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Eye-tracking methodology in mathematics education research: A systematic literature review

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Abstract

Eye tracking is an increasingly popular method in mathematics education. While the technology has greatly evolved in recent years, there is a debate about the specific benefits that eye tracking offers and about the kinds of insights it may allow. The aim of this review is to contribute to this discussion by providing a comprehensive overview of the use of eye tracking in mathematics education research. We reviewed 161 eye-tracking studies published between 1921 and 2018 to assess what domains and topics were addressed, how the method was used, and how eye movements were related to mathematical thinking and learning. The results show that most studies were in the domain of numbers and arithmetic, but that a large variety of other areas of mathematics education research was investigated as well. We identify a need to report more methodological details in eye-tracking studies and to be more critical about how to gather, analyze, and interpret eye-tracking data. In conclusion, eye tracking seemed particularly beneficial for studying processes rather than outcomes, for revealing mental representations, and for assessing subconscious aspects of mathematical thinking.

Keywords Cognitive processes · Eye movements · Eye tracking · Mathematics education · Numerical cognition

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1 Introduction

The eyes play a pivotal role in decoding visual information. Thus, the observation of eye movements can offer insights into cognitive processing (Holmqvist et al., 2011; Just & Carpenter, 1976). This is probably the reason why the method of eye tracking has been used in numerous studies of different domains (see Duchowski, 2007, for an overview), including research on learning (see Lai et al., 2013, for a review) and mathematics education (Barmby, Andrà, Gomez, Obersteiner, & Shvarts, 2014; Hartmann, 2015; Lilienthal & Schindler, 2019; Mock, Huber, Klein, & Moeller, 2016; Perttula, 2017; Schindler, Haataja, Lilienthal, Moreno-Esteva, & Shvarts, 2018).

The increasing emergence of all studies using eye tracking comes with challenges for mathematics education researchers. First, the number of studies has arguably reached a point at which it has become difficult for researchers to monitor. Eye tracking seems to be widespread across many domains of mathematics education research, making it difficult to keep track of its usage, potential, limitations, and specific challenges. Particularly, researchers who use eye tracking should monitor studies not only in their specific domain, but also outside of it, as there could be studies that use a similar methodological approach to a different end.

Second, with the development of new eye-tracking hardware and data analysis software, the possibilities of data collection and interpretation have become increasingly manifold. For instance, using eye-tracking glasses as opposed to a static eye tracker not only introduces the chance to address new research questions but also requires new methodological considerations. Overall, it has become more and more difficult to summarize, compare, and relate results from eye-tracking research. In mathematics education, this trend has been reported in recent years (Lilienthal & Schindler, 2019; Schindler et al., 2018).

Third, among educational research domains, the domain of mathematics is unique in the way it uses text, mathematical symbols, and visualizations and in how these forms of representation are integrated (Andrà et al., 2009; Ott, Brunken, Vogel, & Malone, 2018). Accordingly, studying people's eye movements during mathematical activities (e.g., reading of mathematical proofs) may require different or modified approaches than those applied successfully in other domains (e.g., text reading or science education). However, these specific affordances of the eye-tracking method in studying mathematics are not well understood.

Lastly, manufacturers have greatly improved the usability of eye-tracking devices and made them more affordable so that an increasing number of researchers has gained access to eye-tracking devices. However, using eye tracking in research still requires complex knowledge, which many researchers in mathematics education had to acquire by themselves (Lilienthal & Schindler, 2019). Accordingly, the mathematics education community has seen an increasing call for guidance and clarity about the possibilities and limitations of the method, as evidenced by working groups at international conferences such as the *Annual Conference of the International Group for the Psychology of Mathematics Education* (PME; Barmby et al., 2014; Schindler et al., 2018).

Four previous review studies summarized eye-tracking research relevant for mathematics education. Lai et al.'s (2013) review described the state-of-the-art of eye-tracking research in the field of education but was not specific to *mathematics* education. Moreover, in the 7 years since its publication, the number of studies using eye-tracking technology may have greatly increased, and thus a critical examination of the current potential of eye tracking and its challenges seems timely. The other three studies only covered specific aspects of mathematics education and thus lack comprehensiveness. A conference paper published by Perttula (2017) provided a summary of eye-tracking studies in mathematics education. This review included a limited selection of 28 studies that focused on the use of eye tracking in studies on mathematical representations. Mock et al. (2016) reviewed 45 studies in their systematic review; however, it was solely focused on the subdomain of numerical cognition. Most recently, Lilienthal and Schindler (2019) reviewed 34 contributions related to eye tracking in the proceedings of the PME. This review illustrated the continued relevance and the potential of the eye-tracking method but focused only on the proceeding papers of a specific conference, rather than the mathematics education literature as a whole. A systematic, comprehensive review on the use of eye tracking in the mathematics education literature does not yet exist. The current paper seeks to fill this gap.

2 Goals and research questions

We present a systematic review, which critically investigates the use of eye tracking in mathematics education, defining three aims and associated research questions.

Our first aim was to provide an *overview of all studies using eye tracking in mathematics education.* This included domains and topics that were addressed as well as the date and type of publication. Articulating the range of topics can help researchers to become aware of gaps in the literature, distinguish possible benefits of the method for specific areas of mathematics education, and support them in finding relevant eye-tracking research in fields that are similar to their own. Therefore, our first research questions were:

> RQ1a: How many studies used eye tracking in mathematics education and when and in which journals were they published?
> RQ1b: In which domains of mathematics education is eye tracking used and what overarching topics have been addressed?

Our second aim was to critically review the *methodology* of eye-tracking research in mathematics education, including both technical and statistical aspects. To obtain meaningful and reliable data in an eye-tracking experiment, the implementation of the technology must be carefully considered. This issue regards, for example, the calibration and setup of the apparatus, the design of the stimuli, and the analysis of the raw data. We analyzed how these issues were addressed in the reviewed studies and what implications should be drawn for future research. Accordingly, our second research question was:

> RQ2: How was the eye-tracking methodology implemented and what details of this implementation were reported in the studies?

The third aim of the current review was to assess the way in which eye-tracking data are typically *interpreted* in mathematics education research. The interpretation of eye-tracking data is challenging because the same data may be linked to various cognitive processes (Schindler & Lilienthal, 2019). Interpretations vary depending on the research questions and the particular type of tasks involved. Thus, our third research question was:

RQ3: How were eye-tracking data interpreted in mathematics education research?

3 Method

3.1 Paper selection

We selected papers both through a systematic database search and by carefully checking cross-references from all relevant results. First, we conducted a database search in Scopus, PsycARTICLES, Education Source, ERIC, Science Direct, Web of Science, and MathEduc, which arguably reflect the most common sources for studies in the field of mathematics education. We considered studies that were published until and including 2018. The first step was the database search, for which we used the search string: (eye OR gaze) AND (movement* OR track* OR record*) AND (math* OR "numerical cognition"),[1] referring to titles and abstracts. Duplicates were automatically discarded. This resulted in a total of 1491 studies. Step two involved screening titles and abstracts using the following criteria: (a) The study was published in a journal article, a book chapter, or in conference proceedings; (b) the study was published in English; (c) the topic of the study was broadly related to mathematics education, meaning that the study reported using a mathematical task or investigating mathematical learning in any way. After this screening, 188 studies remained.

In a third step, these studies were coded by the first two authors of this paper. During this step, studies that did not meet the following criteria were excluded: (a) Eye-tracking data were directly related to mathematics education. This applied if a study used eye-tracking data to analyze mathematical abilities, the solution of a mathematical task, or the acquisition of mathematical content.[2] *Mathematical* was considered anything that is part of mathematics curricula; (b) the length of the article was at least three pages. This was necessary since shorter papers did not report enough information about the method to meaningfully review their use of eye tracking; (c) if both a conference paper and a journal article or book chapter reported the same data and analyses, we excluded the conference paper. This third step led to the exclusion of 79 studies.

A fourth and final step was to check the references within all studies that met the aforementioned criteria (i.e., steps two and three), which added another 38 studies. In addition, we included 14 studies from an additional manual search in the Conference Proceedings of the PME.[3]

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[1] Different search strings were compared and tested in preliminary analyses. Here, it turned out that studies from the field of numerical cognition often did not relate themselves to mathematics but were nevertheless considered relevant for the present review. To avoid a blind spot for those studies, we included *numerical cognition* as a separate term. This increased the number of hits by up to 8%, depending on the database. Because we did not find potential blind spots for other domains, we did not consider it necessary or practical to include additional terms (e.g., geometry or statistical reasoning).

[2] This meant that studies were not included that primarily addressed methodological questions (e.g., Schindler & Lilienthal, 2017) or studies where gaze replays were used as stimuli, but that did not analyze the eye-tracking data itself (e.g., Gallagher-Mitchell, Simms, & Litchfield, 2018; van Marlen, van Wermeskerken, Jarodzka, & van Gog, 2016, 2018; van Wermeskerken, Litchfield, & van Gog, 2018; Wang, Pi, & Hu, 2018).

[3] Note that the review by Lilienthal and Schindler (2019) included another 25 PME papers that we did not include in our review for the following reasons: 21 were short reports, 2 did not directly relate data to mathematics education, and 2 have since been published as journal articles that are included in our review.

Eventually, 161 studies were included in this review. Of these, 31 were published in conference proceedings, 5 were book chapters, and the remaining 125 studies were published in journals. It is notable that the total number of studies included in this review was substantially higher than in prior reviews (Perttula, 2017: 28 studies; Mock et al., 2016: 45 studies; Lilienthal & Schindler, 2019: 33 studies).

3.2 Coding procedure

Codes were made according to the research questions in seven overarching categories.[4] With respect to RQ1a and RQ1b, we included the categories (1) *publication* (e.g., year, journal) and (2) *domain and topic* (e.g., domain, task type). RQ2 led to the categories (3) *apparatus* (e.g., manufacturer, sampling rate), (4) *stimuli* (e.g., task type, presentation, areas of interest), (5) *sample and research design* (e.g., sample size, procedure, statistical method), and (6) *data treatment* (e.g., event detection, statistical analysis). RQ3 led to the category (7) *interpretation of eye movements* (e.g., parameters, interpretation). If a categorization was considered unclear by the coder, a consensus was reached in a discussion between the first three authors of this paper. After the initial coding, all data were cross-checked for coherence, for example, in the description of the stimulus.

A table with selected information from all reviewed studies can be found in Appendix Table 3. The forthcoming results section is structured according to these seven overarching categories.

4 Results

4.1 Publication

To address RQ1a, we analyzed when and in which journals the reviewed studies were published. In line with previous reviews of eye-tracking research, we found a notable increase of studies in the period between 2006 and 2014 (see Fig. 1). Since 2014, the number of published studies was around 20 per year, meaning that 61% of the studies included in this review were published in 2014 or later. Only a small percentage (16%) of those studies that were journal articles were published in journals specialized in mathematics education. The mathematics education journal with the largest number of eye-tracking studies was the *International Journal of Science and Mathematics Education* (five studies). Most articles were published in journals focusing on psychology, educational psychology, or eye tracking. The most prevalent journals for the articles in the current review were *Acta Psychologica* (nine studies), *Psychological Research* (seven studies), and the *Quarterly Journal of Experimental Psychology* (seven studies).

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[4] After planning the categories and before the coding of the studies, the first two authors independently coded the same five randomly selected studies. The results from coding these studies were discussed to ensure the information extracted was identical. Throughout the coding procedure, both coders communicated frequently about issues and required refinements of the categories and always used the same set and description of categories.

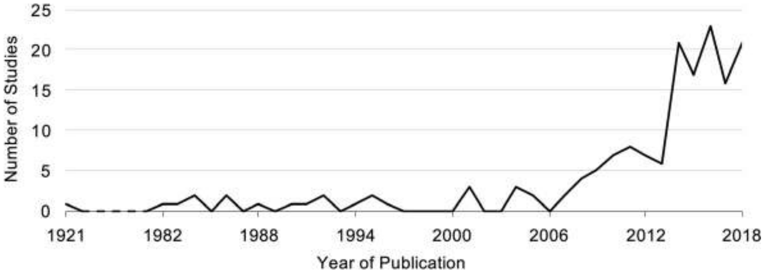

Fig. 1 Number of eye-tracking studies in mathematics education per year

4.2 Domains and topics

An overview of the domains and topics of mathematics education that were addressed by the studies reviewed here is given in Table 1. In the following, we briefly summarize these categories. For the specific tasks used in the studies, see Appendix Table 3.

Numbers and arithmetic The majority of studies included in the current review (90 studies; 56%) addressed numbers and arithmetic. Within this larger category, we grouped the studies into eight subcategories. Necessarily, these subcategories overlap, and their distinction will leave room for debate. The first subcategory included 16 studies (10%) investigating the perception, mental representation, and basic processing of single-digit numbers, number words, and non-symbolic numbers, including counting. The second subcategory included eight studies (5%) that used eye tracking to examine how participants represent and process multi-digit numbers. The third subcategory included 18 studies (11%) where eye tracking was used to investigate spatial-numerical associations (SNAs; Dehaene, Bossini, & Giraux, 1993) in the context of the mental representation of numbers and magnitude (e.g., the *mental number line*) and mathematical operations (e.g., the *operational momentum effect*; Klein et al., 2014). SNAs are assumed to emerge in a variety of numerical cognitive processes (for a critical review, see Shaki & Fischer, 2018). The fourth subcategory included nine studies (6%) that analyzed performance and strategic processes on a number line estimation task. In a fifth subcategory, 23 studies (14%) examined cognitive processes during basic arithmetic operations with Arabic numerals. For example, studies in this subcategory focused on eye movements during equation-solving (e.g., Verschaffel, De Corte, Gielen, & Struyf, 1994) or more complex arithemtic operations like multiplication (e.g., Ganor-Stern & Weiss, 2016). The sixth subcategory included five studies (3%) focusing on the development of number perception and number magnitude by using eye tracking with infants. Finally, the seventh subcategory involved the processing of rational numbers and proportionality, which was composed of 12 studies (7%). Most of these studies analyzed how people process the numerical values of rational numbers, predominantly fractions, although Plummer et al. (2017) included decimals and visual (rather than symbolic) representations of rational numbers.

Geometry, shape, and form The close connection between geometrical thinking and visual perception makes eye tracking a suitable and pertinent method for research that analyzes the perception and processing of geometrical objects. In total, 22 studies in this review (14%) analyzed tasks or abilities in this area. This included geometric proofs, analyzing mental rotation tasks, construction of geometric objects, the perception of objects in a Cartesian plane, geometric calculations in dynamic problems, and the processing of vector fields and geometric shapes.

Table 1 Domains and topics of mathematics education addressed by the studies included in the review

Domain and topic			Total
Numbers and arithmetic			**90**
Perception and mental representation of single digit and non-symbolic numbers, number words, counting	Abreu-Mendoza & Arias-Trejo, 2015 Gandini et al., 2008 Gielen et al., 1991 Li et al., 2010 Merkley & Ansari, 2010 Milosavljevic et al., 2011 Moeller, Neuburger, et al., 2009 Price et al., 2017	Reike & Schwarz, 2016 Rinaldi et al., 2015 Schleifer & Landerl, 2011 Sophian & Crosby, 2008 van Oeffelen & Vos, 1984a van Oeffelen & Vos, 1984b Watson et al., 2005 Watson et al., 2007	16
Perception and mental representation of multi-digit numbers	Bahnmueller et al., 2016 Brysbaert, 1995 Hintz & Meyer, 2015 Huber et al., 2015 Huber, Mann, et al., 2014	Meyerhoff et al., 2012 Moeller, Fischer, et al., 2009a Moeller, Fischer, et al., 2009b Schindler & Lilienthal, 2018	9
Spatial-numerical associations	Bulf et al., 2014 Bulf et al., 2016 Fischer et al., 2004 Hartmann, Mast, & Fischer, 2016 Holmes et al., 2016 Klein et al., 2014 Loetscher et al., 2008 Loetscher et al., 2010 Macchi Cassia et al., 2016	Masson, Letesson, & Pesenti, 2018 Myachykov et al., 2015 Myachykov et al., 2016 Pressigout et al., 2018 Risko et al., 2013 Ruiz Fernández et al., 2011 Salvaggio et al., 2018 Schwarz & Keus, 2004 Zhu et al., 2018	18
Number line estimation task	Gomez et al., 2017 Heine et al., 2010 Klein et al., 2014 Reinert et al., 2015 Schneider et al., 2008	Sullivan et al., 2011 van der Weijden et al., 2018 van Viersen et al., 2013 van't Noordende et al., 2016	9

Table 1 (continued)

Domain and topic			Total
Basic arithmetic	Bolden et al., 2015 Chesney et al., 2013 Curtis et al., 2016 Evans et al., 2011 Ganor-Stern & Weiss, 2016 Godau, Haider, et al., 2014 Godau, Wirth, et al., 2014 Green et al., 2007 Hamada & Iwaki, 2012 Hartmann et al., 2015 Hartmann, Laubrock, & Fischer, 2016 Huebner & LeFevre, 2018	Moeller et al., 2011a Moeller et al., 2011b Okamoto & Kuroda, 2014 Potgieter & Blignaut, 2018 Schneider et al., 2012 Suppes et al., 1982 Suppes et al., 1983 Susac et al., 2014 Verschaffel et al., 1994 Winoto et al., 2017 Zhou et al., 2012	23
Number perception and magnitude in infants	Bremner et al., 2017 Bulf et al., 2016 Canfield & Smith, 1996	Ceulemans et al., 2014 Lécuyer et al., 2004	5
Rational numbers and proportionality	Abrahamson et al., 2016 Atagi et al., 2016 Huber, Klein et al., 2014 Huber, Moeller, & Nuerk, 2014 Hurst & Cordes, 2016 Ischebeck et al., 2016	Miller Singley & Bunge, 2018 Obersteiner & Staudinger, 2018 Obersteiner & Tumpek, 2016 Obersteiner et al., 2014 Plummer et al., 2017 Wall et al., 2015	12
Geometry, shape, and form			**22**
Geometric proof	Alqassab et al., 2018 Lin et al., 2012	Muldner & Burleson, 2015 Schindler et al., 2016	4
Mental rotation	Chen & Yang, 2014 Fry, 1988 Merschmeyer-Brüwer, 2001	Roach et al., 2016 Wang et al., 2014	5

Table 1 (continued)

Domain and topic			Total
Construction	Epelboim & Suppes, 2001 Hannula & Williams, 2016 Lee & Wu, 2018	Schimpf & Spannagel, 2011 Shvarts, 2018a	5
Cartesian plane	Krichevets et al., 2014	Shvarts, 2018b	2
Calculation	Lin & Lin, 2014a	Lin & Lin, 2014b	2
Vector fields	Klein et al., 2018	Ögren et al., 2017	2
Shapes	Haataja et al., 2018	Verdine et al., 2017	2
Reading and word problem solving			**21**
Prototype word problems	De Corte & Verschaffel, 1986a De Corte & Verschaffel, 1986b De Corte et al., 1990 Dewolf et al., 2015 Fry, 1988	Hegarty et al., 1992 Hegarty et al., 1995 van der Schoot et al., 2009 Verschaffel et al., 1992	9
Complex mathematical text or word problems	Cimen & Campbell, 2012 Lee & Wu, 2018 Sajka & Rosiek, 2015 Stolinska et al., 2014	Strohmaier & Reiss, 2018 Strohmaier et al., 2017 Terry, 1921	7
Mathematical parsing	Moutsios-Rentzos & Stamatis, 2013 Moutsios-Rentzos & Stamatis, 2015 Kohlhase et al., 2017	Kohlhase et al., 2018 Peters, 2010	5
Reasoning and Proof			**14**
Reading and comprehension of proofs	Hodds et al., 2014 Inglis & Alcock, 2012 Inglis & Alcock, 2018	Panse et al., 2018 Roy et al., 2017	5
Proportional reasoning	Duijzer et al., 2017	Shayan et al., 2017	2

Table 1 (continued)

Domain and topic			Total
Probabilistic reasoning	Cohen & Staub, 2015	Fleig et al., 2017	2
Logic	Espino et al., 2005 Kim et al., 2018	Ott et al., 2018	3
Functional thinking	Cohors-Fresenborg et al., 2010	Crisp et al., 2011	2
Use of representations	Andrà et al., 2009 Andrà et al., 2015 Atagi et al., 2016 Beitlich et al., 2014 Beitlich et al., 2015 Bolden et al., 2015 Boels et al., 2018	Clinton et al., 2016 Dewolf et al., 2015 Lee & Wu, 2018 Michal et al., 2016 Ott et al., 2018 Rozek et al., 2014 Schindler & Lilienthal, 2018	**14**
Learning difficulties	Abreu-Mendoza & Arias-Trejo, 2015 Gomez et al., 2017 Moeller, Neuburger, et al., 2009 Schindler & Lilienthal, 2018	van der Weijden et al., 2018 van Viersen et al., 2013 van't Noordende et al., 2016 Winoto et al., 2017	**8**
Computer-supported learning	Hernandez-Sabate et al., 2016 Kiili et al., 2014 Olsen et al., 2017	Roy et al., 2017 Schimpf & Spannagel, 2011 Yağmur & Çakır, 2016	**6**
Mathematical problem solving	Andrzejewska & Stolinska, 2016 Haataja et al., 2018	Knoblich et al., 2001 Werner & Raab, 2014	**4**
Statistics	Boels et al., 2018 Cohen & Staub, 2015	Fleig et al., 2017	**3**
Affective variables	Hunt et al., 2015	Strohmaier et al., 2017	**2**

Studies may be assigned to more than one category. Categories are set in **bold**; subcategories are set regular

Reading and word problem solving Studies on mathematical reading and word problem solving comprised 21 (13%) of the studies reviewed here. One of the oldest and most common uses of eye tracking is in research on reading (Rayner, 1998; Rayner, Pollatsek, Ashby, & Clifton, 2012). Consequently, the first studies using eye tracking in mathematics education focused on reading of mathematical texts or word problems. Terry (1921) analyzed fundamental characteristics of reading in mathematics, which he related to the first models of eye movements during reading. This association was also investigated by nine studies that analyzed eye movements during prototype word problem solving. Apart from Terry (1921), six studies considered more complex word problems and longer passages of mathematical text, for example, the integration of illustrations (Dewolf et al., 2015), formulae (Kohlhase et al., 2018), or figures (Lee & Wu, 2018). In addition, basic processes in decoding and parsing of mathematical language were analyzed in five studies.

