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THE EYE-TRACKING RESEARCH METHOD IN THE PROCESS OF SOLVING MATHEMATICAL TASKS REQUIRING DRAWING ANALYSIS

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Abstract. This study presents the results of research using an eye-tracking technique which enables following eyeball movements while solving a scientific task. Also presented is an analysis of the *visual attention* for participants (further called *subjects*) of a different mathematical experience while solving a mathematics test task. The aim of the research is to determine the profile of methods of solution of tasks which require the analysis of a diagram. The research opens new cognitive possibilities in mathematics didactics by showing the utility of the eye-tracking technique in a deeper recognition of the processes of learning and teaching Maths.

Keywords: eye tracking, heat map, scan path, solving mathematical task, education, mathematics didactics.

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1. Introduction

At present, modern measurement instruments enable broadening the realm of empirical research in various fields of science. The article presents a part of the research using a device called an "eye-tracker", applied to tracking the eyeball movements of a test subject. A review of up-to-date eye-tracking research from the period 2000-2012 was presented in the paper of the Taiwanese researchers (Lai et al. 2013). The authors point out the wide application possibilities of the eye tracker in research concerning the analysis of the text reading process, visual perception and the methods of

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problem solving and reasoning processes. Eye-tracking research enables a deeper understanding of conceptual development and many cognitive and behavioural aspects in humans.

Using eye-tracking as a research method permits a deeper look into the thought processes in the field of mathematical reasoning. As an example, research of this kind in the domain of mathematics teaching carried out in parallel to traditional research methods allowed Schwank (2001, 2003), to determine two types of mathematical thinking: functional thinking and predicative thinking. The author differentiated the typical elements of eye-ball movement for each of these types.

Using the eye-tracking method, it has also been proved that prior knowledge in the domain of mathematics, including the acquisition of incorrect operational schemata, can sometimes interfere with learning (Chesney, McNeil, Brockmole, Kelley 2013) and cause difficulties in solving equations with operations on both sides of the equals sign.

The growing availability of technologically advanced devices has also aroused interest in this method among Polish researchers. Polish research using an eye-tracker was carried out, amongst others, in neurobiology (Ober et al. 2009) and translative cognition (Płużyczka 2012).

Increasingly, the method is being used in educational research aiming at exploring knowledge on a broadly defined learning process and its adaptation in the pedagogical and didactic process (Nowakowska-Buryła, Joński 2012; Rosiek, Sajka 2014; Sajka, Rosiek 2014; Stolińska et al. 2014; Wcisło et al. 2014; Andrzejewska et al. 2015).

The application of the aforementioned device has been used in research on the process of solving mathematical tasks which require the visual analysis of data featured in the diagram – a preliminary analysis of this research was outlined in the thesis (Rożek 2014). The article will present a detailed analysis of the process of solving certain mathematical tasks, indicating new results of the mentioned research.

2. Eye-tracker measurement capability

Eye-tracking studies are a collection of research techniques which enable following eyeball movement – that is, changes of their location over a defined period of time. “The collected data regarding time and directions of the visual scanning of a certain area allow to precisely characterise human visual activity and to state how an image and text code is processed” (Nowakowska-Buryła, Joński 2012). An eye tracker enables recording certain parameters of the mechanisms of visual perception – particularly saccades and fixations. “Saccades are rapid eye movements used in repositioning the fovea to a new location in the visual environment. …Saccadic movements are both voluntary and reflexive” (Duchowski 2007, p. 42). On the other hand, fixation is a state of a relative rest of an eye “characterized by miniature eye movements: tremor, drift, and microsaccades” (Duchowski 2007, p. 46).

The eye-tracker registers various data acquired during the study by means of video recordings of the movements of the eyeballs of the subjects. With the BeGaze software, the data are grouped together into datasets of different types which can then be analysed.

Among many varied results, the following can be distinguished:

The Gaze plot (Figure 5) – shows which elements of the picture displayed on the screen were being watched by the tested person. **Saccades** are seen as continuous lines while **fixations** as circles of different diameters. The bigger the diameter, the longer the fixation on a given element. These graphic representations help “answer such questions as: (a) on which elements the subject held their eyes, (b) which elements gained the longest fixation, (c) has one of the elements focused the greatest attention /so called *pendulum effect*/, (d) is there any regularity in focusing on certain elements by a subject, (e) are there any elements that a subject returned to again” (Płużyczka 2012).

Gaze replay – shows in an animated form the performance of the study with the gaze plot of the tested person or several tested persons. It allows the reconstruction of the order in which individual elements of the screen were perceived.

