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To cite this version:

Markku Hannula, Miika Toivanen. The effect of digital tools on visual attention during problem solving: Variance of gaze fixations when working with GeoGebra or on paper. Eleventh Congress of the European Society for Research in Mathematics Education, Utrecht University, Feb 2019, Utrecht, Netherlands. hal-02422293

HAL Id: hal-02422293

https://hal.archives-ouvertes.fr/hal-02422293

Submitted on 21 Dec 2019

The effect of digital tools on visual attention during problem solving: Variance of gaze fixations when working with GeoGebra or on paper

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Research on reading indicates that visual attention is different when using digital media or print. This study aims to explore whether the choice between paper and GeoGebra influences visual attention during collaborative geometry problem solving. We measured eight students' fixation durations during different lesson phases: teacher instruction, individual work, pair work, group work, students presenting on the board, and whole class discussion. During all phases except teacher instruction we observed a difference in the fixation distributions as indicated by Kolmogorov-Smirnov tests. The use of GeoGebra is related to a slight shift from median length fixations to short fixations, suggesting lower cognitive load when students work with computers.

Keywords: Attention, computers, cooperative learning, eye movements.

Introduction

Paper and pen is a different medium than computer and screen and dynamic geometry environment (DGE) is very different from paper when solving a geometry problem. It is well documented that technology in general (Chauhan, 2017) and DGE in specific (Chan & Leung, 2014) have positive effects on mathematics achievement. There is much research on the specific affordances of DGE in learning and problem solving. For example, Christou, Mousoulides, Pittalis, and Pitta-Pantazi (2005) argue that DGE as a mediation tool encourages students to use modeling, conjecturing, experimenting**,** and generalizing in problem solving. Healy & Hoyles (2002) claim that DGE can scaffold the solution process and help students move from argumentation to logical deduction, while for less successful students the DGE may prevent them from expressing their mathematical ideas.

One way to examine how the learners' experiences are different in DGE and paper is eye-tracking. Human gaze consists of approximately three to four fixations (maintaining of the visual gaze on a single location) in a second (Rayner, 1998). Hartmann and Fischer (2016) compare eye-tracking information to mind-reading: the target of a fixation usually tells what we think about and the fixation duration corresponds with processing time. Fixation duration is an established indicator for perceptual or cognitive processing difficulty, also in the context of mathematics (Rayner, 1998). Glöckner and Herbold (2011) summarize research evidence to suggest that gazes related to more automatic processes would have shorter fixations (below 250 ms) and more elaborated information processing generally requires long fixations of more than 500 milliseconds.

Visual attention has been studied mostly in the context of reading and research on mathematics is much less frequent (Hartmann & Fischer, 2016; Rayner, 1998). In a systematic review on reading on paper and digitally, Singer and Alexander (2017) found out that reading comprehension is influenced by the text presentation. However, in the context of mathematics, we did not find any comparative eye-tracking studies between digital and non-digital learning environments.

Existing eye-tracking research on mathematics shows that the method is relevant. Andrá, Lindström, Arzarello, Holmqvist, Robutti, & Sabena, (2015) investigated how students read mathematical texts. In their study, fixation durations were typically in the range from 190 to 250 milliseconds. Fixations were longer for formulas than for graphs or text, but graphs attracted more fixations, leading to longer time spent looking at the graphs. In Lin and Lin (2014) study students were solving problems on tablets, and they suggest fixation counts, time on target, and run counts as relevant measures, because these differentiate successful from unsuccessful solvers and correlate with perceived difficulty.

We find the dominant methodologies for eye-tracking problematic. So far, most studies have been conducted in laboratory situations. We believe that problem solving needs to be studied in ecologically more valid contexts. We are interested in problem solving in contexts, where multiple modalities are present (Arzarello, Paola, Robutti & Sabena 2009) and multiple goals need to be addressed (Hannula, 2006). Most importantly, we are interested in problem solving in collaborative situations. Our earlier studies show that mobile eye tracking provides interesting data on attentional behavior in real classroom situations (e.g. Garcia Moreno-Esteva & Hannula, 2015; Haataja, Garcia Moreno-Esteva, Toivanen, & Hannula, 2018).