Reasoning and proof Fourteen studies (9%) addressed mathematical reasoning and proof. This included studies investigating eye-movement patterns during the reading and validation of proofs or during proportional reasoning. Furthermore, studies in this category addressed probabilistic reasoning, mathematical logic, and functional thinking. Note that studies on reasoning and proof in geometry were included in the category *geometry*.

Use of mathematical representations In general, the role of representations and multimedia in learning is subject to numerous studies in research using eye tracking (see Hyönä, 2010; Lai et al., 2013; Mayer, 2010; van Gog & Scheiter, 2010, for overviews). With respect to the present review, 14 (9%) of the studies investigated the role of mathematical representations. In mathematics, information is commonly represented in three different ways: formulae, graphics, and texts. Using eye tracking, Andrà et al. (2009) and Andrà et al. (2015) showed that these representations differ fundamentally in the way that information is retrieved. Several studies analyzed differences in presentation format in various domains: fractions (Atagi et al., 2016), argumentation and proof (Beitlich et al., 2014; Beitlich et al., 2015), propositional logic (Ott et al., 2018), problem solving (Rozek et al., 2014), multiplication (Bolden et al., 2015), word problem solving (Dewolf et al., 2015), and geometry (Lee & Wu, 2018).

Learning difficulties Eye tracking has been used to characterize and analyze learning disabilities in mathematics. These eight studies (5%) compared typically developing students and students with dyscalculia (Moeller, Neuburger, et al., 2009; van der Weijden et al., 2018; van Viersen et al., 2013), Down syndrome (Abreu-Mendoza & Arias-Trejo, 2015), autism (Winoto et al., 2017), developmental coordination disorder (Gomez et al., 2017), and general mathematical learning difficulties (Schindler & Lilienthal, 2018; van't Noordende et al., 2016).

Computer-supported learning Six studies (4%) used eye tracking to analyze learning processes in a computer-supported learning environment. Kiili et al. (2014) and Hernandez-Sabate et al. (2016) used eye tracking to analyze students' attention to different features of educational mathematics games. Other studies evaluated the usability and effectiveness of learning software, namely, Cinderella (Schimpf & Spannagel, 2011), e-Proof (Roy et al., 2017), and GeoGebra (Yağmur & Çakır, 2016). Olsen et al. (2017) evaluated a collaborative tutoring system using eye tracking by examining joint visual attention.

Mathematical problem solving Mathematical problem solving was examined in four studies (2%), investigating relations between eye movements and objective/subjective task difficulty (Andrzejewska & Stolinska, 2016), insight problem solving (Knoblich et al., 2001), and the association of body movements and problem solving processes, assuming effects of embodied cognition (Werner & Raab, 2014). Haataja et al. (2018) used a collaborative problem-solving task to investigate a teacher's attention during scaffolding.

Statistics Three studies (2%) focused on statistics. Each study analyzed the interpretation of statistical data, addressing misconceptions in contingency (Fleig et al., 2017) and Bayesian reasoning (Cohen & Staub, 2015), and difficulties in interpreting histograms (Boels et al., 2018).

Affective variables Affect reflects an important aspect of learning in general and of mathematics education in particular (e.g., Goldin et al., 2016). Two studies (1%) related eye movements to mathematics-specific affective variables, namely mathematical self-concept (Strohmaier et al., 2017) and mathematics anxiety (Hunt et al., 2015).

4.3 Apparatus

Most of the recent studies (since 2014) in our review used equipment from one of three manufactures (see Holmqvist et al., 2011 for an introduction of the manufacturers): SR Research (Ottawa, Canada; 33%), Tobii (Danderyd, Sweden; 29%), or SMI (Potsdam, Germany; 25%). SR Research models have typically provided a higher sampling rate of 500 to 1000 Hz, which might be necessary to compare temporal measures and reaction times.

Eye trackers are commonly distinguished in two categories (Holmqvist et al., 2011). *Static* systems are attached to the stimulus, which is typically presented on a computer monitor. The second category are *head-mounted* devices, where the eye tracker is attached to a head mount or integrated in *eye-tracking glasses*. Head mounted systems can record data on portable devices like mobile phones. When they do not require a physical connection to a static recording device, we refer to these systems as *mobile*. In this review, 132 studies used a static eye tracker, 19 used head-mounted systems, 8 of which were mobile.

Depending on the set-up, the accuracy of the apparatus varies notably (Holmqvist, Nyström, & Mulvey, 2012). Using current technology, a set-up that allows for free head movements typically provides accuracies of 0.5° to 1° of visual angle. Accuracy can be increased to about 0.1° by fixating participants' heads, for example, with a chin rest. However, depending on the design of the stimulus, such precision might not be necessary as the area of good visual acuity extends to about 2° of visual angle (Rayner, 1998). Only 24% of the studies in this review explicitly reported that participants' heads were free-moving. In 37% of the studies, a head rest, head frame, chin rest, or bite bar was reported or could be inferred from the apparatus type. However, in many studies (39%), no information regarding movement restrictions was reported or could be inferred.

There are a number of different techniques to record eye movements (see Duchowski, 2007, for an overview). The oldest study reported here (Terry, 1921) used the reflection of an ordinary light beam onto a spooling film roll to record eye movements in one dimension (details of this apparatus are reported in Gray, 1917). In the present review, 151 (94%) of the studies used a video-based pupil/corneal reflection technique. For this technique, one or more cameras record an image of the eye with an infrared light source located next to the camera. Two reference points from the recorded image are compared to determine the orientation of the eye. The first reference point is the reflection of the infrared light source on the cornea, and the second reference point is the center of the pupil. The positional difference between these reference points changes with the rotation of the eye and can be translated to the gaze position (see Duchowski, 2007, for a detailed description).

n four studies, eye movements were manually coded by a human observer during the experiment (Moutsios-Rentzos & Stamatis, 2013, 2015), from video recordings (Canfield & Smith, 1996) or both (Macchi Cassia et al., 2016). Three studies used a search coil technique, which determines the gaze position by a contact lens containing a thin wire, which is then detected by a magnetic field surrounding the participant (Duchowski, 2007). A further two studies used electrooculography (EOG), which makes use of a natural, small electric potential between the front and the back of the human eye to detect its movements (Hamada & Iwaki, 2012; Zhou et al., 2012). EOG and search coils are usually used to increase accuracy, while qualitative observation of eye movements is especially advantageous with infants and in authentic learning environments. For one study, it was not possible to identify the eye-tracking technique (Fry, 1988).

Most studies reported details about the stimulus presentation (e.g., monitor size, resolution, refresh rate, or viewing distance). However, information about the eye-tracking apparatus itself was often incomplete: 24% of the studies did not report the sampling rate and 29% did not mention a calibration procedure and if they did, only 12% of these studies reported the accuracy required for accepting a calibration. This information is crucial for interpreting the data since the accuracy of the apparatus and a typical calibration error can easily amount to errors of up to 2° of vision, which corresponds to about 2.5 cm on the screen in a regular, static set-up. Depending on the stimulus design and the required precision, this can negatively affect data quality.

4.4 Stimuli

The design of the stimuli was usually characterized by a trade-off between methodological considerations and authenticity. Some studies used simplified stimuli containing few elements and took technical details, such as background color, font, or the synchronization of sampling rates of the stimulus monitor and the eye tracker into careful consideration. Other studies, in contrast, focused on educational authenticity and were more concerned with creating stimuli that were as close to real-world or school mathematics as possible. This included the implementation of dynamic stimuli (e.g., Canfield & Smith, 1996; Schimpf & Spannagel, 2011; Shayan et al., 2017), tablet computers (Abrahamson et al., 2016; Shayan et al., 2017; Yağmur & Çakır, 2016), material from textbooks (Beitlich et al., 2014; Kohlhase et al., 2018; Lee & Wu, 2018), or pictures (e.g., Dewolf et al., 2015). Studies using head-mounted eye tracking sometimes used realistic, paper-based stimuli (Schindler et al., 2016) or authentic classroom interaction (Haataja et al., 2018; Hannula & Williams, 2016). However, these studies needed to take into account that head-mounted eye tracking typically provides a lower resolution and sampling rate than static eye trackers. Moreover, because the eye-tracking device is not attached to the screen with the stimulus, the gaze coordinates have to be mapped onto the stimulus using a second camera which records the participant’s field of view. This requires a significant amount of computation and adds additional sources of inaccuracy.

For analyses in 101 papers, *Areas of Interest* (AOIs) were defined. These are predefined areas of the stimulus that are used for analyzing eye movements on specific elements of the stimulus, such us representations, target words, or keywords (Holmqvist et al., 2011). Importantly, the size of the AOIs influences many eye-tracking measures. For example, the number of fixations will typically increase in larger AOIs (Holmqvist et al., 2011). Many of the studies that made use of AOIs (49%) avoided this issue by using AOIs that had the same size. However, AOIs with the same size do not necessarily contain the same amount of relevant information. In other cases, AOI data were not compared with each other but between trials or participants (e.g., Bolden et al., 2015; Roy et al., 2017). If a standardization was necessary, for example, to compare eye movements on pictures and text that did not have the same size, some studies standardized the AOI sizes by their area (e.g., Alqassab et al., 2018; Beitlich et al., 2015) or used measures that were less strongly affected by AOI dimensions (e.g., revisits, Hegarty et al., 1995; time to first fixation, Bulf et al., 2014).

4.5 Sample and research design

All studies included in this review, except for three (Olsen et al., 2017; Shvarts, 2018a, 2018b), tested participants individually. The 161 studies included a total of 189 experiments. On average, each experiment included a sample of $M = 28.56$ ($SD =$ 21.70) participants. The majority of studies (59%) included participants from tertiary education, while only 28% included participants form primary or secondary schools.

Of the studies reviewed here, 54% used a within-subject design or a mixed design. Studies that used between-subject designs (22%) usually compared specific populations, for example, a particular age, achievement, or expertise.

4.6 Data treatment

Eye-tracking instruments provide raw data about eye movements, usually in the form of coordinates. Since perception depends on the specific nature of the eye movements (Matin, 1974), it is theoretically important for many research questions to manually (by inspecting visualizations of raw data) or automatically (through an automated algorithm) categorize the raw data into *events*, typically fixations, saccades, and blinks. During saccades and blinks, almost no information is processed, but these events can account for 5 to 15% of the raw data (for typical event durations, see Holmqvist et al., 2011). There are several established automatic event detection algorithms used in eye-tracking research.[5] In most eye-tracking analysis software, these algorithms are applied automatically, but thresholds can be modified. The selection of both the algorithm and the thresholds influences the filtered data and thus potentially the results of a study (Blignaut, 2009). Therefore, they should be reported in publications. However, 60% of the studies included in this review did not report an event detection algorithm, and only 21% reported thresholds.

Data loss is a critical issue in studies using eye tracking (Holmqvist et al., 2011) and was substantial in many studies included in this review. When studies reported participant

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[5] The two most popular algorithms use a dispersion threshold to cluster raw data points to fixations (I-DT) or a velocity or acceleration threshold to detect saccades (I-VT; Salvucci & Goldberg, 2000). Once fixations are detected, saccades can then be defined as movements between fixations, and vice versa.

exclusion, this affected an average of 15% of the total sample size. Data loss seems to be especially common in studies with very young or old participants. Lécuyer et al. (2004) used data only from 12 of their 50 four-month-old infants (a data loss of 76%). Ischebeck et al. (2016) had to exclude 21% of their 6-year-old participants, but only 3% of their 8-year-olds in the same experiment. Similarly, Watson et al. (2005) lost about twice as much data in their group of 57- to 79-year-old adults compared with their group of 18- to 25-year-old students.

In a majority of studies reviewed here (76%), eye tracking was not the only source of data in the experiments. In half of these studies, other data were analyzed in relation to eye movements (50%), while the other half analyzed the additional data independently. Frequently, measures like reaction time and accuracy were analyzed in parallel. In general, if data types were analyzed in relation to each other, it was often the relation between eye movements and accuracy that was analyzed. Richer triangulations were done with gestures and communication (Hannula & Williams, 2016; Shvarts, 2018a, 2018b), interviews and stimulated recall (Klein et al., 2018; Shayan et al., 2017; see also Schindler & Lilienthal, 2019), think-aloud protocols and self-reports (Cimen & Campbell, 2012; Green et al., 2007; Ögren et al., 2017; Schindler & Lilienthal, 2018), cognitive load (Lin & Lin, 2014b), affective variables (Hunt et al., 2015; Strohmaier et al., 2017), or skin conductance and EEG (Muldner & Burleson, 2015).

4.7 Interpretation of eye movements

Eye tracking offers possibilities for qualitative and quantitative research. Of the reviewed studies, 66% used a quantitative approach, 22% used a qualitative approach, and 11% used a combination of qualitative and quantitative approaches.

Interpreting eye-tracking data is not straightforward. Lai et al. (2013) and Holmqvist et al. (2011) provide an overview of the most common measures of eye movements in educational research as well as the theoretical interpretations of these measures. Crucially, eye-tracking

Table 2 Interpretations of eye movements used by the studies included in the review

Interpretation of eye movements	Number of studies	
Visual focus and overt attention, eye mind assumption		96
Attention on single object	6	
Compare attention on 2 or more objects	28	
Order of attention (quantitative)	40	
Order of attention (qualitative)	23	
Mental representation and covert attention		39
Visual mental representation	13	
Motoric mental representation	4	
Brain hemisphericity	2	
Areas of covert attention	3	
Attentional anchors	4	
Reaction time	9	
Anticipation	4	
Cognitive effort and resources		28
Information extraction	25	
Memory capacity	3	
Joint attention		3
Metacognitive control		2
Explorative		2

Studies may be assigned to more than one category measures can be interpreted in various ways. In many cases, the same measure can indicate different cognitive processes (Holmqvist et al., 2011). Therefore, this section is structured by the interpretations of eye movements suggested in the reviewed studies, which are listed in Table 2. In this section, we give the most common measures of eye movements that were used for each interpretation and exemplary studies for each measure. For a list of the measures used in each study and their associated interpretations, see Appendix Table 3.

Visual focus and overt attention, eye mind assumption Although the studies presented here are diverse in their research interests, the link between eye movements and cognitive processes in mathematics education often builds on similar theoretical considerations. The most common interpretation of eye movements is based on the *eye mind assumption* (EMA) formulated by Just and Carpenter (1980). It initially stated that "the eye remains fixated on a word as long as the word is being processed" (p. 330) and has since been interpreted as a more general rule of *visual focus equals cognitive focus*. Recent research showed that this assumption is a strong simplification and indicated that it does not hold rigorously (for a detailed review of research investigating the association between vision and attention, see Carrasco, 2011; see also Duchowski, 2007; Schindler & Lilienthal, 2019). In general, only so-called *overt attention* can be directly observed through the position of the visual focus. However, attention can also be shifted without moving the eyes, which is referred to as *covert attention* (Carrasco, 2011). Even though overt and covert attention do overlap in the majority of cases (Carrasco, 2011), Schindler and Lilienthal (2019) showed that eye movements and self-reports of the attentional focus often diverge, which indicates that the EMA might not hold under certain circumstances. While ambiguity may not be a reason to discard the assumption entirely, it calls for researchers to be aware of the limits of its interpretation. In the studies reviewed here, the majority (60%) interpreted eye movements in accordance with the EMA.

A fundamental question that can be addressed by analyzing eye movements is when, whether, and how much a single aspect of a visual stimulus is attended to by a participant (4% of the studies interpret eye movements this way). The onset of attention can be measured, for example, by the time to first fixation (Schimpf & Spannagel, 2011) and the first fixation position (Ruiz Fernández et al., 2011). It should be noted that these measures can also indicate covert attention indirectly, since it is usually the driving force behind the initiation of fixations (Rayner et al., 2012). The amount of attention to objects or areas of the stimulus is often measured by the number of fixations on the object (Dewolf et al., 2015) or by inspecting visualizations such as *heat maps* or *scan paths* (also referred to as *gaze paths*, Winoto et al., 2017; *scan patterns, or gaze sequences*, Holmqvist et al., 2011). For example, Dewolf et al. (2015) evaluated whether students attended to illustrations in word problem solving by measuring the number of fixations on the illustrations. This approach is also popular in evaluating computer-supported learning, since eye tracking can be used to assess whether students notice certain elements of the learning environment (Kiili et al., 2014; Schimpf & Spannagel, 2011). Critically, attention to a certain element can have two fundamentally different causes: Lin & Lin (2014b) argue that high-performing students spend less time and fixations on important areas because they extract the information faster (see also Gegenfurtner, Lehtinen, & Säljö, 2011). At the same time, other researchers found that experts can better differentiate between relevant and irrelevant information and therefore spend relatively more time on relevant than irrelevant information (e.g., Fleig et al., 2017; Kim et al., 2018).

