EYE-TRACKING AND ITS DOMAIN-SPECIFIC INTERPRETATION. A STIMULATED RECALL STUDY ON EYE MOVEMENTS IN GEOMETRICAL TASKS

Maike Schindler and Achim J. Lilienthal

Örebro University

Eye-tracking offers various possibilities for mathematics education. Yet, even in suitably visually presented tasks, interpretation of eye-tracking data is non-trivial. A key reason is that the interpretation of eye-tracking data is context-sensitive. To reduce ambiguity and uncertainty, we studied the interpretation of eye movements in a specific domain: geometrical mathematical creativity tasks. We present results from a qualitative empirical study in which we analyzed a Stimulated Recall Interview where a student watched the eye-tracking overlaid video of his work on a task. Our results hint at how eye movements can be interpreted and show limitations and opportunities of eye tracking in the domain of mathematical geometry tasks and beyond.

INTRODUCTION

Eye-tracking—the process of capturing eye movements of persons when they are looking at stimuli at hand (Chen, 2011)—is a technology and research method increasingly gaining popularity over the last decade (Andrá et al., 2015; Salvucci & Goldberg, 2012). In the mid-1970s, commercial eye-tracking devices started to become available and since then eye-tracking became more accessible than ever before (Holmkvist et al., 2011). In particular, the recent advent of affordable portable head-mounted devices revived the promise of eye tracking and fuels an increased interest in this technology—also in the PME community as could be seen at PME 40.

Eye-tracking offers various possibilities for mathematics education research (e.g., Andrá et al, 2015; Obersteiner & Tumpek, 2016), in particular it lends itself to "visually presented cognitive tasks, [where] eye movements are assumed to correspond to mental operations" (p. 257). However, even in geometrical or otherwise suitably visually presented tasks, the interpretation of eye-tracking data is non-trivial. It typically rests on the so-called "eye-mind" hypothesis (Just & Carpenter, 1980), which posits that a person's eye movements are tightly related to their cognitive processes (Jang et al., 2014). The interpretation of eye-tracking data is challenging because (1) the eye-mind hypothesis does not always hold (Holmkvist et al., 2011) and (2) the interpretation of eye-movement data is not bijective (Hayhoe, 2004), and (3) is furthermore context-sensitive, in particular conditioned on the task (ibid.). The inherent ambiguity and uncertainty, which comes with the context-sensitivity can be reduced by narrowing down the interpretation of eye movements to a particular domain: "Although the mere presence of gaze at a particular location in the visual field does not reveal the variety of brain computations that might be operating at that

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moment, the experimental context within which the fixation occurs often provides critical information that allows powerful inferences” (p.267).

We therefore see the need to approach the methodological question of how to interpret eye-tracking data in the domain of mathematics education and its sub-domains. In particular, we focus on geometrical tasks, where eye-tracking data are perceived as especially beneficial (e.g., Schindler et al., 2016; Muldner & Burleston, 2015). We refer to a task set (geometrical creativity tasks, so-called Multiple Solution Tasks (MSTs)) and their corresponding entities (figures, lines, corners, etc.). Instead of relying on eye movement measures as common in mathematics education research (e.g., Muldner & Burleston, 2015; Obersteiner & Tupek, 2016), we focus on raw data—eye-tracking overlaid videos—thus avoiding a dependency on the eye-tracking device used or the actual computation of eye movement measures. This paper presents results from a qualitative empirical study in which we analyzed a Stimulated Recall Interview where a student watched the eye-tracking overlaid video of his work on a Multiple Solution Task and described and explained his according thoughts and strategies in detail. Results from the qualitative SRI data analysis hint at how and in what (different) ways eye movements can be interpreted (e.g., fixations on small areas, rapid eye movements). Beyond the directly considered domain of geometrical MSTs, our analysis also sheds light on opportunities and limitations of eye-tracking as a research method in the domain of mathematical geometry tasks and beyond.

THEORETICAL BACKGROUND

Eye-tracking

First methods for eye tracking date back to the beginning of the 1900s and initial methods were obtrusive or even invasive (Jacob & Karn, 2003). Nowadays video-based systems dominate the market for eye trackers; either in the form of head-mounted devices such as eye-tracking goggles (as used in our empirical study) or remote devices attached to a computer screen to display the visual stimuli (Holmkvist et al., 2011). Eye-tracking offers various possibilities for mathematics education research. It is used, for instance, for analyzing students' strategies when comparing fractions (Obersteiner & Tumpek, 2016), for identifying highly creative persons working on geometrical creativity problems (Muldner & Burleston, 2015), and for investigating students' strategies when working on geometrical creativity problems (Schindler et al., 2016). In particular, in geometrical settings researchers focus on “how and which information students are attending to” (Andrá et al., 2015, p. 241).