While we have not found studies examining the visual attention in digital and non-digital mathematics learning environments, it seems likely that a digital tool would have an effect on visual attention even in the context involving collaboration. We formulate our research question as follows: Does the choice of learning environment (paper vs. GeoGebra) have an overall effect on student attentional processes as indicated by fixation durations when students are solving a geometry problem.

Method

Participants

We examined fixation durations for one teacher and her eight students. The teacher taught the same problem solving session twice in two different Finnish grade nine classrooms. The first lesson was recorded in May 2017 and then the students solved the task using paper and pencil. We call this Paper lesson, even if at the end of the lesson the students continued examining the same problem using computers. The second lesson was recorded in May 2018 and then the students solved the task using GeoGebra software. This lesson we call the GeoGebra lesson, even if the students used also pen and paper to some extent. The ethics review has approved our research procedures.

The mathematics teacher Joanne was an experienced teacher. The students were four girls (using paper) and three girls and one boy (using GeoGebra). The students were selected among volunteers. Data from the first lesson has previously been analyzed from the perspective of student and teacher eye-contact (Haataja, Garcia Moreno-Esteva, Toivanen, & Hannula, 2018; Haataja, Salonen, Laine, Toivanen, & Hannula, forthcoming). The focus in this paper is to examine whether use of computers has an influence on students' fixation durations as an indication of an effect on their visual attention.

In both of the lessons, the teacher first introduced the lesson structure and when students got their respective tools (i.e. paper and rulers or laptop and GeoGebra) ready, the teacher posed the geometry problem to the class. Students first worked individually, then with a pair, then four together, and finally the students' solutions were collected on the board and discussed. During the first lesson, the teacher also posed an extension problem and during both lessons they continued to examine the problem with a GeoGebra application after discussion. However, that end part of both lessons is beyond the current paper's analysis. The relevant lesson phases are summarized in Table 1.

Lesson phase	Paper and pen (s)	GeoGebra (s)
Teacher gives instructions regarding the lesson structure (1)	44	38
Students fetch papers and rulers	139	
Teacher gives instructions for GeoGebra		92
Teacher poses the problem (1)	273	111
Individual work (2)	373	387
Teacher gives instructions for pair work (1)	45	22
Pair work (3)	205	513
Teacher gives instructions for group work (1)	30	40
Group work (four) (4)	1210	570
Teacher poses task extension	362	
Students come to the board (5)	190	130
Whole class discussion (6)	106	244

Table 1: Lesson phases and their durations. The numbered phases were analyzed in this study

The teacher was instructed to provide encouragement and to ask questions that require students to explicate their thinking but to not provide hints for how to solve the problem. When students were working individually, in pairs, or in groups of four, the teacher's activity consisted of roaming in the classroom and stopping for scaffolding one group at a time.

For the analysis, we included only those lesson phases that took place during both lessons. Moreover, we grouped together four separate instances when the teacher was giving instructions to the class or posing the problem. This way, we have identified six lesson phases that captured altogether 41 minutes and 16 seconds of the paper lesson and 34 minutes and 15 seconds of the GeoGebra lesson. Our analysis will focus on these parts of the lesson.

Apparatus

We recorded the actions and conversations of the problem-solving session using audio recording and three stationary video cameras in the classroom. In this paper, we analyze data form five gaze-tracking glasses that recorded eye movements of the teacher and the target students. The gaze-tracking device consisted of two eye cameras, a scene camera, and simple electronics attached to 3D-printed frames (Figure 1). The devices and software were self made (see, Toivanen, Lukander, & Puolamäki, 2017). The camera frame rate depended on lightning conditions, and maximum rate in optimal conditions was 30 frames/second. Data was recorded on laptop computers that were carried in backpacks allowing subjects to move freely in the classroom.