Similar to examining single aspects in a visual stimulus, and based on the EMA, the attention allocated to different parts of a visual stimulus can be compared. Out of the studies included in this review, 17% use this interpretation. The most popular measures for this comparison are the relative number of fixations and the relative fixation duration. For example, Ott et al. (2018) compared the number of fixations and total fixation duration between text and formulae and text and graphics, respectively. Furthermore, measures can be compared between different periods of time: De Corte et al. (1990) compared fixation durations on numbers and words between a participant reading the word problem for the first time and the consecutive reading process.

In addition, 25% of the reviewed studies analyzed attentional patterns of eye movements, which are often associated with solution strategies. For example, the number and order of transitions between certain aspects of a stimulus was used to assess parallel compared with sequential strategies in number processing (Merkley & Ansari, 2010; Meyerhoff et al., 2012), fraction comparison strategies (Miller Singley & Bunge, 2018; Obersteiner et al., 2014; Obersteiner & Tumpek, 2016), or information integration processes (Alqassab et al., 2018; Crisp et al., 2011; Ögren et al., 2017). As another measure, the position of the first fixation was considered an indicator for a preferred order of information processing (Michal et al., 2016). Moreover, saccade length was used as an indicator for local (short saccades) compared to global (long saccades) strategies in information retrieval (Inglis & Alcock, 2012; Klein et al., 2018; Stolinska et al., 2014) and information integration (Godau, Wirth, et al., 2014).

When a quantitative description of strategies was not possible, a number of studies (14%) used analyses based on visualizations like scatterplots (Inglis & Alcock, 2018), heat maps, scan paths, or replays of the eye-tracking recording to manually detect patterns of eye movements and associated strategies (e.g., Lee & Wu, 2018). This approach was often limited to smaller sample sizes as it requires more time than computerized analyses.

Mental representation and covert attention Other than eye-tracking measures based on the EMA, 24% of the studies used eye movements as more direct indicators of mental representations (e.g., Klein et al., 2014) and processes (e.g., Hamada & Iwaki, 2012). This approach was found especially in studies on SNAs and number line tasks, where the position of fixations was assumed to map onto a mental, spatial representation of numbers (8%). Additionally, nine studies used the time to the first fixation on a target as a measure of reaction time. By placing the targets in different areas of the visual field, SNAs could be observed (e.g., Schwarz & Keus, 2004). Moreover, some studies associated imperceptible eye movements like microsaccades as a motoric indicator of cognitive representations (four studies; e.g., Myachykov et al., 2016).

Another interpretation was the association between eye movements and brain hemisphericity during mathematical tasks, proposed in two studies (Moutsios-Rentzos & Stamatis, 2013, 2015).

Other studies investigated areas of covert attention, i.e., when the focus of attention is not equivalent to the visual focus, through eye movements. For example, the position of the first fixation on a stimulus was interpreted to map on the previous focus of covert attention (three studies; e.g., Risko et al., 2013). *Attentional anchors*, which are goal-oriented perceptual structures in the sensory field that enable better coupling with the environment, were located through gaze patterns (four studies; e.g., Duijzer et al., 2017). For infants, the gaze time and saccade latency were interpreted as indicators for the mental anticipation of objects (four studies; e.g., Canfield & Smith, 1996).

Cognitive effort and resources A final set of interpretations of eye movements was based on the assumption that eye movements are direct indicators of the cognitive effort involved in decoding visual information. This more fundamental interpretation was used by 17% of the reviewed studies. For instance, the mean duration of fixations was used as an indicator for mental workload or cognitive effort and depth in processing information (e.g., Hodds et al., 2014). Moreover, the number of revisits on specific elements, the total fixation duration, or the time to the first fixation were interpreted as an indication of memory capacity (three studies; e.g., Watson et al., 2005).

Joint attention, metacognitive control The three studies making use of dual eye tracking (i.e., two participants' eye movements being tracked in parallel) used the proximity of learners' fixations as a measure of joint attention (e.g., Shvarts, 2018a). Two studies associated eye movements with metacognition, using the blink rate (Cimen & Campbell, 2012) as well as scan paths and the total fixation duration (Cohors-Fresenborg et al., 2010).

5 Discussion

This review investigated the use of eye tracking in the field of mathematics education research, addressing three research questions. We discuss the results in the order of these questions.

5.1 Overview of the use of eye tracking in mathematics education

In accordance with our first research question, we provided an overview of the domains and topics addressed in mathematics education research using eye tracking, and when and how these studies were published. Our findings illustrated that the number of studies in mathematics education that made use of eye tracking has increased rapidly in the last decade and continues at a rate of around 20 studies published per year. This illustrates the ongoing popularity and importance of eye tracking within mathematics education. Our results showed that eye tracking was used in a wide range of fields within mathematics education, although a majority of studies focused on numbers and arithmetic and fundamental processes of mathematical thinking like number perception, counting, and basic arithmetic operations. These studies were often conducted in controlled and systematically designed laboratory experiments and aimed to precisely assess specific cognitive processes that were often impossible to investigate through other methods. However, it is noteworthy that our review also included a variety of studies that went beyond strictly controlled laboratory settings to include authentic learning situations (e.g., Hannula & Williams, 2016; Kiili et al., 2014; Lin & Lin, 2014b). Here, eye tracking benefited twofold; it allowed for relatively authentic learning environments, and it was an unobtrusive method to gather data about learning processes. In sum, it seems clear that the possibilities offered by the method of eye tracking are diverse in the domain of mathematics education, with this method being adaptable to the various subdomains. Recent developments like mobile or dual eye tracking indicate that the method will continue to evolve in the future, particularly in the direction of more authentic experimental settings. However, the domains found in our review did not cover all mathematical topics in the same depth. Thus, a wealth of opportunity remains for future studies where eye movements could be informative, for example, in the field of statistics, where only three studies were found (see Boels, Bakker, & Drijvers, 2019, for recent developments).

It should be noted that the scope of this first research question was not to summarize the specific research goals of each study but rather to provide an overview of the topics addressed within these goals. Accordingly, our review analyzes the research from a methodological perspective and does not scrutinize the specific results and implications that each study offers in its respective field. We acknowledge that this is a narrow focus that omits findings and consequences of these studies. However, we hope that the overview of domains and topics will guide the reader to a more detailed investigation of the consequences of the specific studies.

5.2 Eye-tracking methodology

To answer our second research question, we reviewed technical and methodological aspects of eye-tracking studies in mathematics education. In terms of research design, most studies used within-subject or mixed designs, which allowed for small sample sizes with large interindividual variance. At the same time, many studies revealed difficulties due to a substantial loss of data, which might be problematic if sample sizes are already small. As for the age of participants, most studies included university students who arguably often represent a convenience sample. Because many research questions in mathematics education are related to school-aged children, the predominance of university students in eye-tracking studies in mathematics education seems problematic. Age is an important factor affecting eye movements (Holmqvist et al., 2011; Rayner et al., 2012) meaning that the generalizability of findings from adults might be limited. Moreover, university students typically reflect a high-achieving selection of young adults. For these reasons, the issue of generalizability should be acknowledged and systematically addressed in future research.

In addition to research design and participant characteristics, we examined the use of the eye-tracking method in the reviewed studies. Although studies necessarily vary in the specific eye-tracking method they use, we found large inconsistencies in the *reporting* of these methods. Because eye-tracking research offers a variety of options in terms of the apparatus itself, the settings of the apparatus, and the specific data analysis methods, it seems especially important to report all necessary details with regard to eye tracking (see also Holmqvist et al., 2011). Full reporting is also crucial for other researchers to understand or replicate the specific analysis of eye movements and to evaluate the implications of the findings. We propose that this should include (but not be limited to) a precise description of the apparatus including sampling rate and average accuracy; the existence or nonexistence of movement restrictions and information regarding the setup; the size of the stimuli; the distance between the stimuli and the participant; the monitor's refresh rate; the calibration procedure and calibration accuracy threshold; the event detection algorithm and event detection thresholds; the position and size of any AOIs; the correlation between all used measures; and the amount of and reasons for data loss.

5.3 Interpretation of eye movements

Finally, our third research question aimed to assess how eye-tracking data were interpreted in the reviewed studies. It became clear that eye tracking not only offers a wide range of possibilities for qualitative and explorative analyses but also provides data suitable for various quantitative analyses. In general, most eye-tracking studies in mathematics education claimed that the method allows for the assessment of cognitive processes that would otherwise not be observable, for example, because they are subconscious. One of the most crucial challenges in eye-tracking research is to properly link eye movements to these assumed underlying cognitive processes. Although reflecting about this link seems obvious, it is by no means ubiquitous in the studies reviewed in this paper. Even when studies analyzed similar cognitive processes, they often made use of numerous or redundant measures of eye movements. Eye-tracking measures can be highly correlated with each other for theoretical or computational reasons, but correlations are scarcely reported. As an example, Merkley and Ansari (2010) reported the correlation between the number of fixations and the number of saccades, which was $r = .997$. This is not surprising as saccades and fixations alternate in regular reading and event detection algorithms typically infer one from the other (Salvucci & Goldberg, 2000). In such a case, the two measures arguably cannot reflect different cognitive processes and researchers should consider using only one of the two measures for analyzing the same research question (e.g., Hurst & Cordes, 2016).

Eye movements alone are seldom informative when the reader is not properly guided on their meaning and relation to the research questions. Thus, eye-tracking studies—as all other experiments—arguably require a plan on data interpretation before they are conducted, and possible implications gained from the data should be anticipated in advance, even in explorative studies. Apart from avoiding the risk of type I errors and post hoc hypotheses, limiting and specifying the to-be-used measures further helps to clarify, compare, and interpret the results (for a discussion of some of these considerations, see Banks et al., 2019).

We found that a majority of studies referred to the EMA as a theoretical foundation for the interpretation of eye movements. The EMA itself is, however, not universally accepted in eye-tracking literature, and there are limitations within the domain of mathematics education as well (Anderson, Bothell, & Douglass, 2004; Rayner, 1998; Schindler & Lilienthal, 2019). Schindler and Lilienthal (2019) addressed the case of a student solving a geometry problem. Using stimulated recall, the authors identified incidents in which the EMA seemed to hold—and others in which the EMA was seemingly violated. Even in incidents in which the EMA did hold, the same eye-movement pattern could have been linked to a variety of cognitive processes. The EMA is arguably a feasible tool for the interpretation of a majority of eye movement data, especially in settings in which participants have to work on visual problems within a limited time. But its suitability should be evaluated from case to case. Triangulation with other data sources could help to interpret eye movements meaningfully.

Our review shows that eye tracking was not limited to detecting the visual focus of attention following the EMA. Rather, eye tracking has also been used to assess, among other things, mental representations, cognitive workload, or joint attention in collaborative learning settings. For these processes, eye tracking provides specific benefits: For example, the relationship between mental representations and eye movements is often very strong and can be best observed during the work on the task and not after the task (e.g., during counting; Hartmann, Mast, & Fischer, 2016).

The amount of different measures that were used in the studies reviewed here illustrates not only the many possibilities that eye tracking provides but also the possible difficulties in comparing studies with regard to the measures used and their interpretation. It would be helpful if future research would make stronger use of previous studies and comprehensive guides when choosing eye-tracking measures. For example, Holmqvist et al. (2011) and Lai et al. (2013) offer overviews of measures of eye movements and their interpretations in general, and we provide an overview of the measures used in the mathematics education literature (Appendix Table 3).

The majority of studies interpreted eye-tracking measures in isolation, even if other behavioral or self-reported variables were assessed in parallel. If such other data are collected, researchers could analyze and report their relationship to eye-tracking measures. However, this was not common practice in the studies reviewed here. The use of think-aloud protocols, interviews, reaction times, or accuracy in relation to eye-tracking data can help to verify and specify the interpretations of eye movements. For example, including stimulated recall or interview data can provide additional indications if assumptions like the EMA are valid in specific experiments and help to decide how the collected data can or cannot be interpreted (e.g., Schindler & Lilienthal, 2019).

5.4 Three benefits of using eye tracking in mathematics education

Eye tracking has become a prominent method in mathematics education research. However, many, if not all, of the topics covered in the papers in this review had previously been examined without eye tracking. Thus, what added value can the method provide? Based on the studies reviewed here, we argue that eye tracking offers unique ways to understand cognitive processes in mathematics education. In many studies reviewed here, eye-tracking measures provided information that could otherwise not be collected. This was usually the case for one of three reasons:

a) The research referred to a time-critical process rather than an outcome. Mathematical tasks often provide a variety of solution approaches and strategies. These strategies are often not visible in the final solution of a task. Moreover, given enough time, students might use strategies and approaches that are sufficient, but not optimal. Thus, observing solution processes without interrupting students is a major challenge that can be tackled through eye tracking (e.g., Inglis & Alcock, 2012; Obersteiner & Tumpek, 2016; van der Weijden et al., 2018).
b) The research included aspects of visualization and mental representations. These questions are typical for mathematics education since mathematics makes use of visualizations in many forms, but at the same time, mathematical objects are often abstract. Making mental representations of these objects visible is a general challenge that can be approached through eye tracking (e.g., Hartmann, Mast, & Fischer, 2016; Myachykov et al., 2015; Risko et al., 2013).
c) The research referred to cognitive processes that cannot be consciously reported. In mathematical thinking, cognitive processes are often complex and therefore hard or impossible to communicate, particularly for younger students. Other representations or cognitive biases might not even be consciously accessible but are nevertheless reflected in eye movements (e.g., Moeller, Neuburger, et al., 2009; Ott et al., 2018; Watson et al., 2005)

When studies further provide a sound and precise theoretical association between eye movements and cognitive processes (e.g., Alqassab et al., 2018; Curtis et al., 2016; Plummer et al., 2017), they usually offer an immediate and unique insight into mathematical thinking. Although a decisive judgment on the specific value of these findings within all areas of mathematics education was beyond the scope of this review, many authors were convinced that eye tracking did offer unique insights that would not have been possible with traditional methods (e.g., written tests or think-aloud protocols) and that brought forward their specific field of research.

6 Conclusion

Eye tracking has the potential to allow novel insights into mathematical thinking and learning. In order to make effective use of this potential, future research should strive for more clarity regarding the theoretical foundations underlying the research questions being addressed and the methodological choices being made. Moreover, the interpretation of eye movements should be based on a reasonable assumption of what eye movements measure and what cognitive processes these measures reflect. Considering the large body of studies that already use eye tracking in mathematics education, it is our hope that this review can guide future researchers in this field and support them in using eye tracking in an efficient and reflective way.

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Appendix A

Table 3 Overview of all studies included in this review and selected information. The table is displayed in two parts

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Abrahamson et al., 2016	05	Proportional equivalence	C, D	11.3, 13.4	30, 46	one group and cases	2	Tobii, X2 (static)	n/a	free
Abreu-Mendoza & Arias-Trejo, 2015	01, 50	Area comparison and number comparison	D	12.3	48	two groups (Down syndrome, control)	1	Tobii, X2–30 (static)	30	n/a
Alqassab et al., 2018	11	Providing feedback on a peer geometry proof	F	24.4	53	two groups (experimental)	1	Ergoneers, Dikablis (head-mounted)	25	n/a
Andrà et al., 2009	40	Multiple choice, different representations	F	n/a	46	two groups (expertise)	4	SMI, Hi-Speed 1250 (static)	1250	head rest
Andrà et al., 2015	40	Multiple choice, different representations	F	n/a	46	one group	2	not reported (static)	n/a	n/a
Andrzejewska & Stolinska, 2016	70	Multiple choice from different subject areas	D	n/a	48	two groups (expertise)	1	SMI, Hi-Speed 1250 (static)	500	head rest
Atagi et al., 2016	40, 07	Multiple choice, different representations	F	21.1	32, 32	one group	1	SR Research, EyeLink 1000 (static)	500	n/a
Bahnmueller et al., 2016	02	Number comparison	F	21.6	48	two groups (language)	2	SR Research, EyeLink 1000 (static)	n/a	n/a
Beitlich et al., 2014	40	Reading undergraduate illustrated textbook	G	26	5	one group	1	SMI, RED500 (static)	500	free
Beitlich et al., 2015	40	Reading heuristic worked examples	E	16	26	one group	1	SMI, RED500 (static)	n/a	n/a
Boels et al., 2018	80, 40	Histogram and case-value plot interpretation	F	19–27	6	one group	4	Tobii, Pro X2–60 (static)	60	n/a
Bolden et al., 2015	05, 40	Matching representations for multiplication	C	9–10	9	one group	2	Eye Tech, VT2 (static)	14	free
Bremner et al., 2017	06	Keeping track of toy figures	A	0.41	34	one group	1	ASL, Model 5000 (static)	n/a	free

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Brysbaert, 1995	02	Reading two-digit arabic numbers	G	n/a	15, 15	one group	2	Generation V (static)	1000	bite bar, head rest
Bulf et al., 2014	03	Target detection	G	24.4, 24.1	16, 17	one group	1	ASL, Model 6 (static)	120	n/a
Bulf et al., 2016	06, 03	Target detection	A	0.70	36	two groups (experimental)	1	ASL, Model 6 (static)	120	car seat
Canfield & Smith, 1996	06	Target detection	A	0.42	44, 32	two groups (experimental)	1	Cohu (manual video coding)	n/a	sitting on parent's lap
Ceulemans et al., 2014	06	Numerosity comparison	A	0.70, 0.69	25, 26	two groups (experimental)	1	Tobii, T60 (static)	60	n/a
Chen & Yang, 2014	12	Mental rotation	F	21–24	20	one group	2	FaceLAB 4.6 (static)	60	n/a
Chesney et al., 2013	05	Addition equation	F	n/a	64	one group	9	SR Research, EyeLink 2000 (static)	1000	head and chin rest
Cimen & Campbell, 2012	22	Studying material on the subject of number theory	F	22	1	one group	1	Tobii, 1750 (static)	n/a	n/a
Clinton et al., 2016	40	Illustrated mathematical task	C	11.1	57	two groups (prior knowledge)	2	SR Research, EyeLink 1000 (static)	1000	head and chin rest
Cohen & Staub, 2015	80, 33	Bayes' theorem task	F	n/a	30	one group	2	SR Research, EyeLink 1000 (static)	500	n/a
Cohors-Fresenborg et al., 2010	35	Progressive matrices test	E	n/a	57	two groups (achievement)	2	not reported, refers to other study (static)	n/a	n/a
Crisp et al., 2011	35	Deriving a function from a sequential table	F	n/a	16	two groups (education)	1	Tobii, T120 (static)	n/a	n/a
Curtis et al., 2016	05	Simple arithmetic	F	20.5	109	four groups (experimental)	1	SR Research, EyeLink 1000 (static)	500	chin rest