Heat maps – show graphically a thermal arrangement of attention directed towards an inspected element distinguishing elements both noticed and ignored during the sight scan. Thus, it displays, using colours, the total attention focus of a subject directed onto a particular element. It is possible to either show the results as **a black and white map (Focus Map)** (Figure 7) and then the brighter the area on the map, the more attention was given to it by a subject, or as **a colour map (Heat Map)** (Figures 8-10) where the redder (warmer) the area, the greater the attention focus on this element by a subject.

Areas of Interest (AOI) (Figure 11) – these are defined by the researcher and represent relevant (for them) areas of the projected image within which detailed measurement data can be obtained.

Key Performance Indicators (KPI) (Figure 12) – present specific statistics specification following the analysis of the study material and the definition of the areas of interest mentioned above. Amongst the statistical data obtained, one can find those concerning: dwell time in a certain area [ms]; time duration to the first fixation [ms]; average fixation time [ms]; number of fixations; number of revisits to the certain area.

3. Methodology and methods

The survey was carried out in February 2014 in the Neuro-Didactics laboratory at the Pedagogical University of Kraków by the newly created Research Group of Cognitive Didactics.

Purpose

This study was mainly aimed at the following:

1. Working out preliminary characteristics of ways of solving a task requiring an analysis of a drawing.

2. Searching for the factors which influence the consideration of all the aspects (including textual) of a task by the subjects.

Method

The research method was eye-tracking. Recording the eyeball movement was performed with the use of a fixed eye tracker manufactured by Senso Motoric Instruments, model iView X Hi-Speed 1250. Analysing the obtained data was possible with the BeGaze software.

The study group was quite varied. There was an analysis of the research results of 99 people including:

– 24 pupils of the 1st class of a Kraków secondary school – in later parts of the article the group is called "*Pupils*";

– 62 students of the Pedagogical University in Kraków, IT or Mathematics Bachelor's studies – further called "*Students*";

– 13 experts, i.e. 9 PhD students of Physics and 4 persons with at least a Doctor's degree in sciences – further called "*Experts*".

The subjects were shown slides on a computer screen with consecutive tasks and were requested to solve them. During solving the tasks, the test subjects were not allowed to make use of any helping devices (e.g. a calculator or a notebook). After solving a certain task they were asked to indicate (by clicking a mouse) one of the five answers placed at the bottom of the displayed slide. Considering the possibility of accidental mouse clicking by the subjects or the intention to change their answer, they were also asked to orally confirm their final answer which was recorded on a separate sheet. The subjects answered 3 questions and solved10 multiple-choice test tasks in Physics, IT and Mathematics. This article analyses one of the tasks, the so-called *ball task*, classified as a Maths task. The slide presented to the subjects (Figure 1) contained a textual instruction, drawing and five numbers – answers, out of which only one was correct:

The circle pyramids were drawn following a certain rule.
How many circles will the **sixth** pyramid be built of?

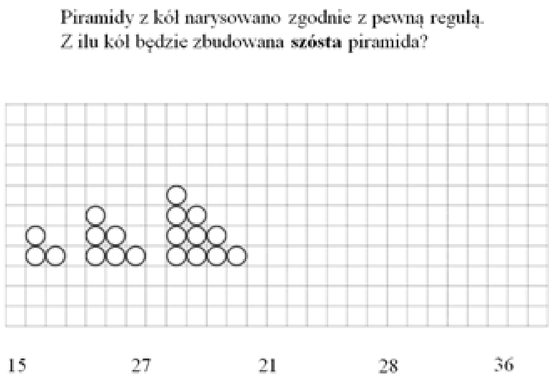

Fig. 1. The slide demonstrating the task

Source: based on (Rożek 2014, p. 386).

4. Results analysis

At the bottom of the slide presented to the subjects were placed five distracters in the form of numbers, of which only one answer – 28 circles – was correct. In the presented analysis of the research results, the consecutive answers occurring on the slide as numbers 15, 27, 21, 28, 36 are designated as answers A, B, C, D and E.

Initial analysis of the research results shows that relatively many people gave the incorrect answer in solving this task (Figure 2). Among the 99-person study group this was more than 80% of all subjects.

Such a drastic discrepancy between the number of the correct and incorrect answers gave rise to the following research questions:

– Which of the incorrect answers A, B, C, E was indicated most frequently?

– Will the analysis of the research material gathered using an eye-tracker allow the formulation of hypothetical reasons for choosing the answer which appeared most often?