Figure 1: The gaze-tracking equipment.

Procedure

The recorded data was first analyzed to identify all fixations for all subjects. The fixation durations were estimated from the eye image difference between consecutive cropped eye image frames and setting a threshold for the average pixel-wise difference. This results in more accurate measure, compared to using gaze coordinates which might fluctuate due to algorithmic miscomputations. The information of fixation onsets and durations was then combined with information about timing of lesson phases from a video following teacher actions in the class. After this preliminary organization of data in Excel, the data was imported to SPSS 24 for statistical analyses.

First we analyzed the descriptive statistics of fixation durations. As the distributions were non-normal, we used non-parametric tests in our consequent analyses. When comparing fixation durations of two samples, we decided to use the Kolmogorov-Smirnov *Z*-test rather than Mann-Whitney's *U*-test, because it has more power to detect changes in the shape of the distributions. We analyzed the variation of gaze durations across the different lesson phases separately for students and the teacher for both the paper lesson and the GeoGebra lesson.

We predicted that the gaze behavior might be different across different lesson phases and, therefore, we analyzed the data separately for different lesson phases. Our expectation was that the fixation durations would on average be similar across those lesson phases where the use of tool would not be central (i.e. teacher instruction, students to the board, and discussion) while the possible effect of computer as a tool could be seen during individual work, pair work, and group work.

To check for sufficient similarity of visual behavior of compared individuals in the two conditions, we made pairwise Kolmogorov-Smirnov *Z*-tests for fixation distributions between individuals. For this analysis we selected the lesson phases where we expected the effect of computers to be minimal, i.e. teacher instruction, students to the board, and discussion. We used the information of pairwise differences to identify individuals whose fixation distribution was not comparable with other subjects' distribution. We then removed from future analysis those students whose fixation distribution deviated from other students the most. Finally, we made a comparison between student and teacher fixation distributions for the two lessons (paper and GeoGebra) for the different lesson phases using Kolmogorov-Smirnov *Z*-test.

Results

The total number of fixations during the analyzed lesson phases for all participants was 41,119. The shortest possible fixation to observe was 80 ms (two frames). The observed fixation durations varied from 80 ms to 15066 ms (*Mdn* = 234 ms, *M* = 430 ms, *SD* = 654.00). The durations were non-normally distributed, with skewness of 6.52 (*SE* = 0.012) and kurtosis of 69.62 (*SE* = 0.024).

We then analyzed the similarity of fixation durations for both sessions for the teacher and all students for the lesson phases that were less tool dependent (i.e. teacher instructions, students at the board, and discussion). The Kolmogorov-Smirnov *Z*-tests showed that the teacher fixations over both sessions were similar across the two sessions and different from all but one students' fixations. All but one compared student pairs had statistically significant differences for at least one of the lesson phases. However, it was possible to identify two students, who stood out more strongly from the group as having a different distribution of fixation durations. We removed these students from the analysis. After this removal, we had three female students from the paper lesson and two female and one male students from the computer lesson.

We then made Kolmogorov-Smirnov tests for each lesson phase to compare fixation durations between the two conditions (working with paper or working with GeoGebra) (Table 2). The results show that during pair work and group work the distributions differ statistically very significantly. The medians indicate that students using GeoGebra had shorter fixations during pair work than students using pen and paper, while the difference was small and opposite during group work. Differences for the other lesson phases were statistically significant ($p < .01$) for pair work and group work.

Lesson phase	Tool	*n*	*Mdn (ms)*	*Z*	*p*
Teacher instruction	Paper	933	269	.75	.627
	GeoGebra	1826	269		
Individual work	Paper	1775	269	1.38	.045
	GeoGebra	1918	267		
Pair work	Paper	2692	264	3.10	.000
	GeoGebra	1151	204		

Group work	Paper	2880	240	2.17	.000
	GeoGebra	5611	250		
Students at the board	Paper	786	233	1.57	.015
	GeoGebra	923	240		
Discussion	Paper	1177	268	1.59	.013
	GeoGebra	464	233		

Table 2: Kolmogorov-Smirnov *Z*-test results for tool effect on fixation durations.