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
De Corte & Verschaffel, 1986a	21	Word problem solving	C	n/a	20	two groups (achievement)	2	Debic 80 (static)	50	head rest
De Corte & Verschaffel, 1986b	21	Word problem solving	C	n/a	6	two groups (achievement)	4	Debic 80 (static)	50	head rest
De Corte et al., 1990	21	One-step compare problems	C	n/a	20	two groups (achievement)	1	Debic 80 (static)	50	head rest
Dewolf et al., 2015	21, 40	Word problems with illustrations	F	20.8	30	three groups (experimental)	2	SR Research, EyeLink II (head-mounted)	250	chin rest
Duijzer et al., 2017	32	Proportional equivalence	C	11.28	38	one group	4	Tobii, X2–30 (static)	n/a	n/a
Epelboim & Suppes, 2001	13	Geometry word problems	G	24.4	3	one group	4	Maryland Revolving-Field monitor (sensor coil)	488	head rest
Espino et al., 2005	34	Syllogistic reasoning	F	n/a	32	one group	1	Forward Technologies (static)	1000	chin rest
Evans et al., 2011	05	Dual-task of syntactic and arithmetic operations	F	n/a	40	one group	1	SR Research, EyeLink II (head-mounted)	n/a	n/a
Fischer et al., 2004	03	Parity	F	17–24	15	one group	1	Dr. Bouis, Oculometer (static)	130	bite bar, head and chin rest
Fleig et al., 2017	80, 33	Pseudo-contingency	F	21.8	56	one group	1	SMI, RED500 (static)	500	n/a
Fry, 1988	12, 21	Two-step word problems, mental rotation test	F	23.1	37	one group	3	Micromeasurements, System 1200 (not reported)	60	n/a
Gandini et al., 2008	01	Approximating dots	G	n/a	30	two groups (age)	1	SMI, iView X (static)	50	free
Ganor-Stern & Weiss, 2016	05	Estimating two-digit multiplication	F	20–26	20, 20	one group	1	SR Research, EyeLink 1000 (static)	n/a	chin rest

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Gielen et al., 1991	01	Number comparison	F	n/a	11, 11	one group	2	Debic 80 (static)	50	head rest
Godau et al., 2014	05	Addition	C	8.6	20	one group	1	SMI, RED250 (static)	250	n/a
Godau et al., 2014	05	Estimation, arithmetic problem	C	8.6	33	two groups (experimental)	2	SMI, RED (static)	250	free
Gomez et al., 2017	04, 50	Number line	C	8.4	40	two groups (DCD, control)	1	Tobii, TX300 (static)	300	n/a
Green et al., 2007	05	Addition of three-digit numbers	H, F	20–24, 68.0	48	two groups (age)	1	SMI, iView X (static)	50	free
Haataja et al., 2018	17, 70	Scaffolding on collaborative geometric problem-solving task	G	30	1	case	4	Own development (mobile)	25	free
Hamada & Iwaki, 2012	05	Mental addition of 12 three-digit numbers	F	n/a	1	case	4	not reported (EOG)	n/a	free
Hannula & Williams, 2016	13	Collaborative geometry problem solving, constructing a specific triangle	D	n/a	1	case	4	Own development (mobile)	n/a	free
Hartmann et al., 2015	05	Simple addition or subtraction	F	23	25	one group	1	SMI, RED (static)	50	n/a
Hartmann, Laubrock, et al., 2016	05	Verbal addition/subtraction with visual presentation of numbers	F	23.2	29	one group	1	SR Research, EyeLink 1000 (static)	n/a	chin rest
Hartmann, Mast, et al., 2016	03	Counting upwards and downwards	F	23.0	18	one group	1	SMI, RED (static)	50	free
Hegarty et al., 1992	21	One-step and two-step arithmetic word problems	F	n/a	32	one group	1	Iscan, RK 426 (static)	60	head rest
Hegarty et al., 1995	21	Arithmetic word problems	F	n/a	38	one group	1	Iscan, RK 426 (static)	60	head rest
Heine et al., 2010	04	Number line	C	8	66	three groups (age)	2	SR Research, EyeLink 1000 (static)	1000	n/a
Hernandez-Sabate et al., 2016	60	Tower defense game	D	14	2	case	4	SMI, RED500 (static)	n/a	free

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Hintz & Meyer, 2015	02	Arithmetic equation: producing a solution vs. predict a word	F	22, 25	24, 24	one group	1	SR Research, EyeLink 1000 (static)	1000	chin rest
Hodds et al., 2014	31	Reading of a mathematical proof	F	n/a	28	experimental vs. control	1	Tobii, T120 (static)	60	n/a
Holmes et al., 2016	03	Blackjack card game decision (simple addition)	F	n/a	30, 28	one group	1	Tobii, ET-17 (static)	30	n/a
Huber et al., 2015	02	Two-digit whole number comparison	F	25.7	24	one group	1	SR Research, EyeLink 1000 (static)	n/a	chin rest
Huber et al., 2014	07	Decimal fraction comparison	F	24.8	22	one group	1	SR Research, EyeLink 1000 (static)	1000	n/a
Huber et al., 2014	02	Two-digit natural number comparison	F	26.9	24	one group	1	SR Research, EyeLink 1000 (static)	1000	chin rest
Huber et al., 2014	07	Fraction comparison	F	24.6	33	one group	1	SR Research, EyeLink 1000 (static)	1000	n/a
Huebner & LeFevre, 2018	05	Simple addition	F	20	40	one group	1	SR Research, EyeLink 1000 (static)	500	chin rest
Hunt et al., 2015	90	Two-digit addition problems	F	23.8	78	one group	3	SR Research, EyeLink II (head-mounted)	500	n/a
Hurst & Cordes, 2016	07	Number comparison, notation whole/fraction/decimal	F	19.4	49	one group	1	SMI, RED (static)	120	free
Inglis & Alcock, 2012	31	Reading a mathematical proof	F, G	n/a	30	two groups (expertise)	2	Tobii, T120 (static)	60	n/a
Inglis & Alcock, 2018	31	Reading a mathematical proof	G	n/a	10	one group	4	Tobii, T120 (static)	60	free

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Ischebeck et al., 2016	07	Fraction comparison	F	24.5	20	one group	1	SR Research, EyeLink II (head-mounted)	500	chin rest
Kiili et al., 2014	60	Mathematical game	C	n/a	8	one group	4	Tobii, T60 (static)	n/a	free
Kim et al., 2018	34	Finding the error in false proof	F	n/a	35	two groups (expertise)	2	Gazepoint, G3 (static)	n/a	n/a
Klein et al., 2014	03, 04	Number line task after addition or subtraction	F	24.8	20	one group	1	SR Research, EyeLink 1000 (static)	1000	head and chin rest
Klein et al., 2014	16	Vector field tasks	F	20.9	41	one group	2	Tobii, X3–120 (static)	120	n/a
Knoblich et al., 2001	70	Matchstick arithmetic	F	18–29	24	one group	1	Dr. Bouis, Oculometer (static)	1000	bite bar
Kohlhase et al., 2017	23	Reading of mathematical expressions	G	n/a	23, 29	two groups (expertise)	4	Tobii, T60 (static)	n/a	n/a
Kohlhase et al., 2018	23	Reading of mathematical textbook	F	n/a	23	one group	4	Tobii, T60 (static)	n/a	n/a
Krichevets et al., 2014	14	Locating points in cartesian plane	F	n/a	44	three groups (expertise)	1	SMI, RED (static)	120	n/a
Lécuyer et al., 2004	06	Possible/impossible teddy bear appearance	A	0.35	12	one group	2	ASL, Model 504 (static)	20	free
Lee & Wu, 2018	13, 22, 40	Reading illustrated geometry text	F	n/a	65	one group	2	SR Research, EyeLink 1000 (static)	1000	chin rest
Li et al., 2010	01	Counting vs. looking	F	n/a	10, 12	one group	1	SR Research, EyeLink II (head-mounted)	250	chin rest
Lin & Lin, 2014a	15	Geometry problem solving	E	17–19	58	one group	1	SR Research, EyeLink 1000 (static)	500	n/a

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Lin & Lin, 2014b	15	Geometry problem solving	E	18	57	one group	1	SR Research, EyeLink 1000 (static)	500	n/a
Lin et al., 2012	11	Reading geometry proof	F	n/a	50	one group	1	SR Research, EyeLink 1000 (static)	1000	chin rest
Loetscher et al., 2008	03	Bisection	G	29	9	one group	1	Skalar (sensor coil)	1000	free
Loetscher et al., 2010	03	Generating random numbers	G	n/a	12	one group	1	Skalar (sensor coil)	1000	free
Macchi Cassia et al., 2016	03	Observing ascending vs. descending pattern	A	1.02	40	two groups (experimental)	1	not reported (manual video coding)	n/a	car seat
Masson et al., 2018	03	Audio multidigit addition or subtraction	F	20–24	19	one group	1	SR Research, EyeLink 1000 (static)	1000	head and chin rest
Merkley & Ansari, 2010	01	Number comparison	F	21.7	22	one group	1	Tobii, T120 (static)	n/a	n/a
Merschmeyer-Brüwer, 2001	12	Counting cubes in 3D shape	C	7.1–11.4	4	cases	4	Omnitrack (static)	n/a	head rest
Meyerhoff et al., 2012	02	Multi-digit number comparison	F	25.8	18	one group	1	SR Research, EyeLink 1000 (static)	1000	chin rest
Michal et al., 2016	40	Extracting magnitude information from bar graph	A	23	16, 26	three groups (age)	2	SR Research, EyeLink 1000 (static)	1000	head rest
Miller Singley & Bunge, 2018	07	Fraction comparison	F	20.3	30	one group	1	Tobii, T120 (static)	120	n/a
Milosavljevic et al., 2011	01	Ultra-rapid magnitude comparison	F	n/a	12, 12, 12	one group	2	SR Research, EyeLink 1000 (static)	1000	head and chin rest
Moeller et al., 2009a	02	Bisection	F	22.2	14	one group	1	Dr. Bouis, Oculometer (static)	333	bite bar, head rest

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Moeller et al., 2009b	02	Two-digit number comparison	F	22.7	10	one group	2	SR Research, EyeLink II (head-mounted)	250	n/a
Moeller et al., 2011a	05	Two-digit addition	E	10.5, 24.4	25	two groups (age)	1	SR Research, EyeLink 1000 (static)	1000	chin rest
Moeller et al., 2011b	05	Validating addition problems	F	22.7	19	one group	2	SR Research, EyeLink 1000 (static)	1000	chin rest
Moeller et al., 2009	01, 50	Dot counting	E	10.5	10	two groups (dyscalculia, control)	2	SR Research, EyeLink 1000 (static)	1000	head rest
Moutsios-Rentzos & Stamatis, 2013	23	Addition and subtraction	C	8–9	40	one group	4	None (observation)	n/a	free
Moutsios-Rentzos & Stamatis, 2015	23	Change and compare problems	C	6	30	one group	4	None (observation)	n/a	free
Muldner & Burleson, 2015	11	Generating multiple geometry proofs	F	n/a	21	two groups (post-hoc)	2	Tobii, TX60 (static)	60	free
Myachykov et al., 2015	03	Target fixation	G	19.8, 22.0	19, 17	one group	2	SR Research, EyeLink 1000 (static)	1000	head and chin rest
Myachykov et al., 2016	03	Fixating a dot during auditory number cue	F	20.2, 22.3	17, 17	one group	2	SR Research, EyeLink 1000 (static)	1000	head and chin rest
Obersteiner & Staudinger, 2018	07	Fraction addition	F	24.3	24	one group	1	SMI, Red500 (static)	500	n/a
Obersteiner & Tumpek, 2016	07	Fraction comparison	F	24.1	22	one group	1	SMI, RED500 (static)	500	free
Obersteiner et al., 2014	07	Fraction comparison	G	26	7	one group	1	SMI, RED500 (static)	500	free
Ögren et al., 2017	16	Vector calculus problems confirm or reject	F	21.5	36	two groups (experimental)	1	SMI, RED250 (static)	250	n/a

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Okamoto & Kuroda, 2014	05	Subtraction puzzle	F	21.1	12	two groups (prior knowledge)	4	NAC, EMR-9 (mobile)	60	free
Olsen et al., 2017	60	Collaborative tutoring system for fraction learning	C	n/a	56	two groups (experimental)	2	SMI, RED250 (static)	250	n/a
Ott et al., 2018	34, 40	Logic task	F	25.8	19	one group	1	Tobii, X2–60 (static)	60	free
Panse et al., 2018	31	Proof comprehension and validation	F	n/a	26	two groups (expertise)	1	Tobii, T120 (static)	120	free
Peters, 2010	23	Questions about conceptual knowledge	F	n/a	2	two groups (expertise)	4	Eye Response Technologies, Gaze Tracker (static)	50	head rest
Plummer et al., 2017	07	Assigning representation to number	F	n/a	40	one group	1	SR Research, EyeLink II (head-mounted)	250	free
Potgieter & Blignaut, 2018	05	Divisibility of 5-digit numbers	C	n/a	78	one group	1	Tobii, X2 Wide (static)	60	n/a
Pressigout et al., 2018	03	Parity	F	22.8, 21.3	32, 15	one group	1	SR Research, EyeLink 1000 (static)	1000	head and chin rest
Price et al., 2017	01	Number comparison	F	19.4	56	one group	1	SR Research, EyeLink 1000 (static)	1000	chin rest
Reike & Schwarz, 2016	01	Number comparison	F	18–33	43	one group	2	SMI, iView X (static)	240	head and chin rest
Reinert et al., 2015	04	Number line	F	23.6	27	one group	1	SR Research, EyeLink 1000 (static)	1000	n/a
Rinaldi et al., 2015	01	Memorization	G	26–37	10	one group	1	EyeSeeCam (mobile)	220	chin rest
Risko et al., 2013	03	Number comparison	F	n/a	42	one group	1	SR Research, EyeLink 1000 (static)	1000	n/a

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Roach et al., 2016	12	Mental rotation	F	20–30	20	three groups (achievement)	2	SR Research, EyeLink 1000 (static)	1000	n/a
Roy et al., 2017	31, 60	Reading mathematical proofs	F	n/a	34	two groups (experimental)	1	Tobii, T120 (static)	60	n/a
Rozek et al., 2014	40	Mathematical problem solving	C, F	n/a	99	five groups (post-hoc)	4	SMI, Hi-Speed 1250 (static)	n/a	n/a
Ruiz Fernández et al., 2011	03	Free choice between two faces	F	22.3	139	one group	1	ASL, Model 504 (static)	n/a	head and chin rest
Sajka & Rosiek, 2015	22	Word problem solving	D	15	11	two groups (achievement)	4	SMI, Hi-Speed 1250 (static)	500	head rest
Salvaggio et al., 2018	03	Audio number comparison	F	21.5, 20.2	19, 20	one group	1	SR Research, EyeLink 1000 (static)	1000	head rest
Schimpf & Spannagel, 2011	13, 60	Target detection in user interface	F	n/a	51	three groups	2	LC Technologies (static)	120	n/a
Schindler & Lilienthal, 2018	02, 40, 50	Abacus counting	D	10.9	11	two groups (math. Learning difficulties, control)	4	Tobii, Pro Glasses 2 (mobile)	50	free
Schindler et al., 2016	11	Generating multiple geometry proofs	E	18	1	case	4	Pupil Labs, Pupil Pro (mobile)	n/a	free
Schleifer & Landerl, 2011	01	Dot counting	D, E	8–26	60	one group	1	SR Research, EyeLink 1000 (static)	1000	n/a
Schneider et al., 2012	05	Addition and multiplication	G	23–24	13, 13, 9	one group	1	SR Research, EyeLink 2000 (static)	2000	n/a
Schneider et al., 2008	04	Number line	C	8.0	66	three groups (age)	1	SR Research, EyeLink 1000 (static)	1000	n/a

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Schwarz & Keus, 2004	03	Parity	F	22, 30	16, 16	one group	1	SMI, EyeLink-HiSpeed 2D (static)	250	chin rest
Shayan et al., 2017	32	Proportional equivalence	C	11.3, 13.4	30, 46	one group	4	Tobii, X2–60 (static)	n/a	free
Shvarts, 2018a	13	Collaborative geometry task	F	n/a	8	one group	4	Pupil Labs (head-mounted)	n/a	free
Shvarts, 2018b	14	Cartesian plane	C	n/a	10	one group	4	SMI RED and Eye Tribe (mobile)	120	free
Sophian & Crosby, 2008	01	Object counting	F	n/a	33	one group	1	ASL, Eye Movement Monitor (static)	n/a	n/a
Stolinska et al., 2014	22	Text reading	F	n/a	86	two groups (expertise)	2	SMI, Hi-Speed 1250 (static)	500	chin rest
Strohmaier & Reiss, 2018	22	PISA-items	F	n/a	118	one group	1	SMI, RED500 (static)	n/a	n/a
Strohmaier et al., 2017	22, 90	PISA-items	F	n/a	55	one group	2	SMI, RED500 (static)	500	n/a
Sullivan et al., 2011	04	Number line	G	n/a	16	two groups (experimental)	1	SR Research, EyeLink 1000 (static)	n/a	head and chin rest
Suppes et al., 1982	05	Addition and subtraction	D, G	11–14, n/a	6	cases	9	PERSEUS (static)	n/a	bite bar
Suppes et al., 1983	05	Addition and subtraction	D, G	n/a	5	cases	9	PERSEUS (static)	n/a	bite bar
Susac et al., 2014	05	Rearranging equations	F	20–26	40	one group	1	SMI, Hi-Speed 500 (static)	500	head rest
Terry, 1921	22	Word problem solving	F	n/a	n/a	one group	4	no manufacturer (static)	n/a	bite bar, head rest
van der Schoot et al., 2009	21	Two-step compare problems	C	11.5	40	two groups (achievement)	1	SR Research, EyeLink II (head-mounted)	250	n/a

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
van der Weijden et al., 2018	04, 50	Number line (bounded and unbounded)	F	22.5	16	two groups (dyscalculia, control)	4	Tobii, T60 (static)	60	n/a
van Oeffelen & Vos, 1984a	01	Counting	F	n/a	7	one group	4	Whittaker, 1998-S EVM (static)	50	head rest
van Oeffelen & Vos, 1984b	01	Dot counting	B	5.6	6	one group	4	Whittaker, 1998-S EVM (static)	50	n/a
van Viersen et al., 2013	04, 50	Number line	C	9.1	11	case (dyscalculia) vs. control	4	Tobii, T60 (static)	n/a	n/a
van't Noordende et al., 2016	04, 50	Number line	C	10.9	28	two groups (math. learning difficulties, control)	1	Tobii, T60 (static)	60	n/a
Verdine et al., 2017	17	Target detection	B	3.6	79	two groups (SES)	2	Tobii, T60XL (static)	60	n/a
Verschaffel et al., 1992	21	One-step or two-step compare problems	F	n/a	19, 15, 20	one group	1	Debic 80 (static)	50	head rest
Verschaffel et al., 1994	05	Addition and subtraction word problems	C	8.5	23	two groups (achievement)	1	Debic 80 (static)	50	head rest
Wall et al., 2015	07	Fraction comparison	F	20	14	one group	4	Tobii, T60XL (static)	n/a	n/a
Wang et al., 2014	12	Geometry test, mental rotation, spatial perception and visualization	C	11.9	16	two groups (expertise)	4	SR Research, EyeLink 2000 (static)	n/a	head rest
Watson et al., 2005	01	Visual search, enumeration	F, G	18–26, 57–7-9	24, 20	two groups (age)	1	SMI, RED (static)	50	free
Watson et al., 2007	01	Counting	F	21.9, 20.0	7, 10	one group	1	SR Research, EyeLink II (head-mounted)	250	free
Werner & Raab, 2014	70	Water-jar problem	F	23.7	33	two groups (experimental)	2	Tobii, Glasses (mobile)	n/a	n/a
Winoto et al., 2017	05, 50	Addition	C	7.5	1	case	4	Tobii, X2–60 (static)	n/a	n/a

Table 3 (continued)

	Domain and topic	Task type, stimulus	Age group	Mean age/age range	Sample size	Experimental groups (grouping variable)	Statistical design	Manufacturer, model (type)	Sampling rate	Movement restriction
Yağmur & Çakır, 2016	60	Working with Geogebra	F	26.5	10	one group	2	Tobii, X2–60 (static)	60	free
Zhou et al., 2012	05	Single digit addition and multiplication	F	23.2	33	two groups (experimental)	1	SCAN system (EOG)	1000	free
Zhu et al., 2018	03	Addition and subtraction	F	20.4	26, 26	one group	1	SR Research, EyeLink (static)	500	chin rest