Interpreting eye-tracking data

In order to reduce the effort for analyzing eye-tracking data, events—computed from raw eye-tracking data—are typically analyzed instead of the raw data itself (Holmkvist et al., 2011). This holds also true for eye-tracking research in the domain of mathematics education. In particular, fixations and saccades are used (Salvucci & Goldberg, 2012). Fixations are moments when the eye remains relatively still and focuses—consciously or not—stably on certain focus point or a small area. Saccades are fast eye movements in between fixations (Chen, 2011).

However, the interpretation of eye-tracking data is non-trivial—and this is one key reason that prevents eye-tracking technology to fully live up to its potential (Jacob & Karn, 2003). Interpreting eye-tracking data typically draws on the so-called "eye-mind" hypothesis, which "posits that there is no appreciable lag between what is being fixated and what is being processed" (Just & Carpenter, 1980, p. 331), meaning that "what a person looks at is assumed to indicate the thought 'on top of the stack' of cognitive processes" (Jang et al., 2014, p. 318). However, the eye-mind hypothesis does not always hold: people can, e.g., look at an object without registering it in their working memory and, conversely, they may also recall non-fixated objects (Holmkvist et al., 2011). A second difficulty is that the mapping of students' eye movements to their attention and their cognitive processes is *not bijective*: "Although a given cognitive event might reliably lead to a particular fixation, the fixation itself does not uniquely specify the cognitive event" (Hayhoe, 2004, p. 268). Fixations can, for instance, indicate difficulty of information extraction and interpretation (Jacob & Karn, 2003) or cognitive attention on the aspect of a task looked at (Andrá et al., 2015). We hypothesize that it can even indicate other processes, such as staring because of tiredness or boredom, or else. Finally, the interpretation of eye movements needs to be *context-sensitive*: conditioned on the task, the internal state of the participant, and their "cognitive goals" (Hayhoe, 2004, p. 268). A comprehensive theory about how to interpret eye-tracking data is thus limited to rather general relationships, for instance, that "saccades are preceded by an attentional shift to the target location" (p. 267) and that "shifts in attention made by the observer are usually reflected in the fixations" (p. 268). Notably, these general relationships do not relate to the semantics of the entities that caused visual attention. In order to reduce the inherent difficulty and ambiguity that comes through context-sensitivity, we suggest to investigate domain-specific interpretation (focusing on geometrical tasks) and take into account the corresponding, known semantics of visual entities in this domain (figures, lines, corners, etc.). Accordingly, we ask the research question: *How can students' eye movements be interpreted domain-specifically?* We approach this question through a Stimulated Recall study (see below), which will also shed light on the questions of *What opportunities does the analysis of eye movements offer over the analysis of simple videos in our domain?* and *What limitations does the analysis of eye movements entail?*

METHOD

Setting the scene

This study took place in the Swedish research project KMT ("kreativa matteträffar"), where mathematically interested upper secondary school students worked on multifaceted mathematical problems and were fostered in their mathematical creativity over one year. This paper focuses on a students' work on a particular MST (Fig. 1)—a geometrical MST, which had revealed itself rich and suitable for addressing mathematical creativity in prior work (Schindler et al., 2016).

Task: Solve the following problem. Can you find different ways to solve the problem? Show as many ways as you can find.
Problem: This figure is an equilateral hexagon: How big is the angle ε?
Remember: In an equilateral hexagon, all sides have the same length and all angles have the same size, which is 120°.

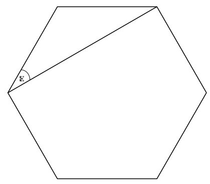

Figure 1: The hexagon-problem (Multiple Solution Task)

The student participating in this study was an 18-year old Swedish student in his last school year, David. David was very interested, talented, and dedicated to mathematics; he read mathematics books in his spare time and furthermore went on studying mathematics six months after this study had taken place. David worked on the MST wearing eye-tracking goggles and then an additional SRI was conducted using the eye-tracking overlaid video of his work on the MST with a length of 17:30 min.

The study described in this paper was carried out with the headset Pupil Pro (Kassner, Patera & Bulling, 2014). Though remote eye-trackers measuring eye movements on a computer screen can be advantageous in terms of accuracy (see Muldner & Burleston, 2015), goggles allow portable, unobtrusive eye-tracking and are easy to set-up. They can be used in a natural setting (the student worked on the MSTs with pen and paper) and in a familiar room, avoiding biases through an artificial surrounding.