To further explore the difference between paper and GeoGebra for visual attention, we looked at the distributions of different fixation lengths. We used the whole session for these students to identify the cut points for deciles. These cut points were then used to divide the distribution of fixation durations for the two lesson phases for paper and GeoGebra condition. We see that the GeoGebra condition had more deviation from the expected distribution of ten percent in each category. For pair work (Figure 2), the students using GeoGebra had more fixations in the time range 100 ms to 200 ms and fewer fixations of longer duration in comparison to paper condition. For group work (Figure 3), students using GeoGebra had fewer gazes in the time range 200 ms to 300 ms and more very long fixations. While the two distributions in the GeoGebra condition are somewhat different, there seems to be a trend for somewhat more short fixations at the cost of average duration fixations.

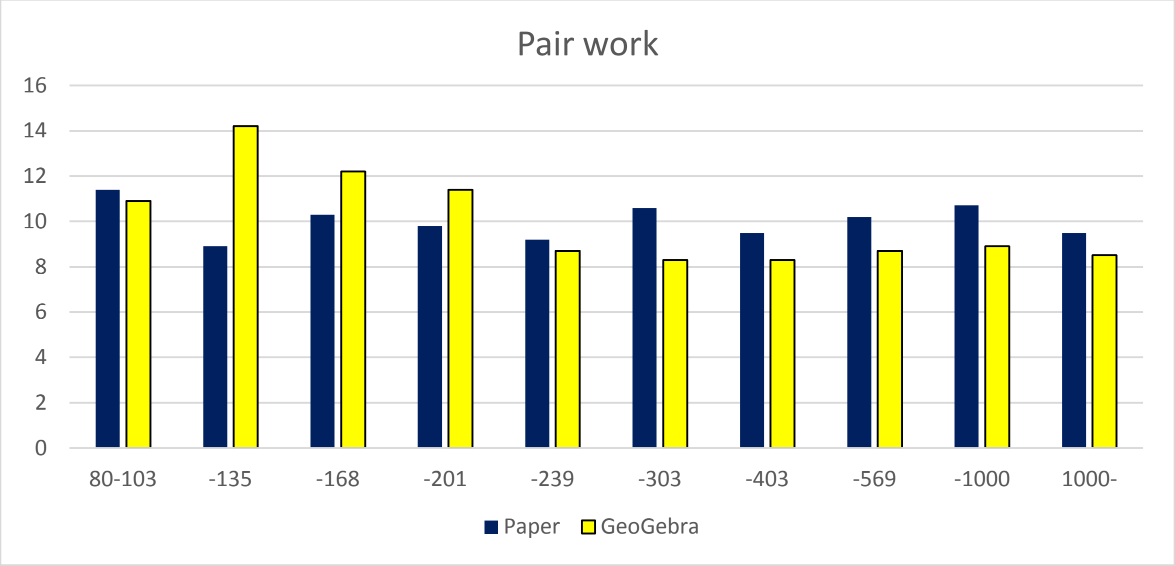

Figure 2: The distribution of fixation durations (ms) for the selected students for pair work

