (Eds.), *Proceedings of the 44th Conference of the International Group for the Psychology of Mathematics Education* (Vol. 4, pp. 179–186). PME.

Shvarts, A. & Abrahamson, D. (2019). Dual-eye-tracking Vygotsky: A microgenetic account of a teaching/learning collaboration in an embodied-interaction technological tutorial for mathematics. *Learning, Culture and Social Interaction*, *22*, 100316. https://doi.org/10.1016/j.lcsi.2019.05.003.

Sprenger, M., & Benz, A. J. (2020). Children's perception of structures when determining cardinality of sets – Results of an eye-tracking study with 5-year-old children. *ZDM - Mathematics Education*, *52*(4), 754–765. https://doi.org/10.1007/s11858-020-01137-x.

Stahnke, R. & Blömeke, S. (2021). Novice and expert teachers' noticing of classroom management in whole-group and partner work activities: Evidence from teachers' gaze and identification of events. *Learning and Instruction*, *74*, 101464. https://doi.org/10.1016/j.learninstruc.2021.101464.

Stahnke, R. & Friesen, M. (2023). The subject matters for the professional vision of classroom management: an exploratory study with biology and mathematics expert teachers. *Frontiers in Education*, *8*, 1253459. https://doi.org/10.3389/feduc.2023.1253459.

Strohmaier, A. R., MacKay, K. J., Obersteiner, A., & Reiss, K. M. (2020). Eye-tracking methodology in mathematics education research: A systematic literature review. *Educational Studies in Mathematics*, *104*, 147–200. https://doi.org/10.1007/s10649-020-09948-1.

Stuart, S. (Ed.) (2022). *Eye tracking: Background, methods, and applications* (Vol. 183). Springer.

Wang, J., Antonenko, P., Celepkolu, M., Jimenez, Y., Fieldman, E., & Fieldman, A. (2019). Exploring relationships between eye tracking and traditional usability testing data. *International Journal of Human-Computer Interaction*, *35*(6), 483–494. https://doi.org/10.1080/10447318.2018.1464776.

Williams, S. R., & Leatham, K. R. (2017). Journal quality in mathematics education. *Journal for Research in Mathematics Education JRME*, *48*(4), 369–396. https://doi.org/10.5951/jresematheduc.48.4.0369.