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
Abrahamson et al., 2016	n/a	n/a	SP	25	n/a	n/a	Finger movements, videography, interviews (rel.)	4
Abreu-Mendoza & Arias-Trejo, 2015	5-point (n/a)	Tobii fixation filter (n/a)	DLL	31	n/a	n/a	n/a	4
Alqassab et al., 2018	yes (n/a)	n/a	FD, IC	13	1.9	n/a	Proof comprehension and peer feedback type, accuracy (ind.)	4
Andrà et al., 2009	13-point (n/a)	n/a	FD	12	n/a	n/a	n/a	1
Andrà et al., 2015	n/a	n/a	FD, FC, DT, IC	13	n/a	n/a	n/a	4
Andrzejewska & Stolinska, 2016	yes (n/a)	BeGaze (n/a)	BD, BFQ, BC, FD, FFQ	31	7.7	n/a	Self-reports of accuracy, subjective difficulty (rel.)	4
Atagi et al., 2016	5-point (n/a)	n/a	FD, FC	12	8.6	n/a	Accuracy, response time, interview (ind.)	4
Bahnmueller et al., 2016	9-point (n/a)	n/a	DT	14	n/a	n/a	Response time (ind.)	4
Beitlich et al., 2014	9-point (n/a)	n/a	FD	12	16.7	n/a	n/a	1
Beitlich et al., 2015	yes (n/a)	n/a	FD, IC	12	n/a	n/a	Reports of perception (rel.)	1

Table 3 (continued)

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
Boels et al., 2018	5-point (n/a)	manual (n/a)	SP, HM	12	n/a	n/a	Cued retrospective interview (rel.)	1
Bolden et al., 2015	yes (n/a)	n/a	FD, SP	14	n/a	n/a	Attainment, accuracy (rel.)	4
Bremner et al., 2017	yes (n/a)	ASL Eyenal (n/a)	FD	27	45.2	n/a	n/a	4
Brysbaert, 1995	yes (n/a)	n/a (50 ms)	FD	31	n/a	n/a	Two additional experiments (ind.)	4
Bulf et al., 2014	9-point (n/a)	n/a	TFF	26	n/a	16	n/a	4
Bulf et al., 2016	3-point (n/a)	n/a	TFF	26	25.0	n/a	Accuracy (ind.)	4
Canfield & Smith, 1996	n/a	manual (n/a)	SC	27	7.3	26	n/a	4
Ceulemans et al., 2014	5-point (n/a)	Tobii fixation filter (35px)	FD	31	10.5	n/a	n/a	4
Chen & Yang, 2014	yes (1°)	GazeTracker (100 ms)	FD, FDA, RC	31	n/a	n/a	Accuracy, performance, interview (rel.)	4
Chesney et al., 2013	n/a	I-VT (0.2°, 9500°/s^2, 30°/s)	IC	13	n/a	n/a	Strategy use (rel.)	4
Cimen & Campbell, 2012	n/a	n/a	BF	50	n/a	n/a	Heart rate, think aloud, facial expressions, body movements, self-reports (rel.)	1
Clinton et al., 2016	yes (n/a)	n/a	FD, FDA	31	8.1	n/a	n/a	2
Cohen & Staub, 2015	9-point (1°)	n/a	FD	12	n/a	0.2	Accuracy (rel.)	4
Cohors-Fresenborg et al., 2010	n/a	QuaDiPF-Eye (n/a)	FD, SP	14, 50	n/a	n/a	Metacognitive behavior (rel.)	4
Crisp et al., 2011	n/a	n/a	IC	13	n/a	n/a	n/a	1
Curtis et al., 2016	9-point (n/a)	I-DT (100 ms, 0.15°)	FFP, FD, FC	12, 24	n/a	5	Accuracy, response time (ind.)	4
De Corte & Verschaffel, 1986a	n/a	manual (n/a)	FD, SP	14	9.1	n/a	Achievement (rel.)	1
De Corte & Verschaffel, 1986b	n/a	manual (n/a)	SP	14	n/a	n/a	Achievement (rel.)	1

Table 3 (continued)

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
De Corte et al., 1990	n/a	I-DT (100 ms, 1°)	FD	12	n/a	n/a	Response time, performance (rel.)	3
Dewolf et al., 2015	9-point (n/a)	n/a	FC	11	n/a	0.6	Perceived correctness (ind.), second experiment (ind.)	4
Duijzer et al., 2017	yes (n/a)	Tobii fixation filter (5 points, 25px)	FC, FDA, SP	25	15.6	n/a	Think aloud, interview (ind.)	4
Epelboim & Suppes, 2001	9-point (n/a)	manual (n/a)	FD	32	n/a	n/a	Verbal protocol (rel.)	4
Espino et al., 2005	yes (n/a)	n/a	DT	31	n/a	n/a	Accuracy (ind.)	4
Evans et al., 2011	n/a	n/a	DT	12	n/a	n/a	Accuracy (ind.)	4
Fischer et al., 2004	yes (0.5°)	n/a	FD, SL	26	n/a	n/a	n/a	4
Fleig et al., 2017	n/a	I-VT (12 ms, 40°/s)	FD	12	6.7	n/a	Performance (rel.), second experiment (ind.)	4
Fry, 1988	n/a	n/a (50 ms)	FD	12	n/a	n/a	Spatial abilities (rel.)	1
Gandini et al., 2008	9-point (n/a)	I-DT (n/a)	FD, FC, SL	13	n/a	n/a	Second experiment (ind.)	4
Ganor-Stern & Weiss, 2016	5-point (2°)	n/a	FD, FC, FFP	12	4.8	n/a	Accuracy, response time, strategy use (ind.)	4
Gielen et al., 1991	yes (n/a)	I-DT (100 ms, 1°/0.75°)	FFD, FD	31	n/a	n/a	n/a	4
Godau et al., 2014	5-point (n/a)	n/a	FC	13	n/a	n/a	Second experiment (ind.)	4
Godau et al., 2014	5-point (n/a)	n/a	SL	13	2.9	n/a	Response time (ind.)	3
Gomez et al., 2017	n/a	I-VT (30°/s)	FD, FC, FDA, SL	13	n/a	n/a	Performance, disorder score (rel.), accuracy, reaction time (ind.)	4
Green et al., 2007	9-point (n/a)	I-DT (n/a)	FD	13	n/a	n/a	Self-reports (rel.), Response time (ind.)	4
Haataja et al., 2018	n/a	n/a (80 ms)	DT	12	n/a	n/a	n/a	1
Hamada & Iwaki, 2012	n/a	n/a	FDA, SDA	21	n/a	n/a	Magnetoencephalogram (MEG, rel.)	3
Hannula & Williams, 2016	manual (n/a)	n/a	SP	14	n/a	n/a	Body language (rel.)	1
Hartmann et al., 2015	n/a	I-DT (80 ms, 100px)	FFP	21	n/a	7.3	Response time (ind.)	4

Table 3 (continued)

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
Hartmann, Laubrock, et al., 2016	9-point (n/a)	EyeLink data viewer (cognitive configuration)	FD, TFF, RFC	21	3.3	n/a	Accuracy, response time (ind.)	4
Hartmann, Mast, et al., 2016	5-point (0.8°)	BeGaze (80 ms, 100px)	FP	22	10.0	n/a	n/a	4
Hegarty et al., 1992	n/a	manual (n/a)	FC, RFC	13	15.8	n/a	Accuracy, response time, interview (rel.)	4
Hegarty et al., 1995	yes (n/a)	manual (n/a)	RFC	13	n/a	n/a	Accuracy (rel.)	4
Heine et al., 2010	n/a	n/a	FP, FC, FD	21	n/a	5.6	Accuracy (rel.)	4
Hernandez-Sabate et al., 2016	yes (n/a)	BeGaze (n/a)	FP	13	n/a	n/a	n/a	1
Hintz & Meyer, 2015	yes (n/a)	EyeLink software (n/a)	FD, TFF	21	2.0	n/a	n/a	4
Hodds et al., 2014	9-point (n/a)	n/a	FDA, IC	13, 31	12.5	n/a	n/a	4
Holmes et al., 2016	5-point (n/a)	n/a	FP	21	n/a	2.3	n/a	4
Huber et al., 2015	9-point (n/a)	n/a	FC	31	n/a	4.7	Response time (ind.)	4
Huber et al., 2014	9-point (n/a)	n/a	DT	12	12.0	n/a	Accuracy, response time (ind.)	4
Huber et al., 2014	9-point (n/a)	n/a	FD	31	n/a	n/a	Accuracy, response time (ind.)	4
Huber et al., 2014	9-point (n/a)	n/a	FC, FFP	31	8.3	n/a	Accuracy, response time (ind.)	4
Huebner & LeFevre, 2018	9-point (n/a)	I-DT (100 ms, 0.15°)	FD, FC	13	n/a	13	Response time (rel.)	4
Hunt et al., 2015	yes (n/a)	n/a	FD, FC, RC, SC	12	n/a	n/a	Accuracy, math anxiety (rel.), response time (ind.)	3
Hurst & Cordes, 2016	4-point (1°)	own (80 ms, in AOI)	FD	21, 31	21.0	n/a	Accuracy, response time (ind.)	4
Inglis & Alcock, 2012	9-point (n/a)	Tobii fixation filter (n/a)	FD, FDA, IC, SL	13	n/a	n/a	Validity judgment (ind.)	4

Table 3 (continued)

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
Inglis & Alcock, 2018	9-point (n/a)	n/a	FP	14	n/a	n/a	n/a	1
Ischebeck et al., 2016	9-point (0.3°)	I-VT (9500°/s^2, 35°/s)	FC, FP, FFP, LFP	31	n/a	12	Accuracy, response time (ind.)	4
Kiili et al., 2014	yes (n/a)	n/a	FC, HM	11	n/a	n/a	Cued retrospective interview (rel.)	4
Kim et al., 2018	9-point (n/a)	Gazepoint (n/a)	FC, FDA, DT	14	7.9	n/a	Accuracy (ind.)	1
Klein et al., 2014	9-point (n/a)	n/a	FFP, LFP	21	13.0	n/a	Accuracy, response time (ind.)	4
Klein et al., 2014	9-point (n/a)	I-VT (8500°/s^2, 30°/s)	FD, FC, SL, SD	13	n/a	n/a	Accuracy and interview (rel.)	4
Knoblich et al., 2001	yes (n/a)	I-DT (5 ms, 1/9°)	FD, FDA	12	n/a	n/a	Performance (rel.)	4
Kohlhase et al., 2017	n/a	n/a	SP, HM	14	n/a	n/a	Think aloud, questionnaire (ind.)	1
Kohlhase et al., 2018	n/a	n/a (60 ms)	FC, VC	14	n/a	n/a	Think aloud (rel.)	1
Krichevets et al., 2014	9-point (0.5°)	I-VT (120°/s)	SD, FC, SL	21	n/a	n/a	Response time (ind.)	4
Lécuyer et al., 2004	2-point (n/a)	n/a	FD	27	76.0	n/a	Second experiment (ind.)	4
Lee & Wu, 2018	yes (n/a)	n/a	FD, IC, FC, SP	14	4.4	8.8	Accuracy, response time (ind.)	4
Li et al., 2010	9-point (0.5°)	n/a	FC, RFC	13	n/a	n/a	Accuracy, response time (ind.)	4
Lin & Lin, 2014a	yes (n/a)	n/a	FD, FC, RFC	31	9.4	n/a	Cognitive load (rel.), perceived difficulty, second experiment (ind.)	4
Lin & Lin, 2014b	yes (n/a)	EyeLink data viewer (n/a)	FFP, FFD, FD, FC, LFD	90	9.5	n/a	Accuracy, perceived difficulty, cognitive load (rel.)	4
Lin et al., 2012	yes (n/a)	n/a	FD, SC	12	23.1	n/a	n/a	1
Loetscher et al., 2008	n/a	n/a	FP	21	n/a	n/a	n/a	3
Loetscher et al., 2010	n/a	n/a	FP	21	n/a	n/a	n/a	3

Table 3 (continued)

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
Macchi Cassia et al., 2016	n/a	manual (n/a)	FD	27	31.0	n/a	n/a	4
Masson et al., 2018	9-point (n/a)	n/a	FP	22	n/a	n/a	Response time (rel.)	4
Merkley & Ansari, 2010	yes (n/a)	I-DT (50 ms, in AOI)	FD, FC, IC	13	12.0	n/a	Accuracy, response time (rel.)	3
Merschmeyer-Brüwer, 2001	n/a	Vision (n/a)	FDA, FD	31	n/a	n/a	Accuracy, response time (rel.)	1
Meyerhoff et al., 2012	9-point (n/a)	n/a	FC, IC	13	n/a	n/a	Response time (ind.)	4
Michal et al., 2016	9-point (n/a)	n/a	SL, SD	13	10.6	n/a	Response time (rel.)	4
Miller Singley & Bunge, 2018	9-point (n/a)	n/a	IC	13	21.1	n/a	Accuracy, response time (ind.)	4
Milosavljevic et al., 2011	n/a	n/a	TFF	26	n/a	n/a	Accuracy (rel.)	4
Moeller et al., 2009a	manual (n/a)	n/a	FD	31	n/a	n/a	Response time (ind.)	4
Moeller et al., 2009b	9-point (n/a)	n/a	FC	12	n/a	n/a	Response time (ind.)	4
Moeller et al., 2011a	9-point (n/a)	n/a	DT	12	n/a	n/a	Accuracy, response time (ind.)	4
Moeller et al., 2011b	9-point (n/a)	n/a	FFD, DT, IC	31	5.0	n/a	Accuracy, response time (ind.)	4
Moeller et al., 2009	9-point (n/a)	n/a	FC, FDA	13, 31	n/a	n/a	Response time (ind.)	4
Moutsios-Rentzos & Stamatis, 2013	n/a	n/a	FP	23	n/a	n/a	Response time (rel.)	4
Moutsios-Rentzos & Stamatis, 2015	n/a	n/a	FP	23	n/a	n/a	Accuracy, response time (ind.)	4

Table 3 (continued)

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
Muldner & Burleson, 2015	9-point (n/a)	n/a	FC, FD, FDA, SL, SV, PS	31	n/a	n/a	Skin conductance and EEG (rel.)	4
Myachykov et al., 2015	9-point (n/a)	I-VT (50 ms, 3°)	TFF, FP	26	n/a	n/a	n/a	4
Myachykov et al., 2016	9-point (n/a)	I-VT (50 ms, 3°)	TFF, FP	22	n/a	n/a	n/a	4
Obersteiner & Staudinger, 2018	5-point (n/a)	n/a	FC, SC, IC	13	14.3	n/a	Strategy self-reports, accuracy, response times (ind.)	4
Obersteiner & Tumpek, 2016	9-point (n/a)	n/a	FC, IC	13	12.0	n/a	Response time (ind.)	4
Obersteiner et al., 2014	9-point (n/a)	n/a	FD	13	12.5	n/a	n/a	1
Ögren et al., 2017	5-point (0.5°)	BeGaze (n/a)	FD, IC	13	n/a	n/a	Accuracy (rel.), think aloud (ind.)	4
Okamoto & Kuroda, 2014	9-point (n/a)	manual (n/a)	FC	14	n/a	n/a	Strategy knowledge (rel.)	3
Olsen et al., 2017	n/a	n/a	JA	40	n/a	n/a	Achievement (rel.)	2
Ott et al., 2018	9-point (n/a)	Tobii fixation filter (n/a)	FD, FC, DT, IC, LFP	12	9.5	n/a	Accuracy, time on task (ind.)	4
Panse et al., 2018	yes (n/a)	n/a	FD, FDA, PS, RC, TFF, IC	13	18.8	n/a	n/a	4
Peters, 2010	yes (n/a)	n/a (10 ms)	FD, FC	14	n/a	n/a	n/a	1
Plummer et al., 2017	9-point (n/a)	n/a	FC, FP, RFC	14	n/a	1.2	Accuracy (ind.)	4
Potgieter & Blignaut, 2018	9-point (n/a)	Tobii fixation filter (n/a)	FD	12	n/a	1.8	Accuracy, strategy use (rel.)	4
Pressigout et al., 2018	9-point (n/a)	n/a	TFF	26	2.1	2.2	Manual repsonse (rel.)	4
Price et al., 2017	n/a	n/a	FC, DT, FFP	12, 24	23.3	n/a	Accuracy, response time (rel.)	4
Reike & Schwarz, 2016	n/a	I-VT (75°/s)	TFF, SL	26	n/a	4	n/a	4

Table 3 (continued)

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
Reinert et al., 2015	yes (n/a)	n/a	FC, FFP	25	n/a	n/a	Accuracy (ind.)	3
Rinaldi et al., 2015	5-point (n/a)	n/a	FP	13	n/a	n/a	Response time (ind.)	4
Risko et al., 2013	9-point (n/a)	n/a	TFF, FFP	24	n/a	n/a	Response time (ind.)	4
Roach et al., 2016	n/a	n/a	FDA, FC, FP	31	13.0	n/a	Response time (rel.)	4
Roy et al., 2017	yes (n/a)	n/a	FD, FDA	12, 31	n/a	n/a	Second experiment (ind.)	4
Rozek et al., 2014	n/a	BeGaze (n/a)	FDA, FFD, FC, RC, SP, HM	11	n/a	n/a	Stategy use (rel.)	4
Ruiz Fernández et al., 2011	n/a	n/a	FFP	11	7.3	n/a	n/a	3
Sajka & Rosiek, 2015	yes (0.5°)	BeGaze (n/a)	SP, HM	14	n/a	n/a	n/a	1
Salvaggio et al., 2018	9-point (n/a)	n/a	FP	21	2.5	12.8	Response time (ind.)	4
Schimpf & Spannagel, 2011	n/a	n/a	TFF	11	27.1	n/a	Second experiment (ind.)	4
Schindler & Lilienthal, 2018	n/a	n/a	SP	14	45.0	n/a	Think aloud (rel.)	1
Schindler et al., 2016	yes (n/a)	n/a	SP	14	n/a	n/a	Written solution, video recording (rel.)	1
Schleifer & Landerl, 2011	9-point (0.5°)	n/a	SF	13	n/a	n/a	Response time (ind.)	4
Schneider et al., 2012	n/a	n/a	SP	14	n/a	n/a	Response time (rel.)	4
Schneider et al., 2008	n/a	n/a	FC	12	n/a	4.6	Accuracy (rel.)	4
Schwarz & Keus, 2004	yes (n/a)	I-VT (0.1°, 8000°/s^2, 30°/s)	TFF	26	n/a	25	Accuracy, response time (rel.)	4
Shayan et al., 2017	n/a	n/a	FP, SD	25	n/a	n/a	Interview (rel.)	2
Shvarts, 2018a	n/a	n/a	JA	40	n/a	n/a	Dialog transcript (rel.)	1
Shvarts, 2018b	yes (n/a)	n/a	JA	40	n/a	n/a	Gestures, audio (rel.)	1

Table 3 (continued)