Stimulated Recall Interview (SRI) based on eye-tracking overlaid video

In our endeavor to illuminate what eye movements may indicate and how they can be interpreted, we conducted a Stimulated Recall Interview (SRI) using the eye-tracking overlaid video of his work on the MST. Stimulated recall is a research method that is to be understood as an introspection procedure "through which cognitive processes can be investigated by inviting subjects to recall, when prompted by a video sequence, their concurrent thinking during that event" (Lyle, 2003, p. 861). In our case, we wanted the student to describe and explain his thinking using the eye-tracking overlaid video. SRI avoids the disadvantages that a thinking aloud method may have (e.g., high levels of interaction, time constraints, or emotive contexts, see Lyle, 2003). However, it also comprises weaknesses that have to be taken into account when planning an SRI study (Lyle, 2003): For instance, we reduced anxiety through (a) creating a trustful personal relation between the interviewer and the teacher over the project time span, (b) conducting the SRI in an environmental context well-known to the student (the room regularly used in the project), and (c) avoiding judgmental utterances by the interviewer, who rather indicated interest in the student's thought.

In the SRI, the student and interviewer jointly looked at the eye-tracking overlaid video arising from the student's work on the MST. The interviewer asked the student to comment on his eye movements. Both the student and the interviewer were able to stop the video and to go back. Also the student took the opportunity to explain his eye movements and thoughts. The SRI was taped by two cameras.

One important concern regarding SRI is about incomplete memories leading students to react to what they see on the video and accordingly rather re-construct their thoughts than recalling them (Lyle, 2003). David's utterances (in which he mostly used present tense when talking about his proceeding) indicate that he could recall his original thoughts impressively clearly. We further think that the eye-tracking overlaid video, a clear and strong stimulus, helped the student recalling his thoughts.

Data analysis

This paper focuses on the video data from the SRI with David (approx. 76 min). In a first step, we transcribed the largest parts of the video: Passages were left out when the discussion did not address the student's eye movements. We transcribed the student's and interviewer's utterances as well as the eye movements were addressed.

The data analysis was conducted in an inductive manner, which was suitable as our research questions are explorative and descriptive in their nature. Following Mayring's (2014) qualitative content analysis (focusing on the techniques of summarizing and inductive category development) and Beck and Maier's (1994) category developing text interpretation, we conducted the following analysis steps (see Tab. 1 for an example) that aimed at handling the comprehensive transcript and at inductively working out categories (e.g., special patterns of eye movements and their interpretation). In a *paraphrasing step*, we paraphrased the content-bearing semantic elements in the transcript relevant for our research questions. In a *transposing step*, we generalized these entities to the defined level of abstraction and transposed them to a uniform stylistic level (see Tab. 1). In a *category development step*, we went through all data (transposes) and inductively assigned categories and according descriptions/definitions. In a *category revision step*, we revised the category system after having categorized all data and—based on the revised category system—went through all data again, partially re-categorizing if necessary. In a *subsumption step*, for every category we collected all instances matching this category. Thus, we found, for instance, for the category "looking outside the task sheet" all interpretations of this eye movement arising from our data.

Transcript	Paraphrase	Transpose	Category
(D. looking outside the task sheet (saccade)) D: Now I'm just thinking and trying to remember how you calculate an interior angle in a regular polygon.	Looking outside the task sheet (saccade): thinking and trying to remember a calculation.	Looking outside the task sheet (saccade) indicates that he is thinking and trying to remember a calculation.	Looking outside task sheet

Table 1: Data analysis steps—examples

RESULTS

The analysis of the data from the case study gives hints on how eye movements can be interpreted and shows limitations and opportunities of eye tracking in the domain of mathematical geometry tasks. Below we summarize the categories of eye movement patterns and their interpretation and illustrate them with according instances.

Interpretation of eye movement patterns

David's SRI hints on how to interpret eye movements in different instances. In many cases, his visual attention matched his cognitive attention: When he was looking back and forth between two corners, he, for instance, thought "how can I use the fact that these two (angles, authors' note) are equal to start determining how big they are?" When encircling a triangle with his eyes, he "was thinking if I should do something with this right triangle over here" [see link for both]. Here, the cognitive attention largely agreed with the visual focus of attention; however, it was not inferable in what way the visual focus was relevant for the ongoing cognitive process. Fixations on a corner of the hexagon indicated, that David was summing up the adjacent angles in this corner [link]. The attention was on the corner (in line with the eye-mind hypothesis), however, the process of calculating was hardly inferable from the eye movement. As this clip furthermore illustrates, some fixations indicated that David noticed a mistake he had made before: "After I calculated that, then I realized that my final answer down here [which he then fixated, authors' note] was also wrong and so I must have made a mistake." Here, the eye-mind hypothesis holds: the focus of visual attention was the focus of cognitive attention (the mistake). The SRI revealed further ambiguities in the interpretation of eye movements. E.g., the eye movement of looking along a line can indicate both: envisioning this line in his mind [see link for several instances] or taking into account or comparing the two adjacent areas [link] with peripheral vision.