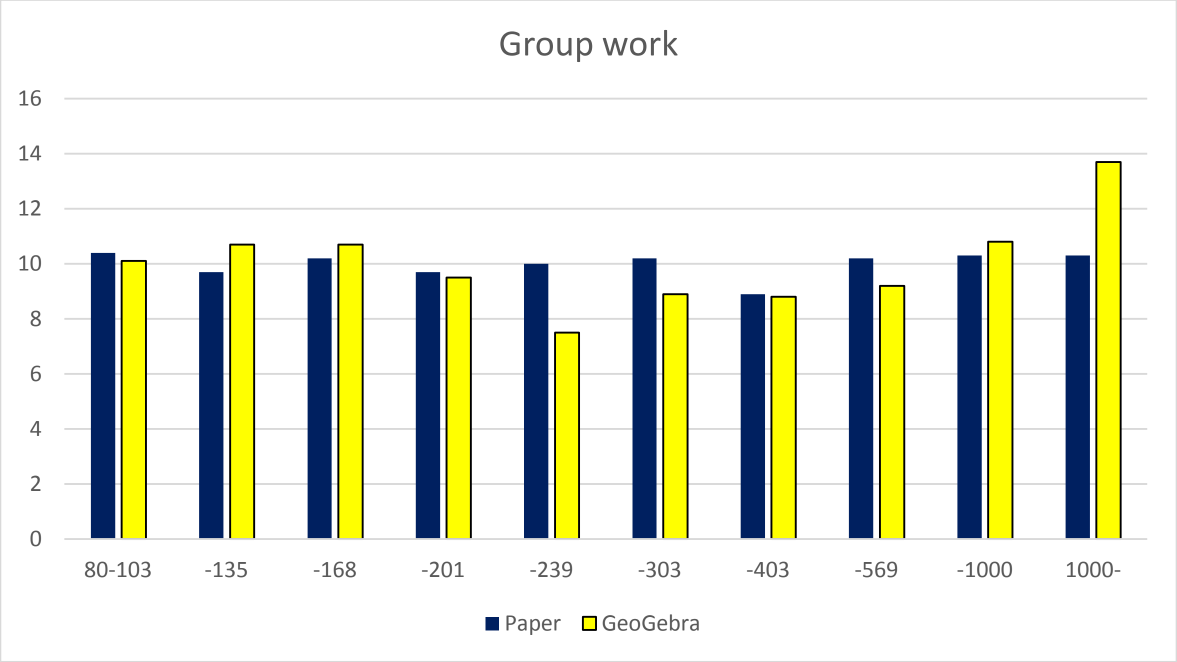

Figure 3: The distribution of fixation durations (ms) for the selected students for group work

Discussion

The results show an effect in student fixation durations for the choice between computer and paper as a media to solve a geometry problem. Use of GeoGebra is related with slight shift in fixation durations towards short fixations during collaborative phases of the problem solving. During this phase, students are comparing their individual solutions and discussing for alternative options. With respect to visual attention, this phase should include attention to other students and their drawings.

Shorter fixations usually indicate lower cognitive load. In this context, it might mean that students who worked interactively with GeoGebra, executed more often simple search tasks, such as searching for cursor on screen, which have a low cognitive demand. Alternatively, it might be related to easier extraction of information from neat GeoGebra drawings in comparison to peers' hand written solutions. Thirdly, the computer screen has a lot of visual attracters (e.g. menus) that may lead to short fixations on distracting elements. We provide one more possible explanation. In our earlier studies we have noticed that during interpersonal interaction in class, short fixations at the other person's face are frequent. It may be that the students working with GeoGebra have more short fixations on peers' faces, either because they have longer discussions or as it is more difficult to share screens than notebooks, they have less time for looking at solutions. These possible explanations can't be answered before we have analyzed student behavior during these events and annotated the targets of the fixations.

These results need to be taken with caution. There is significant variation in fixation durations between individuals and even within an individual across time. Although we tried to control for this variation and removed students with obviously deviating fixation duration distributions, the remaining students are by no means identical in their gaze behavior. Future studies should address lager variation of individual and situational differences. A larger sample of students would allow us to identify clusters of students whose visual attention follows a similar pattern and then compare these groups with different attentional profiles across digital and non-digital contexts. There is also need to examine qualitatively the nature of visual attention where a difference has been found. For example, what are the targets of longest fixations when solving the problem with GeoGebra and not? We also need additional data with different types of tasks. Perhaps some of the differences identified here are specific to the task used? Overall, this is just a beginning of a long journey.

Acknowledgment

This research was funded by the Academy of Finland grant no. 297856 (MathTrack -project).

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