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
Sophian & Crosby, 2008	yes (n/a)	n/a	FC	12	2.9	n/a	Accuracy (ind.)	4
Stolinska et al., 2014	yes (n/a)	BeGaze (n/a)	SC, SL, SV, SDA	13	n/a	n/a	n/a	1
Strohmaier & Reiss, 2018	n/a	n/a	FDA, SC, RC, DT	13, 31	n/a	n/a	n/a	1
Strohmaier et al., 2017	n/a	I-DT (100 ms, 2.4°)	FDA, FD, RC, SC, FC	13, 31	n/a	n/a	Self-concept (rel.)	1
Sullivan et al., 2011	9-point (n/a)	n/a	FD, FC	12	27.3	1.3	Accuracy (rel.)	4
Suppes et al., 1982	121-point (n/a)	n/a	FD, IC	13	n/a	n/a	n/a	2
Suppes et al., 1983	121-point (n/a)	n/a	FD, IC	13	n/a	n/a	n/a	4
Susac et al., 2014	13-point (n/a)	n/a	FD, FC	14	n/a	n/a	Accuracy, response time, interview about metacognition (rel.)	4
Terry, 1921	n/a	n/a	FC	14	n/a	n/a	n/a	4
van der Schoot et al., 2009	yes (1°)	I-VT (0.1°, 8500°/s^2, 30°/s)	RFC, FD	12	n/a	n/a	Accuracy, reading comprehension, working memory (rel.)	4
van der Weijden et al., 2018	9-point (n/a)	I-VT (Tobii default)	FC	13	n/a	3.1	Cued retrospective interview (rel.), accuracy (ind.)	4
van Oeffelen & Vos, 1984a	9-point (n/a)	n/a	FD, SC, SDA, BD	13	n/a	n/a	Response time (ind.)	4
van Oeffelen & Vos, 1984b	9-point (n/a)	n/a	FC, SC, CV, BD, FD, SD	14, 31	n/a	n/a	Response time (ind.)	4
van Viersen et al., 2013	n/a	n/a	SP	14	n/a	0.5	Accuracy, working memory, number sense (ind.)	4
van't Noordende et al., 2016	9-point (n/a)	I-DT (100 ms, 0.5 cm × 0.5 cm)	FC	13	n/a	1.84	Accuracy (ind.)	4

Table 3 (continued)

	Calibration (threshold)	Event detection algorithm or software (thresholds)	Measures	Interpretation of eye movements	Participants excluded (percent)	Data excluded (percent)	Other methods	Publication type
Verdine et al., 2017	5-point (n/a)	n/a	TFF	32	22.5	n/a	SES, spatial abilities (rel.)	4
Verschaffel et al., 1992	n/a	n/a (100 ms)	FD	13	n/a	2	Accuracy, response time (ind.)	4
Verschaffel et al., 1994	n/a	I-DT (n/a)	LFP	13	n/a	n/a	Accuracy, responsr time, retrospective reports (rel.)	2
Wall et al., 2015	yes (n/a)	n/a	FC	12	n/a	n/a	Confidence rating (ind.)	1
Wang et al., 2014	n/a	n/a	SP, HM	14	n/a	n/a	Achievement (ind.)	4
Watson et al., 2005	9-point (n/a)	I-VT (45°/s, fix. Dur. 120 ms)	FFQ, RFC	32	6.4	5	Accuracy, response time (ind.)	4
Watson et al., 2007	9-point (n/a)	EyeLink data viewer (n/a)	SF, FD, SD	22	5.6	5	Response time (ind.)	4
Werner & Raab, 2014	n/a	n/a	FC	21	17.5	n/a	Stategy use (ind.)	4
Winoto et al., 2017	n/a	n/a	SP, HM	11	50.0	n/a	n/a	1
Yağmur & Çakır, 2016	n/a	Tobii fixation filter (n/a)	FD, FC, FDA	90	n/a	n/a	Visual coding (rel.); usability questionnaire (ind.)	1
Zhou et al., 2012	n/a	n/a	FP	13	2.9	6.5	n/a	4
Zhu et al., 2018	yes (n/a)	n/a	TFF	26	n/a	n/a	Accuracy, response time (ind.)	4

Domain and topic: (0X—numbers and arithmetic (01—perception and mental representation of single digit and non-symbolic numbers, number words, counting; 02—perception and mental representation of multi-digit numbers; 03—spatial-numerical associations; 04—number line estimation task; 05—basic arithmetic; 06—number perception and magnitude in infants; 07—rational numbers and proportionality); 1X—geometry, shape, and form (11—geometric proof; 12—mental rotation; 13—construction; 14—Cartesian plane; 15—calculation; 16—vector fields; 17—shapes); 2X—reading and word problem solving (21—prototype word problems; 22—complex mathematical text or word problems; 23—mathematical parsing); 3X—reasoning and proof (31—reading and comprehension of proofs; 32—proportional reasoning; 33—probabilistic reasoning; 34—logic; 35—functional thinking); 40—use of representations; 50—learning difficulties; 60—computer-supported learning; 70—mathematical problem solving; 80—statistics; 90—affective variables

Age group: A—infants; B—kindergarten; C—primary education (grades 1–-6); D—lower secondary education (grades 7–-9); E—higher secondary education (grades 10–-13); F—tertiary education; G—other adults; H—seniors

Statistical design: 1—mixed or within-subject design; 2—between-subject design; 3—correlational; 4—descriptive; 9—other

Measures: BC—blink count; BD—blink duration; BF—blink frequency; DLL—difference in longest look; DT—dwell time, reading time; FC—fixation count; FD—total fixation duration; FDA—average fixation duration; FFD—first fixation duration; FFP—first fixation position; FFQ—fixation frequency; FP—fixation position; HM—heat map; IC—inter-scanning count, transitions; JA—joint visual attention; LFP—last fixation position; LFD—last fixation duration; PS—pupil size; RC—regressive saccades count; RFC—revisiting fixations count; SC—saccade count; SD—saccade direction; SDA—average saccade duration; SF—saccade frequency; SL—saccade length; SP—scan path pattern; SV—saccade velocity; TFF—time to first fixation, fixation latency, saccade latency; VC—visit count

Interpretation of eye movements: 1X—visual focus and overt attention, eye mind assumption (11—attention on single object; 12—compare attention on 2 or more objects; 13—order of attention (quantitative); 14—order of attention (qualitative)); 2X—mental representation and covert attention (21—visual mental representation; 22—motoric mental representation; 23—brain hemisphericity; 24—areas of covert attention; 25—attentional anchors; 26—reaction time; 27—anticipation); 3X—cognitive effort and resources (31—information extraction; 32—memory capacity); 40—joint attention; 50—metacognitive control; 90—explorative

Other methods: rel.—in relation to eye tracking; ind.—independent of eye tracking

Publication type: 1—proceedings paper; 2—book chapter; 3—short paper; 4—full paper

References

Note: Papers marked with an asterisk (*) are those selected for the review.

*Abrahamson, D., Shayan, S., Bakker, A., & Van der Schaaf, M. (2016). Eye-tracking Piaget: Capturing the emergence of attentional anchorrefers in the coordination of proportional motor action. *Human Development, 58*(4–5), 218–224. https://doi.org/10.1159/000443153

*Abreu-Mendoza, R. A., & Arias-Trejo, N. (2015). Numerical and area comparison abilities in Down syndrome. *Research in Developmental Disabilities, 41–42*, 58–65. https://doi.org/10.1016/j.ridd.2015.05.008

*Alqassab, M., Strijbos, J.-W., & Ufer, S. (2018). The impact of peer solution quality on peer-feedback provision on geometry proofs: Evidence from eye-movement analysis. *Learning and Instruction, 58*, 182–192. https://doi.org/10.1016/j.learninstruc.2018.07.003

Anderson, J. R., Bothell, D., & Douglass, S. (2004). Eye movements do not reflect retrieval processes: Limits of the eye-mind hypothesis. *Psychological Science*, *15*(4), 225–231. https://doi.org/10.1111/j.0956-7976.2004.00656.x

*Andrà, C., Arzarello, F., Ferrara, F., Holmqvist, K., Lindstrom, P., Robutti, O., & Sabena, C. (2009). How students read mathematical representations: An eye tracking study. In M. Kaldrimidou & H. Sakonidis (Eds.), *Proceedings of the 33rd Conference of the International Group for the Psychology of Mathematics Education* (Vol. 2, pp. 49–56). Thessaloniki, Greece: PME.

*Andrà, C., Lindström, P., Arzarello, F., Holmqvist, K., Robutti, O., & Sabena, C. (2015). Reading mathematics representations: An eye tracking study. *International Journal of Science and Mathematics Education, 13*, 237–259. https://doi.org/10.1007/s10763-013-9484-y

*Andrzejewska, M., & Stolinska, A. (2016). Comparing the difficulty of tasks using eye tracking combined with subjective and behavioural criteria. *Journal of Eye Movement Research, 9*(3), 1–16. https://doi.org/10.16910/jemr.9.3.3

*Atagi, N., DeWolf, M., Stigler, J. W., & Johnson, S. P. (2016). The role of visual representations in college students' understanding of mathematical notation. *Journal of Experimental Psychology-Applied, 22*(3), 295–304. https://doi.org/10.1037/xap0000090

*Bahnmueller, J., Huber, S., Nuerk, H. C., Gobel, S. M., & Moeller, K. (2016). Processing multi-digit numbers: A translingual eye-tracking study. *Psychological Research-Psychologische Forschung, 80*(3), 422–433. https://doi.org/10.1007/s00426-015-0729-y

Banks, G. C., Field, J. G., Oswald, F. L., O'Boyle, E. H., Landis, R. S., Rupp, D. E., & Rogelberg, S. G. (2019). Answers to 18 questions about open science practices. *Journal of Buisness and Psychology*, *3*(4), 257–270. https://doi.org/10.1007/s10869-018-9547-8

Barmby, P., Andrà, C., Gomez, D., Obersteiner, A., & Shvarts, A. (2014). The use of eye-tracking technology in mathematics education research. In P. Liljedahl, C. Nicol, S. Oesterle, & D. Allan (Eds.), *Proceedings of the 38th Conference of the International Group for the Psychology of Mathematics Education and the 36th Conference of the North American Chapter of the Psychology of Mathematics Education* (vol. 1, p. 253). Vancouver, Canada: PME.

*Beitlich, J. T., Obersteiner, A., Moll, G., Mora Ruano, J. G., Pan, J., Reinhold, S., & Reiss, K. (2014). The role of pictures in reading mathematical proofs: An eye movement study. In P. Liljedahl, C. Nicol, S. Oesterle, & D. Allan (Eds.), *Proceedings of the 38th Conference of the International Group for the Psychology of Mathematics Education and the 36th Conference of the North American Chapter of the Psychology of Mathematics Education* (Vol. 2, pp. 121–128). Vancouver, Canada: PME.

*Beitlich, J. T., Obersteiner, A., & Reiss, K. (2015). How do secondary school students make use of different representation formats in heuristic worked examples? An analysis of eye movements. In K. Beswick, T. Muir, & J. Wells (Eds.), *Proceedings of the 39th Conference of the International Group for the Psychology of Mathematics Education* (Vol. 2, pp. 97–104). Hobart, Australia: PME.

Blignaut, P. (2009). Fixation identification: The optimum threshold for a dispersion algorithm. *Attention, Perception & Psychophysics*, *71*(4), 881–895. https://doi.org/10.3758/APP.71.4.881

*Boels, L., Bakker, A., & Drijvers, P. (2019). Eye-tracking secondary school students' strategies when interpreting statistical graphs. In M. Graven, A. Venkat, A. Essien, & P. Vale (Eds.), *Proceedings of the 43rd Conference of the International Group for the Psychology of Mathematics Education* (Vol. 2, pp. 113–120). Pretoria, South-Africa: PME.

Boels, L., Ebbes, R., Bakker, A., Van Dooren, W., & Drijvers, P. (2018). Revealing conceptual difficulties when interpreting histograms: An eye tracking study. In M. A. Sorto, A. White, & L. Guyot (Eds.), *Looking back, looking forward. Proceedings of the Tenth International Conference on Teaching Statistics (ICOTS10, July, 2018)*. Kyoto, Japan: International statistical institute.

*Bolden, D., Barmby, P., Raine, S., & Gardner, M. (2015). How young children view mathematical representations: A study using eye-tracking technology. *Educational Research, 57*(1), 59–79. https://doi.org/10.1080/00131881.2014.983718

*Bremner, J. G., Slater, A. M., Hayes, R. A., Mason, U. C., Murphy, C., Spring, J., Draper L., Gaskell D. Johnson, S. P. (2017). Young infants' visual fixation patterns in addition and subtraction tasks support an object tracking account. *Journal of Experimental Child Psychology, 162*, 199–208. https://doi.org/10.1016/j.jecp.2017.05.007

*Brysbaert, M. (1995). Arabic number reading: On the nature of the numerical scale and the origin of phonological recoding. J*ournal of Experimental Psychology: General, 124*(4), 434–452. https://doi.org/10.1037/0096-3445.124.4.434

*Bulf, H., de Hevia, M. D., & Macchi Cassia, V. (2016). Small on the left, large on the right: Numbers orient visual attention onto space in preverbal infants. *Developmental Science, 19*(3), 394–401. https://doi.org/10.1111/desc.12315

*Bulf, H., Macchi Cassia, V., & de Hevia, M. D. (2014). Are numbers, size and brightness equally efficient in orienting visual attention? Evidence from an eye-tracking study. *PLoS One, 9*(6), e99499. https://doi.org/10.1371/journal.pone.0099499

*Canfield, R. L., & Smith, E. G. (1996). Number-based expectations and sequential enumeration by 5-month-old infants. *Developmental Psychology, 32*(2), 269–279. https://doi.org/10.1037/0012-1649.32.2.269

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

*Ceulemans, A., Loeys, T., Hoppenbrouwers, K., & Desoete, A. (2014). To be or not to be: An informative non-symbolic numerical magnitude processing study about small versus large numbers in infants. *Journal of Special Education and Rehabilitation, 15*(1–2), 75–90. https://doi.org/10.2478/jser-2014-0005

*Chen, Y.-C., & Yang, F.-Y. (2014). Probing the relationship between process of spatial problems solving and science learning: An eye tracking approach. *International Journal of Science and Mathematics Education, 12*(3), 579–603. https://doi.org/10.1007/s10763-013-9504-y

*Chesney, D. L., McNeil, N. M., Brockmole, J. R., & Kelley, K. (2013). An eye for relations: Eye-tracking indicates long-term negative effects of operational thinking on understanding of math equivalence. *Memory & Cognition, 41*(7), 1079–1095. https://doi.org/10.3758/s13421-013-0315-8

*Cimen, O. A., & Campbell, S. R. (2012). Studying, self-reporting, and restudying basic concepts of elementary number theory. In T. Y. Tso (Ed.), *Proceedings of the 36th Conference of the International Group for the Psychology of Mathematics Education* (Vol. 2, pp. 163–170). Taipeh: PME.

*Clinton, V., Cooper, J. L., Michaelis, J. E., Alibali, M. W., & Nathan, M. J. (2016). How revisions to mathematical visuals affect cognition: Evidence from eye tracking. In C. Was, F. Sansosti, & B. Morris (Eds.), *Eye-tracking technology applications in educational research* (pp. 195–218). Hershey, PA: IGI Global.

*Cohen, A. L., & Staub, A. (2015). Within-subject consistency and between-subject variability in Bayesian reasoning strategies. *Cognitive Psychology, 81*, 26–47. https://doi.org/10.1016/j.cogpsych.2015.08.001

*Cohors-Fresenborg, E., Kramer, S., Pundsack, F., Sjuts, J., & Sommer, N. (2010). The role of metacognitive monitoring in explaining differences in mathematics achievement. *ZDM Mathematics Education, 42*(2), 231–244. https://doi.org/10.1007/s11858-010-0237-x

*Crisp, R., Inglis, M., Mason, J., & Watson, A. (2011). Individual differences in generalisation strategies. In C. Smith (Ed.), *Proceedings of the British Society for Research into Learning Mathematics* 31 (Vol. 3, pp. 35–40): London, UK: British Society for Research into Learning Mathematics (BSRLM).

*Curtis, E. T., Huebner, M. G., & LeFevre, J. A. (2016). The relationship between problem size and fixation patterns during addition, subtraction, multiplication, and division. *Journal of Numerical Cognition, 2*, 91–115. https://doi.org/10.5964/jnc.v2i2.17

*De Corte, E., & Verschaffel, L. (1986a). *Eye-movement data as access to solution processes of elementary addition and subtraction problems*. Paper presented at the Annual Meeting of the American Educational Research Association, San Francisco, USA.

*De Corte, E., & Verschaffel, L. (1986b). Eye-movements of first graders during word problem solving. In University of London Institute of Education (Ed.), *Proceedings of the 10th Conference of the International Group for the Psychology in Mathematics Education* (pp. 421–426). London PME.

*De Corte, E., Verschaffel, L., & Pauwels, A. (1990). Influence of the semantic structure of word problems on second graders' eye movements. *Journal of Educational Psychology, 82*(2), 359–365. https://doi.org/10.1037/0022-0663.82.2.359

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*(3), 371–396. https://doi.org/10.1037//0096-3445.122.3.371

*Dewolf, T., Van Dooren, W., Hermens, F., & Verschaffel, L. (2015). Do students attend to representational illustrations of non-standard mathematical word problems, and, if so, how helpful are they? *Instructional Science,* 43(1), 147–171. https://doi.org/10.1007/s11251-014-9332-7

Duchowski, A. (2007). *Eye tracking methodology. Theory and practice*. London, UK: Springer.

*Duijzer, C., Shayan, S., Bakker, A., Van der Schaaf, M. F., & Abrahamson, D. (2017). Touchscreen tablets: Coordinating action and perception for mathematical cognition. *Frontiers in Psychology, 8*. https://doi.org/10.3389/fpsyg.2017.00144

*Epelboim, J., & Suppes, P. (2001). A model of eye movements and visual working memory during problem solving in geometry. *Vision Research, 41*(12), 1561–1574. https://doi.org/10.1016/S0042-6989(00)00256-X

*Espino, O., Santamaria, C., Meseguer, E., & Carreiras, M. (2005). Early and late processes in syllogistic reasoning: Evidence from eye-movements. *Cognition, 98*(1), B1–B9. https://doi.org/10.1016/j.cognition.2004.12.010

*Evans, W. S., Caplan, D., & Waters, G. (2011). Effects of concurrent arithmetical and syntactic complexity on self-paced reaction times and eye fixations. *Psychonomic Bulletin & Review, 18*(6), 1203–1211. https://doi.org/10.3758/s13423-011-0159-9

*Fischer, M. H., Warlop, N., Hill, R. L., & Fias, W. (2004). Oculomotor bias induced by number perception. *Experimental Psychology, 51*(2), 91–97. https://doi.org/10.1027/1618-3169.51.2.91

*Fleig, H., Meiser, T., Ettlin, F., & Rummel, J. (2017). Statistical numeracy as a moderator of (pseudo)contingency effects on decision behavior. *Acta Psychologica, 174*, 68–79. https://doi.org/10.1016/j.actpsy.2017.01.002

*Fry, C. J. (1988). Eye fixations during the reading and solution of word problems containing extraneous information: Relation to spatial visualization ability. In A. Borbas (Ed.), *Proceedings of the twelfth Conference of the International Group for the Psychology of Mathematics Education* (Vol. 1, pp. 326–333). Veszprem: PME.