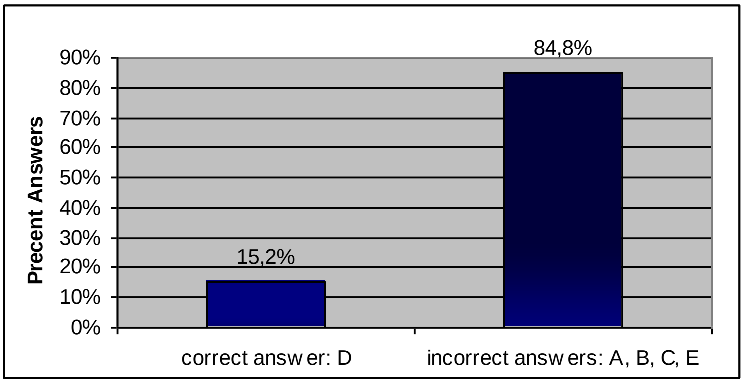

Fig. 2. Percentage summary of task solutions

Source: own elaboration.

Chart (Figure 3) presents the percentage arrangement of the number of particular answers:

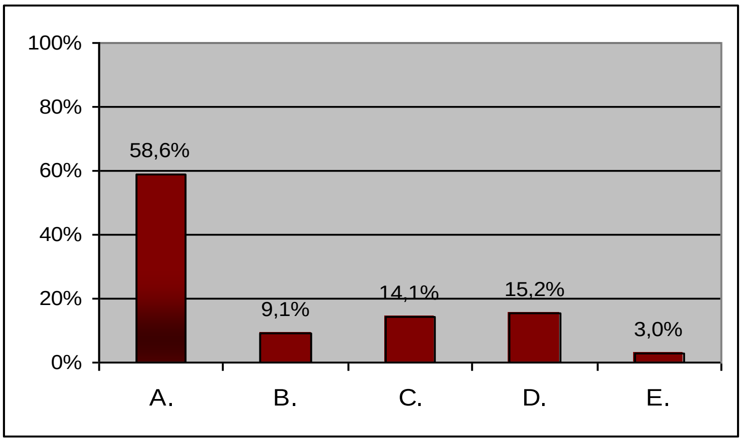

Fig. 3. Answer arrangement for the test of 99 people

Source: own elaboration.

The conclusion drawn from the chart is not only the fact that answer A was the most frequently chosen one, but also something much more surprising, i.e. that on average every second subject indicated answer A. This result directed further analysis of the study material. The possible answer options to this task were divided into three groups: (1) answer A – incorrect (it is actually the number of circles of the fourth, not the sixth pyramid), (2) answers B, C, E – other incorrect answers, (3) answer D – correct (the number of the circles of the sixth pyramid).

The average task solving time for such prepared groups is shown in the chart (Figure 4).

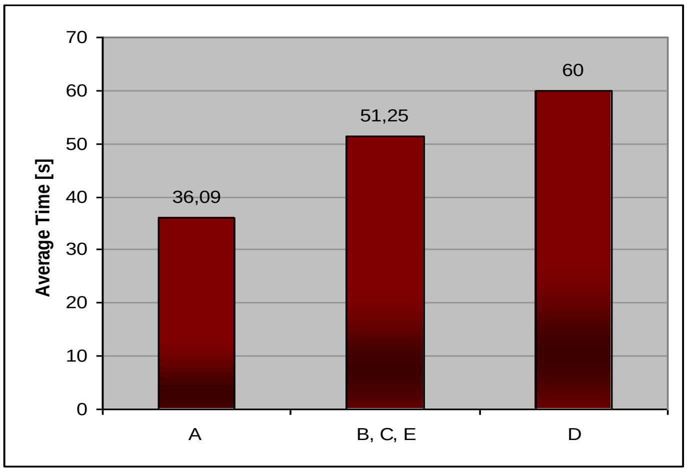

Fig. 4. The average task solving time

Source: own elaboration.

The average time needed by the subjects to indicate the correct answer is 1 minute. The short task-solving time by the people indicating answer A – below 40 seconds – might suggest a "random" solution and the significance of placing this answer as the first from the left side. This hypothesis may be discredited by the gaze plots of the people indicating this answer. The example gaze plot of such a person presented in Figure 2 clearly shows intensive searching for regularities within the third pyramid.