In other instances, the eye-mind hypothesis did not hold. In one instance, David explained that while fixating a point in the figure, he was calculating something else in his mind that did not have any connection to the fixated area [link]. Another eye movement pattern that David commented on seven times in the SRI was a quick saccade where he looked outside the task sheet [e.g., link]. This pattern always indicated that he was thinking or reflecting: how to proceed next, trying to remember a calculation, or conducting a mental calculation. He argued that this helped him to focus on a certain thought: "Then I look up and just think for a second. Because if I look at this (the task, authors' note), I get distracted a little bit. So I just wanna follow the exact same trail of thoughts for a couple of seconds." Furthermore, David commented on two instances where his eyes wandered around in the task rather "hectically", with quick saccades, without fixating meaningful entities (such as corners or lines). He described that in these instances, he was "panicking a little bit", because he had realized that he "had made a quite big mistake". The eye-mind hypothesis held insofar as the saccades were interrupted by a fixation on the mistake on the task sheet [see link]). A related observation was that accelerated eye movements, where saccades and fixations get shorter, can indicate excitement, e.g. induced by time pressure or a new discovery.

Opportunities and limitations of analyzing eye-tracking data

Order of approaches. The SRI revealed that David's eye moments reflected the order of strategies used even when this was not always reflected in his drawings, gestures, and writing. This indicates that the analysis of eye-tracking data has an analytical advantage over the analysis of pure, simple video data.

Discarded approaches. Our analysis indicated that when working on the geometrical task, David went into several "dead ends" that he finally discarded. He describes such approaches five times in the SRI commenting on his eye movements; however, none of them expressed themselves in any gesture, drawing, or writing.

Up-to-dateness. David's eye movements in many instances preceded his writing, drawing, and gestures, e.g. pointing. The SRI indicated that he was already thinking of and envisioning a line-to-be-drawn 10 sec or even 30 sec before he then drew it. The up-to-dateness is a further advantage of eye-tracking analysis; which especially becomes significant if researchers or educators want to interact with students and immediately react to their problem-solving (giving feedback, support, or similar).

Ambiguity. As outlined above, our results indicate that a bijective relation between eye movements and cognitive processes solving a geometrical task cannot be assumed.

Emotional arousal. In the SRI, it appeared that in all instances where David mentioned emotional arousal (excitement, panicking), the reliability of the tracking was reduced. It is currently not clear whether this is an artefact of the eye tracker used in the study.

DISCUSSION

There is no doubt that eye-tracking offers various opportunities for mathematics education research. However the so-called "eye-mind" hypothesis is a rather vague guiding principle for analysis, especially because—as pointed out— eye movement interpretation can only be valid if the specifics of the domain and context are taken into account. Accordingly, we see the need to address the question of how to interpret eye movements in the context of mathematics education and of how closely eye movements are in fact related to students' cognitive attention and processes.

The results from our study confirm the power that eye-tracking data analysis holds in geometrical MSTs and relates to previous research (e.g., Muldner & Burleston, 2015). We found that in many instances cognitive attention agreed well with visual attention, eye movements indicated approaches that were not perceivable in gestures or drawings, and eye movements often allowed for immediate access to students' cognitive attention. This relates to the perceived merit of eye-tracking "that we can examine how and which information students are attending to" (Andrá et al., 2015, p. 241). However, in other instances, the cognitive attention did not go along with the visual attention. In these cases, the eye-tracking data are misleading and can thus easily be misinterpreted. Furthermore, many cognitive processes were not perceivable in the eye movements. What a student is thinking while fixating a point or looking along a line is not visible and is—in an analytical viewpoint—subject to interpretation. This confirms the bijectivity of the mapping of students' eye movements to their cognitive processes (Hayhoe, 2004) also for the domain of geometrical tasks.

It is a challenge for future research to deal with the ambiguities and possible misinterpretations that our paper gives a glimpse on. We believe our case study to be a springboard for further discussion and research on the interpretation of eye-tracking.

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