Gallagher-Mitchell, T., Simms, V., & Litchfield, D. (2018). Learning from where "eye" remotely look or point: Impact on number line estimation error in adults. *Quarterly Journal of Experimental Psychology*, *71*(7), 1526–1534. https://doi.org/10.1080/17470218.2017.1335335

*Gandini, D., Lemaire, P., & Dufau, S. (2008). Older and younger adults' strategies in approximate quantification. *Acta Psychologica, 129*(1), 175–189. https://doi.org/10.1016/j.actpsy.2008.05.009

*Ganor-Stern, D., & Weiss, N. (2016). Tracking practice effects in computation estimation. *Psychological Research, 80*(3), 434–448. https://doi.org/10.1007/s00426-015-0720-7

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

*Gielen, I., Brysbaert, M., & Dhondt, A. (1991). The syllable-length effect in number processing is task-dependent. *Perception & Psychophysics, 50*(5), 449–458. https://doi.org/10.3758/BF03205061

*Godau, C., Haider, H., Hansen, S., Schubert, T., Frensch, P. A., & Gaschler, R. (2014). Spontaneously spotting and applying shortcuts in arithmetic—A primary school perspective on expertise. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00556

*Godau, C., Wirth, M., Hansen, S., Haider, H., & Gaschler, R. (2014). From marbles to numbers—Estimation influences looking patterns on arithmetic problems. *Psychology, 5*, 127–133. https://doi.org/10.4236/psych.2014.52020

Goldin, G. A., Hannula, M. S., Heyd-Metzuyanim, E., Jansen, A., Kaasila, R., Lutovac, S., … Zhang, Q. (Eds.). (2016). *Attitudes, beliefs, motivation and identity in mathematics education. An overview of the field and future directions*. Hamburg, Germany: Springer Open.

*Gomez, A., Piazza, M., Jobert, A., Dehaene-Lambertz, G., & Huron, C. (2017). Numerical abilities of school-age children with developmental coordination disorder (DCD): A behavioral and eye-tracking study. *Human Movement Science, 55*, 315–326. https://doi.org/10.1016/j.humov.2016.08.008

Gray, C. T. (1917). *Types of reading ability as exhibited through tests and laboratory experiments*. Chicago, IL: The University of Chicago Press.

*Green, H. J., Lemaire, P., & Dufau, S. (2007). Eye movement correlates of younger and older adults' strategies for complex addition. *Acta Psychologica, 125*(3), 257–278. https://doi.org/10.1016/j.actpsy.2006.08.001

*Haataja, E., Moreno-Esteva, E. G., Toivanen, M., Hannula, M. S. (2018). Teacher's gaze behavior when scaffolding peer interaction and mathematical thinking during collaborative problem-solving activity. In E. Bergqvist, M. Österholm, C. Granberg, & L. Sumpter (Eds.), *Proceedings of the 42nd Conference of the International Group for the Psychology of Mathematics Education (Vol. 2, pp. 475–482). Umeå: PME.*

*Hamada, T., & Iwaki, S. (2012). Speed of mental addition in an abacus expert, estimated by eye movements and neural activities. *Perceptual and Motor Skills, 115*(1), 1–6. https://doi.org/10.2466/22.04.11.PMS.115.4.1-6

*Hannula, M., & Williams, G. (2016). Silent gazing during geometry problem solving, insights from eye tracking. In C. Csíkos, A. Rausch, & J. Szitányi (Eds.), *Proceedings of the 40th Conference of the International Group for the Psychology of Mathematics Education* (Vol. 2, pp. 353–360). Szeged: PME.

Hartmann, M. (2015). Numbers in the eye of the beholder: What do eye movements reveal about numerical cognition? *Cognitive Processing*, *16*, S245–S248. https://doi.org/10.1007/s10339-015-0716-7

*Hartmann, M., Laubrock, J., & Fischer, M. H. (2016). The visual number world: A dynamic approach to study the mathematical mind. *Quarterly Journal of Experimental Psychology, 71*(1), 28–36. https://doi.org/10.1080/17470218.2016.1240812

*Hartmann, M., Mast, F. W., & Fischer, M. H. (2015). Spatial biases during mental arithmetic: Evidence from eye movements on a blank screen. *Frontiers in Psychology, 6*. https://doi.org/10.3389/fpsyg.2015.00012

*Hartmann, M., Mast, F. W., & Fischer, M. H. (2016). Counting is a spatial process: Evidence from eye movements. *Psychological Research, 80*(3), 399–409. https://doi.org/10.1007/s00426-015-0722-5

*Hegarty, M., Mayer, R. E., & Green, C. E. (1992). Comprehension of arithmetic word problems: Evidence from students' eye fixations. *Journal of Educational Psychology, 84*(1), 76–84. https://doi.org/10.1037/0022-0663.87.1.18

*Hegarty, M., Mayer, R. E., & Monk, C. A. (1995). Comprehension of arithmetic word-problems—A comparison of successful and unsuccessful problem solvers. *Journal of Educational Psychology, 87*(1), 18–32. https://doi.org/10.1037//0022-0663.87.1.18

*Heine, A., Thaler, V., Tamm, S., Hawelka, S., Schneider, M., Torbeyns, J., . . . Jacobs, A. M. (2010). What the eyes already 'know': Using eye movement measurement to tap into children's implicit numerical magnitude representations. *Infant and Child Development, 19*(2), 175–186. https://doi.org/10.1002/icd.640

*Hernandez-Sabate, A., Albarracin, L., Calvo, D., & Gorgorio, N. (2016). EyeMath: Identifying mathematics problem solving processes in a RTS video game. In R. Bottino, J. Jeuring, & R. C. Veltkamp (Eds.), *Games and Learning Alliance* (Vol. 10056, pp. 50–59) Cham: Springer.

*Hintz, F., & Meyer, A. S. (2015). Prediction and production of simple mathematical equations: Evidence from visual world eye-tracking. *PLoS One, 10*(7). https://doi.org/10.1371/journal.pone.0130766

*Hodds, M., Alcock, L., & Inglis, M. (2014). Self-explanation training improves proof comprehension. *Journal for Research in Mathematics Education, 45*(1), 62–101. https://doi.org/10.5951/jresematheduc.45.1.0062

*Holmes, K. J., Ayzenberg, V., & Lourenco, S. F. (2016). Gamble on gaze: Eye movements reflect the numerical value of blackjack hands. *Psychonomic Bulletin and Review, 23*(6), 1974–1981. https://doi.org/10.3758/s13423-016-1055-0

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, UK: Oxford University Press.

Holmqvist, K., Nyström, M., & Mulvey, F. (2012). Eye tracker data quality. In S. N. Spencer (Ed.), *ETRA '12: Proceedings of the Symposium on Eye Tracking Research and Applications* (pp. 45–52). New York, NY: ACM.

*Huber, S., Cornelsen, S., Moeller, K., & Nuerk, H. C. (2015). Toward a model framework of generalized parallel componential processing of multi-symbol numbers. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*(3), 732–745. https://doi.org/10.1037/xlm0000043

*Huber, S., Klein, E., Willmes, K., Nuerk, H. C., & Moeller, K. (2014). Decimal fraction representations are not distinct from natural number representations—Evidence from a combined eye-tracking and computational modeling approach. *Frontiers in Human Neuroscience, 8*, 172. https://doi.org/10.3389/fnhum.2014.00172

*Huber, S., Mann, A., Nuerk, H. C., & Moeller, K. (2014). Cognitive control in number magnitude processing: Evidence from eye-tracking. *Psychological Research, 78*(4), 539–548. https://doi.org/10.1007/s00426-013-0504-x

*Huber, S., Moeller, K., & Nuerk, H. C. (2014). Adaptive processing of fractions—Evidence from eye-tracking. *Acta Psychologica, 148*, 37–48. https://doi.org/10.1016/j.actpsy.2013.12.010

*Huebner, M. G., & LeFevre, J. A. (2018). Selection of procedures in mental subtraction: Use of eye movements as a window on arithmetic processing. *Canadian Journal of Experimental Psychology, 72*(3), 171–182. https://doi.org/10.1037/cep0000127

*Hunt, T. E., Clark-Carter, D., & Sheffield, D. (2015). Exploring the relationship between mathematics anxiety and performance: An eye-tracking approach. *Applied Cognitive Psychology, 29*(2), 226–231. https://doi.org/10.1002/acp.3099

*Hurst, M., & Cordes, S. (2016). Rational-number comparison across notation: Fractions, decimals, and whole numbers. *Journal of Experimental Psychology: Human Perception and Performance, 42*(2), 281–293. https://doi.org/10.1037/xhp0000140

Hyönä, J. (2010). The use of eye movements in the study of multimedia learning. *Learning and Instruction*, *20*, 172–176. https://doi.org/10.1016/j.learninstruc.2009.02.013

*Inglis, M., & Alcock, L. (2012). Expert and novice approaches to reading mathematical proofs. *Journal for Research in Mathematics Education, 43*(4), 358–390. https://doi.org/10.5951/jresematheduc.43.4.0358

*Inglis, M., & Alcock, L. (2018). Watching mathematicians read mathematics. In E. Bergqvist, M. Österholm, C. Granberg, & L. Sumpter (Eds.), *Proceedings of the 42nd Conference of the International Group for the Psychology of Mathematics Education* (Vol. 3, pp. 139–146). Umeå: PME.

*Ischebeck, A., Weilharter, M., & Körner, C. (2016). Eye movements reflect and shape strategies in fraction comparison. *Quarterly Journal of Experimental Psychology, 69*(4), 713–727. https://doi.org/10.1080/17470218.2015.1046464

Just, M. A., & Carpenter, P. A. (1976). Eye fixations and cognitive processes. *Cognitive Psychology*, *8*, 441–480. https://doi.org/10.1016/0010-0285(76)90015-3

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

*Kiili, K., Ketamo, H., Koivisto, A., & Finn, E. (2014). Studying the user experience of a tablet based math game. *International Journal of Game-Based Learning, 4*(1), 60–77.

*Kim, S., Pollanen, M., Reynolds, M. G., & Burr, W. S. (2018). Identification of errors in mathematical symbolism and notation: Implications for software design. In J. H. Davenport, M. Kauers, G. Labahn, & J. Urban (Eds.), Mathematical software – ICMS 2018 (pp. 297–304). Cham, Switzerland: Springer.

*Klein, E., Huber, S., Nuerk, H.-C., & Moeller, K. (2014). Operational momentum affects eye fixation behaviour. *Quarterly Journal of Experimental Psychology, 67*(8), 1614–1625. https://doi.org/10.1080/17470218.2014.902976

*Klein, P., Viiri, J., Mozaffari, S., Dengel, A., & Kuhn, J. (2018). Instruction-based clinical eye-tracking study on the visual interpretation of divergence: How do students look at vector field plots? *Physical Review Physics Education Research, 14*(1). https://doi.org/10.1103/PhysRevPhysEducRes.14.010116

*Knoblich, G., Ohlsson, S., & Raney, G. E. (2001). An eye movement study of insight problem solving. *Memory and Cognition, 29*(7), 1000–1009. https://doi.org/10.3758/BF03195762

*Kohlhase, A., Kohlhase, M., & Fürsich, M. (2017). Visual structure in mathematical expressions. In H. Geuvers, M. England, O. Hasan, F. Rabe, & O. Teschke (Eds.), *Intelligent computer mathematics* (pp. 208–223). Cham, Switzerland: Springer.

*Kohlhase, A., Kohlhase, M., & Ouypornkochagorn, T. (2018). Discourse phenomena in mathematical documents. In F. Rabe, W. M. Farmer, G. O. Passmore, & A. Youssef (Eds.), *Intelligent computer mathematics* (pp. 147–163). Cham, Switzerland: Springer.

*Krichevets, A. N., Shvarts, A. Y., & Chumachenko, D. V. (2014). Perceptual action of novices and experts in operating visual representations of a mathematical concept. *Психология. Журнал Высшей школы экономики, 11*(3), 55–78.

Lai, M.-L., Tsai, M.-J., Yang, F.-Y., Hsu, C.-Y., Liu, T.-C., Lee, S. W.-Y., … 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

*Lécuyer, R., Berthereau, S., Ben Taïeb, A., & Tardif, N. (2004). Location of a missing object and detection of its absence by infants: Contribution of an eye-tracking system to the understanding of infants' strategies. *Infant and Child Development, 13*, 287–300. https://doi.org/10.1002/icd.357

*Lee, W.-K., & Wu, C.-J. (2018). Eye movements in integrating geometric text and figure: Scanpaths and given-new effects. *International Journal of Science and Mathematics Education, 16*, 699–714. https://doi.org/10.1007/s10763-016-9790-2

*Li, X., Logan, G. D., & Zbrodoff, N. J. (2010). Where do we look when we count? The role of eye movements in enumeration. *Attention, Perception, and Psychophysics, 72*(2), 409–426. https://doi.org/10.3758/APP.72.2.409

Lilienthal, A., & Schindler, M. (2019). Current trends in the use of eye tracking in mathematics education research: A PME survey. In M. Graven, H. Venkat, A. A. Essien, & P. Vale (Eds.), *Proceedings of 43rd Annual Meeting of the International Group for the Psychology of Mathematics Education*. Pretoria, South-Africa: PME.

*Lin, J. J. H., & Lin, S. S. J. (2014a). Cognitive load for configuration comprehension in computer-supported geometry problem solving: An eye movement perspective. *International Journal of Science and Mathematics Education, 12*(3), 605–627. https://doi.org/10.1007/s10763-013-9479-8

*Lin, J. J. H., & Lin, S. S. J. (2014b). Tracking eye movements when solving geometry problems with handwriting devices. *Journal of Eye Movement Research, 7*(1), 1–15.

*Lin, T.-W., Wu, C.-J., & Sommers, S. (2012). The influence of reading figures in geometry text on eye movement. In T. Y. Tso (Ed.), *Proceedings of the 36th Conference of the International Group for the Psychology of Mathematics Education* (Vol. 3, pp. 147–152). Taipeh, Taiwan: PME.

*Loetscher, T., Bockisch, C. J., & Brugger, P. (2008). Looking for the answer: The mind's eye in number space. *Neuroscience, 151*(3), 725–729. https://doi.org/10.1016/j.neuroscience.2007.07.068

*Loetscher, T., Bockisch, C. J., Nicholls, M. E. R., & Brugger, P. (2010). Eye position predicts what number you have in mind. *Current Biology, 20*(6), R264–R265. https://doi.org/10.1016/j.cub.2010.01.015

*Macchi Cassia, V., McCrink, K., Dolores de Hevia, M., Gariboldi, V., & Bulf, H. (2016). Operational momentum and size ordering in preverbal infants. *Psychological Research, 80*, 360–367. https://doi.org/10.1007/s00426-016-0750-9

*Masson, N., Letesson, C., & Pesenti, M. (2018). Time course of overt attentional shifts in mental arithmetic: Evidence from gaze metrics. *Quarterly Journal of Experimental Psychology, 71*(4), 1009–1019. https://doi.org/10.1080/17470218.2017.1318931

Matin, E. (1974). Saccadic suppression: A review. *Psychological Bulletin*, *81*, 899–917. https://doi.org/10.1037/h0037368

Mayer, R. E. (2010). Unique contributions of eye-tracking research to the study of learning with graphics. *Learning and Instruction*, *20*, 167–171. https://doi.org/10.1016/j.learninstruc.2009.02.012

*Merkley, R., & Ansari, D. (2010). Using eye tracking to study numerical cognition: The case of the ratio effect. *Experimental Brain Research, 206*(4), 455–460. https://doi.org/10.1007/s00221-010-2419-8

*Merschmeyer-Brüwer, C. (2001). How do primary school pupils "see" and structure two-dimensional representations of cube configurations? Case studies with analyses of eye movements during spatial structuring processes. In W. H.-G., A. Peter-Koop, K. Reiss, G. Toerner, & B. Wollring (Eds.), *Developments in mathematics education in German-speaking countries* (pp. 83–97). Hildesheim, Germany: Franzbecker.

*Meyerhoff, H. S., Moeller, K., Debus, K., & Nuerk, H.-C. (2012). Multi-digit number processing beyond the two-digit number range: A combination of sequential and parallel processes. *Acta Psychologica, 140*(1), 81–90. https://doi.org/10.1016/j.actpsy.2011.11.005

*Michal, A. L., Uttal, D., Shah, P., & Franconeri, S. L. (2016). Visual routines for extracting magnitude relations. *Psychonomic Bulletin and Review, 23*(6), 1802–1809. https://doi.org/10.3758/s13423-016-1047-0

*Miller Singley, A. T., & Bunge, S. A. (2018). Eye gaze patterns reveal how we reason about fractions. *Thinking and Reasoning, 24*(4), 445–468. https://doi.org/10.1080/13546783.2017.1417909

*Milosavljevic, M., Madsen, E., Koch, C., & Rangel, A. (2011). Fast saccades toward numbers: Simple number comparisons can be made in as little as 230 ms. *Journal of Vision, 11*(4), 1–12. https://doi.org/10.1167/11.4.4

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

*Moeller, K., Fischer, M. H., Nuerk, H. C., & Willmes, K. (2009a). Eye fixation behaviour in the number bisection task: Evidence for temporal specificity. *Acta Psychologica, 131*(3), 209–220. https://doi.org/10.1016/j.actpsy.2009.05.005

*Moeller, K., Fischer, M. H., Nuerk, H. C., & Willmes, K. (2009b). Sequential or parallel decomposed processing of two-digit numbers? Evidence from eye-tracking. *Quarterly Journal of Experimental Psychology, 62*(2), 323–334. https://doi.org/10.1080/17470210801946740

*Moeller, K., Klein, E., & Nuerk, H. C. (2011a). (No) small adults: Children's processing of carry addition problems. *Developmental Neuropsychology, 36*(6), 702–720. https://doi.org/10.1080/87565641.2010.549880

*Moeller, K., Klein, E., & Nuerk, H. C. (2011b). Three processes underlying the carry effect in addition - Evidence from eye tracking. *British Journal of Psychology, 102*(3), 623–645. https://doi.org/10.1111/j.2044-8295.2011.02034.x

*Moeller, K., Neuburger, S., Kaufmann, L., Landerl, K., & Nuerk, H. C. (2009). Basic number processing deficits in developmental dyscalculia: Evidence from eye tracking. *Cognitive Development, 24*(4), 371–386. https://doi.org/10.1016/j.cogdev.2009.09.007

*Moutsios-Rentzos, A., & Stamatis, P. J. (2013). Non-verbal communication in thinking about arithmetic problems. *Quaderni di Ricerca in Didattica (Mathematics), 23*, 25–36.

*Moutsios-Rentzos, A., & Stamatis, P. J. (2015). One-step 'change' and 'compare' word problems: Focusing on eye-movements. *Electronic Journal of Research in Educational Psychology, 13*(3), 503–528. https://doi.org/10.14204/ejrep.37.14133

*Muldner, K. K. M. A. E., & Burleson, W. (2015). Utilizing sensor data to model students' creativity in a digital environment. *Computers in Human Behavior, 42*, 127–137. https://doi.org/10.1016/j.chb.2013.10.060

*Myachykov, A., Cangelosi, A., Ellis, R., & Fischer, M. H. (2015). The oculomotor resonance effect in spatial-numerical mapping. *Acta Psychologica, 161*, 162–169. https://doi.org/10.1016/j.actpsy.2015.09.006

*Myachykov, A., Ellis, R., Cangelosi, A., & Fischer, M. H. (2016). Ocular drift along the mental number line. *Psychological Research, 80*(3), 379–388. https://doi.org/10.1007/s00426-015-0731-4

*Obersteiner, A., Moll, G., Beitlich, J. T., Cui, C., Schmidt, M., Khmelivska, T., & Reiss, K. (2014). Expert mathematicians' strategies for comparing the numerical values of fractions – Evidence from eye movements. In P. Liljedahl, C. Nicol, S. Oesterle, & D. Allan (Eds.), *Proceedings of the 38th Conference of the International Group for the Psychology of Mathematics Education and the 36th Conference of the North American Chapter of the Psychology of Mathematics Education* (Vol. 4, pp. 337–344). Vancouver, Canada: PME.

*Obersteiner, A., & Staudinger, I. (2018). How the eyes add fractions: Adult eye movement patterns during fraction addition problems. *Journal of Numerical Cognition, 4*(2), 317–336. https://doi.org/10.5964/jnc.v4i2.130

*Obersteiner, A., & Tumpek, C. (2016). Measuring fraction comparison strategies with eye-tracking. *ZDM Mathematics Education, 48*(3), 255–266. https://doi.org/10.1007/s11858-015-0742-z

*Ögren, M., Nyström, M., & Jarodzka, H. (2017). There's more to the multimedia effect than meets the eye: Is seeing pictures believing? *Instructional Science: An International Journal of the Learning Sciences, 45*(2), 263–287. https://doi.org/10.1007/s11251-016-9397-6

*Okamoto, N., & Kuroda, Y. (2014). Understanding strategy development in mathematics: Using eye movement measurement in educational research. *European Journal of Research on Education, 2*(2), 94–100. https://doi.org/10.15527/ejre.201426252

*Olsen, J. K., Aleven, V., & Rummel, N. (2017). Exploring dual eye tracking as a tool to assess collaboration. In A. A. von Davier, M. Zhu, & P. C. Kyllonen (Eds.), *Innovative Assessment of Collaboration* (pp. 157–172). Cham, Switzerland: Springer.

*Ott, N., Brunken, R., Vogel, M., & Malone, S. (2018). Multiple symbolic representations: The combination of formula and text supports problem solving in the mathematical field of propositional logic. *Learning and Instruction, 58*, 88–105. https://doi.org/10.1016/j.learninstruc.2018.04.010

*Panse, A., Alcock, L., & Inglis, M. (2018). Reading proofs for validation and comprehension: An expert-novice eye-movement study. *International Journal of Research in Undergraduate Mathematics Education, 4*(3), 357–375. https://doi.org/10.1007/s40753-018-0077-6

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). Valencia, Spain: IATED Academy.

*Peters, M. (2010). Parsing mathematical constructs: Results from a preliminary eye tracking study. In M. Joubert (Ed.), *Proceedings of the British Society for Research into Learning Mathematics 30* (Vol. 2, pp. 47–52): London, UK: British Society for Research into Learning Mathematics (BSRLM).

*Plummer, P., DeWolf, M., Bassok, M., Gordon, P. C., & Holyoak, K. J. (2017). Reasoning strategies with rational numbers revealed by eye tracking. *Attention, Perception, and Psychophysics, 79*(5), 1426–1437. https://doi.org/10.3758/s13414-017-1312-y

*Potgieter, P., & Blignaut, P. (2018). The effect of learners' knowledge of the divisibility rules on their gaze behaviour. *African Journal of Research in Mathematics, Science and Technology Education, 22*(3), 351–362. https://doi.org/10.1080/18117295.2018.1533611

*Pressigout, A., Charvillat, A., Mersad, K., & Doré-Mazars, K. (2018). Time dependency of the SNARC effect for different number formats: Evidence from saccadic responses. *Psychological Research*. https://doi.org/10.1007/s00426-018-1010-y

*Price, G. R., Wilkey, E. D., & Yeo, D. J. (2017). Eye-movement patterns during nonsymbolic and symbolic numerical magnitude comparison and their relation to math calculation skills. *Acta Psychologica, 176*, 47–57. https://doi.org/10.1016/j.actpsy.2017.03.012

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422. https://doi.org/10.1037/0033-2909.124.3.372

Rayner, K., Pollatsek, A., Ashby, J., & Clifton, C. (2012). *Psychology of reading* (2nd ed.). New York, NY: Psychology Press.

*Reike, D., & Schwarz, W. (2016). One model fits all: Explaining many aspects of number comparison within a single coherent model-a random walk account. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*(12), 1957–1971. https://doi.org/10.1037/xlm0000287

*Reinert, R. M., Huber, S., Nuerk, H. C., & Moeller, K. (2015). Strategies in unbounded number line estimation? Evidence from eye-tracking. *Cognitive Processing, 16*, 359–363. https://doi.org/10.1007/s10339-015-0675-z

*Rinaldi, L., Brugger, P., Bockisch, C. J., Bertolini, G., & Girelli, L. (2015). Keeping an eye on serial order: Ocular movements bind space and time. *Cognition, 142*, 291–298. https://doi.org/10.1016/j.cognition.2015.05.022

*Risko, E. F., Maloney, E. A., & Fugelsang, J. A. (2013). Paying attention to attention: Evidence for an attentional contribution to the size congruity effect. *Attention, Perception, and Psychophysics, 75*(6), 1137–1147. https://doi.org/10.3758/s13414-013-0477-2

*Roach, V. A., Fraser, G. M., Kryklywy, J. H., Mitchell, D. G. V., & Wilson, T. D. (2016). The eye of the beholder: Can patterns in eye movement reveal aptitudes for spatial reasoning? *Anatomical Sciences Education, 9*(4), 357–366. https://doi.org/10.1002/ase.1583

*Roy, S., Inglis, M., & Alcock, L. (2017). Multimedia resources designed to support learning from written proofs: An eye-movement study. *Educational Studies in Mathematics, 96*(2), 249–266. https://doi.org/10.1007/s10649-017-9754-7

*Rozek, B., Blasiak, W., Andrzejewska, M., Godlewska, M., Peczkowski, P., Rosiek, R., . . . Wcislo, D. (2014). The eye-tracking research method in the process of solving mathematical tasks requiring drawing analysis. *Didactics of Mathematics., 11*(15), 43–58.

*Ruiz Fernández, S., Rahona, J. J., Hervás, G., Vázquez, C., & Ulrich, R. (2011). Number magnitude determines gaze direction: Spatial–numerical association in a free-choice task. *Cortex, 47*(5), 617–620. https://doi.org/10.1016/j.cortex.2010.10.006

*Sajka, M., & Rosiek, R. (2015). *Solving a problem by students with different mathematical abilities: A comparative study using eye-tracking.* Paper presented at the CERME 9 - Ninth Congress of the European Society for Research in Mathematics Education, Prague, Czech Republic.

*Salvaggio, S., Masson, N., & Andres, M. (2018). Eye position reflects the spatial coding of numbers during magnitude comparison. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. https://doi.org/10.1037/xlm0000681

Salvucci, D. D., & Goldberg, J. H. (2000). Identifying Fixations and Saccades in Eye-Tracking Protocols. In *Proceedings of the Eye Tracking Research and Applications Symposium* (pp. 71–78). New York: ACM Press.

*Schimpf, F., & Spannagel, C. (2011). Reducing the graphical user interface of a dynamic geometry system. *ZDM Mathematics Education, 43*(3), 389–397. https://doi.org/10.1007/s11858-011-0325-6

Schindler, M., Haataja, E., Lilienthal, A. J., Moreno-Esteva, E. G., & Shvarts, A. (2018). Eye-tracking in Mathematics Education research: A follow-up on opportunities and challenges. In E. Bergqvist, M. Österholm, C. Granberg, & L. Sumpter (Eds.), *Proceedings of the 42nd Conference of the International Group for the Psychology of Mahematics Education* (vol. 1, pp. 209–210). Umeå, Sweden: PME.

Schindler, M., & Lilienthal, A. J. (2017). Eye-tracking and its domain-specific interpretation. A stimulated recall study on eye movements in geometrical tasks. In B. Kaur, W. K. Ho, T. L. Toh, & B. H. Choy (Eds.), *Proceedings of the 41st Conference of the International Group for the Psychology of Mathematics Education* (vol. 4, pp. 153–160). Singapore: PME.

*Schindler, M., & Lilienthal, A. J. (2018). Eye-tracking for studying mathematical difficulties—also in inclusive settings. In E. Bergqvist, M. Österholm, C. Granberg, & L. Sumpter (Eds.), *Proceedings of the 42nd Conference of the International Group for the Psychology of Mathematics Education* (Vol. 4, pp. 115–122). Umeå, Sweden: PME.

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*, 1–17. https://doi.org/10.1007/s10649-019-9878-z

Schindler, M., Lilienthal, A. J., Chadalavada, R., & Ögren, M. (2016). Creativity in the eye of the student. Refining investigations of mathematical creativity using eye-tracking goggles. In C. Csíkos, A. Rausch, & J. Szitányi (Eds.), *Proceedings of the 40th Conference of the International Group for the Psychology of Mathematics Education* (vol. 4, pp. 163–170). Szeged, Hungary: PME.

*Schleifer, P., & Landerl, K. (2011). Subitizing and counting in typical and atypical development. *Developmental Science, 14*(2), 280–291. https://doi.org/10.1111/j.1467-7687.2010.00976.x

*Schneider, E., Maruyama, M., Dehaene, S., & Sigman, M. (2012). Eye gaze reveals a fast, parallel extraction of the syntax of arithmetic formulas. *Cognition, 125*(3), 475–490. https://doi.org/10.1016/j.cognition.2012.06.015

*Schneider, M., Heine A., Thaler V., Torbeyns J., De Smedt B., Verschaffel L., … Stern, E. (2008). A validation of eye movements as a measure of elementary school children's developing number sense. *Cognitive Development, 23*(3), 409–422. https://doi.org/10.1016/j.cogdev.2008.07.002

*Schwarz, W., & Keus, I. M. (2004). Moving the eyes along the mental number line: Comparing SNARC effects with saccadic and manual responses. *Perception and Psychophysics, 66*(4), 651–664. https://doi.org/10.3758/BF03194909

Shaki, S., & Fischer, M. H. (2018). Deconstructing spatial-numerical associations. *Cognition*, *175*, 109–113. https://doi.org/10.1016/j.cognition.2018.02.022

*Shayan, S., Abrahamson, D., Bakker, A., Duijzer, C. A. C. G., & Van der Schaaf, M. (2017). Eye-tracking the emergence of attentional anchors in a mathematics learning tablet activity. In C. Was, F. Sansosti, & B. Morris (Eds.), *Eye-Tracking Technology Applications in Educational Research* (pp. 166–194). Hershey, PA, USA: IGI Global.

*Shvarts, A. (2018a). A dual eye-tracking study of objectification as student-tutor joint activity appropriation. In E. Bergqvist, M. Österholm, C. Granberg, & L. Sumpter (Eds.), *Proceedings of the 42nd Conference of the International Group for the Psychology of Mathematics Education* (Vol. 4, pp. 171–178). Umeå, Sweden: PME.

*Shvarts, A. (2018b). Joint attention in resolving the ambiguity of different presentations: A dual eye-tracking study of the teaching-learning process. In N. Presmeg, L. Radford, W. M. Roth, & G. Kadunz (Eds.), *Signs of Signification: Semiotics in Mathematics Education Research* (pp. 73–102). Cham, Switzerland: Springer.

*Sophian, C., & Crosby, M. E. (2008). What eye fixation patterns tell us about subitizing. *Developmental Neuropsychology, 33*(3), 394–409. https://doi.org/10.1080/87565640801982460

*Stolinska, A., Andrzejewska, M., Blasiak, W., Peczkowski, P., Rosiek, R., Rozek, B., . . . Wcislo, D. (2014). Analysis of saccadic eye movements of experts and novices when solving text tasks. In M. Nodzynska, P. Ciesla, & K. Rozowicz (Eds.), *New Technologies in Science Education* (pp. 21–29). Krakow, Poland: Pedagogical University of Krakow.

*Strohmaier, A. R., & Reiss, K. M. (2018). Mathematics in disguise: Effects of the external context of mathematical word problems. In E. Bergqvist, M. Österholm, C. Granberg, & L. Sumpter (Eds.), *Proceedings of the 42nd Conference of the International Group for the Psychology of Mathematics Education* (Vol. 4, pp. 251–258). Umeå, Sweden: PME.

*Strohmaier, A. R., Schiepe-Tiska, A., Müller, F., & Reiss, K. (2017). *Mathematical reading patterns - The influence of self-concept and situational context.* Paper presented at the Annual Meeting of the American Educational Research Association (AERA), San Antonio, TX.

*Sullivan, J. L., Juhasz, B. J., Slattery, T. J., & Barth, H. C. (2011). Adults' number-line estimation strategies: Evidence from eye movements. *Psychonomic Bulletin & Review, 18*(3), 557–563. https://doi.org/10.3758/s13423-011-0081-1

*Suppes, P., Cohen, M., Laddaga, R., Anliker, J., & Floyd, R. (1982). Research on eye movements in arithmetic performance. In R. Groner & P. Fraisse (Eds.), *Cognition and eye movements* (pp. 57–73). Amsterdam, the Netherlands: North Holland.

*Suppes, P., Cohen, M., Laddaga, R., Anliker, J., & Floyd, R. (1983). A procedural theory of eye movements in doing arithmetic. *Journal of Mathematical Psychology, 27*(4), 341–369. https://doi.org/10.1016/0022-2496(83)90033-0

*Susac, A., Bubic, A., Kaponja, J., Planinic, M., & Palmovic, M. (2014). Eye movements reveal students' strategies in simple equation solving. *International Journal of Science and Mathematics Education, 12*(3), 555–577. https://doi.org/10.1007/s10763-014-9514-4

*Terry, P. W. (1921). The Reading Problem in Arithmetic. *Journal of Educational Psychology, 12*(7), 365–377.

*van der Schoot, M., Bakker Arkema, A. H., Horsley, T. M., & van Lieshout, E. C. D. M. (2009). The consistency effect depends on markedness in less successful but not succesful problem solvers: An eye movement study in primary school children. *Contemporary Educational Psychology, 34*, 58–66. https://doi.org/10.1016/j.cedpsych.2008.07.002

*van der Weijden, F. A., Kamphorst, E., Willemsen, R. H., Kroesbergen, E. H., & van Hoogmoed, A. H. (2018). Strategy use on bounded and unbounded number lines in typically developing adults and adults with dyscalculia: An eye-tracking study. *Journal of Numerical Cognition, 4*(2), 337–359. https://doi.org/10.5964/jnc.v4i2.115

van Gog, T., & Scheiter, K. (2010). Eye tracking as a tool to study and enhance multimedia learning. *Learning and Instruction*, *20*, 95–99. https://doi.org/10.1016/j.learninstruc.2009.02.009

van Marlen, T., van Wermeskerken, M., Jarodzka, H., & van Gog, T. (2016). Showing a model's eye movements in examples does not improve learning of problem-solving tasks. *Computers in Human Behavior*, *65*, 448–459. https://doi.org/10.1016/j.chb.2016.08.041

van Marlen, T., van Wermeskerken, M., Jarodzka, H., & van Gog, T. (2018). Effectiveness of eye movement modeling examples in problem solving: The role of verbal ambiguity and prior knowledge. *Learning and Instruction*, *58*, 274–283. https://doi.org/10.1016/j.learninstruc.2018.07.005

*van Oeffelen, M. P., & Vos, P. G. (1984a). Enumeration of dots: An eye movement analysis. *Memory & Cognition, 12*(6), 607–612. https://doi.org/10.3758/BF03213349 *van Oeffelen, M. P., & Vos, P. G. (1984b). The young child's processing of dot patterns: A chronometric and eye movement analysis. *International Journal of Behavioral Development, 7*(1), 53–66. https://doi.org/10.1177/016502548400700104

*van Viersen, S., Slot, E. M., Kroesbergen, E. H., van't Noordende, J. E., & Leseman, P. P. M. (2013). The added value of eye-tracking in diagnosing dyscalculia: A case study. *Frontiers in Psychology, 4*. https://doi.org/10.3389/fpsyg.2013.00679

van Wermeskerken, M., Litchfield, D., & van Gog, T. (2018). What am I looking at? Interpreting dynamic and static gaze displays. *Cognitive Science*, *42*(1), 220–252. https://doi.org/10.1111/cogs.12484

*van't Noordende, J. E., van Hoogmoed, A. H., Schot, W. D., & Kroesbergen, E. H. (2016). Number line estimation strategies in children with mathematical learning difficulties measured by eye tracking. *Psychological Research, 80*(3), 368–378. https://doi.org/10.1007/s00426-015-0736-z

*Verdine, B. N., Bunger, A., Athanasopoulou, A., Golinkoff, R. M., & Hirsh-Pasek, K. (2017). Shape up: An eye-tracking study of preschoolers' shape name processing and spatial development. *Developmental Psychology, 53*(10), 1869–1880. https://doi.org/10.1037/dev0000384

*Verschaffel, L., Corte, E. d., Gielen, E., & Struyf, E. (1994). Clever rearrangement strategies in children's mental arithmetic: A confrontation of eye-movement data and verbal protocols. In J. E. H. Van Luit (Ed.), *Research on learning and instruction of mathematics in kindergarten and primary school* (pp. 153–180). Doetinchem, the Netherlands: Graviant.

*Verschaffel, L., De Corte, E., & Pauwels, A. (1992). Solving compare problems: An eye movement test of Lewis and Mayer's Consistency Hypothesis. *Journal of Educational Psychology, 84*(1), 85–94. https://doi.org/10.1037/0022-0663.84.1.85

*Wall, J., Thompson, C. A., & Morris, B. J. (2015). *Confidence judgments and eye fixations reveal adults' fractions knowledge.* Paper presented at the 37th Annual Meeting of the Cognitive Science Society, Pasadena, CA.

Wang, H., Pi, Z., & Hu, W. (2018). The instructor's gaze guidance in video lectures improves learning. *Journal of Computer Assisted Learning*, *35*, 42–50. https://doi.org/10.1111/jcal.12309

*Wang, H.-S., Yi-Ting, C., & Chih-Hung, L. (2014). The learning benefits of using eye trackers to enhance the geospatial abilities of elementary school students. *British Journal of Educational Technology, 45*(2), 340–355. https://doi.org/10.1111/bjet.12011

*Watson, D. G., Maylor, E. A., & Bruce, L. A. M. (2005). Search, enumeration, and aging: Eye movement requirements cause age-equivalent performance in enumeration but not in search tasks. *Psychology and Aging, 20*(2), 226–240. https://doi.org/10.1037/0882-7974.20.2.226

*Watson, D. G., Maylor, E. A., & Bruce, L. A. M. (2007). The role of eye movements in subitizing and counting. *Journal of Experimental Psychology: Human Perception and Performance, 33*(6), 1389–1399. https://doi.org/10.1037/0096-1523.33.6.1389

*Werner, K., & Raab, M. (2014). Moving your eyes to solution: Effects of movements on the perception of a problem-solving task. *Quarterly Journal of Experimental Psychology, 67*(8), 1571–1578. https://doi.org/10.1080/17470218.2014.889723

*Winoto, P., Tang, T. Y., Huang, Z., & Chen, P. (2017). "Thinking in pictures?" Performance of chinese children with autism on math learning through eye-tracking technology. In P. Zaphiris & A. Ioannou (Eds.), *Learning and Collaboration Technologies. Technology in Education* (pp. 215–226). Cham, Switzerland: Springer.

*Yağmur, S., & Çakır, M. P. (2016). Usability evaluation of a dynamic geometry software mobile interface through eye tracking. In P. Zaphiris & A. Ioannou (Eds.), *Learning and Collaboration Technologies* (Vol. 9753, pp. 391–402). Cham, Switzerland: Springer.

*Zhou, F., Zhao, Q., Chen, C., & Zhou, X. (2012). Mental representations of arithmetic facts: Evidence from eye movement recordings supports the preferred operand-order-specific representation hypothesis. *Quarterly Journal of Experimental Psychology, 65*(4), 661–674. https://doi.org/10.1080/17470218.2011.616213

*Zhu, R., Luo, Y., You, X., & Wang, Z. (2018). Spatial bias induced by simple addition and subtraction: From eye movement evidence. *Perception*, *47*(2), 143–157. https://doi.org/10.1177/0301006617738718