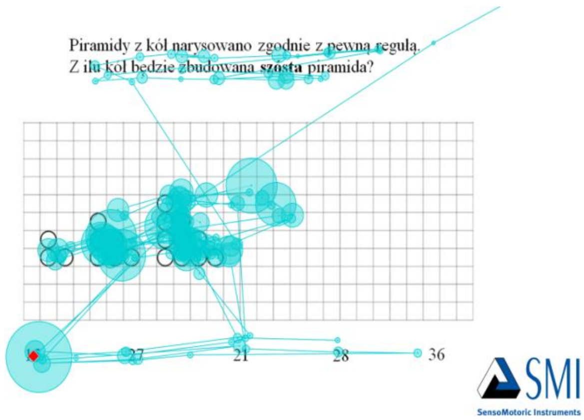

Fig. 5. Scan path of a person indicating answer A

Source: own elaboration.

Such a scan path indicates clearly that the person tested was intensively counting the number of circles, concentrating their sight on the third pyramid – which means that it was not a random solving method.

These observations made the researchers look for other sources of domination of choosing answer A among the tested people. Thus naturally, new research questions emerged: in which research group (*Pupils*, *Students*, *Experts*) was answer A given most frequently?

The answer to this question can be seen in the chart (Figure 6):

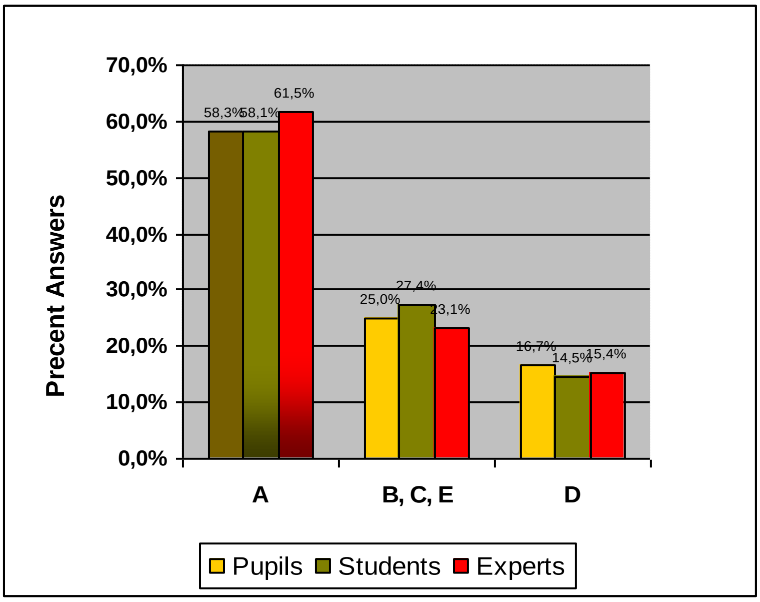

Fig. 6. The arrangement of answers in groups of: Pupils, Students, Experts

Source: own elaboration.

Over half of the people (about 60%) in each research group pointed out answer A as the solution to this task (however, it should be remembered that the groups compared were not equinumerable). This surprising regularity (also in the arrangement of the remaining types of answers) suggests deeper reasons for the participants' decisions. Moreover, in view of the above, the hypothesis: *answer A was indicated most frequently because it was placed as the first one from the left side,* also seems highly improbable.

Another incoming hypothesis which explains such a frequent and regular choice of answer A among the different research groups could be related to the fact that the sight of the subjects omitted the word **"sixth"** in the task instruction (even though it was highlighted by the use of boldface). The word **“sixth”** contained a significant textual condition of the task, which, when taken into account, determined the correct answer. A hypothesis has been formulated assuming that the subjects omitted this key word and immediately sought regularities in the given figure. Focusing attention on the calculations resulted in the fact that answer A – the number of circles in the next, fourth pyramid – became a rational answer and was regarded as the correct one.

Heat maps were analysed in order to find confirmation of this hypothesis. We present below a black-and-white Focus Map (Figure 7) and acoloured Heat Map (Figure 8) made for all the subjects.

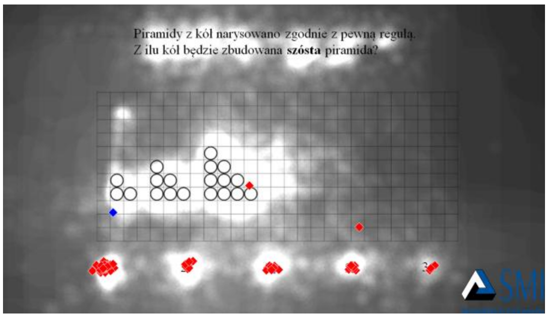

Fig. 7. Focus Map – All

Source: own elaboration.

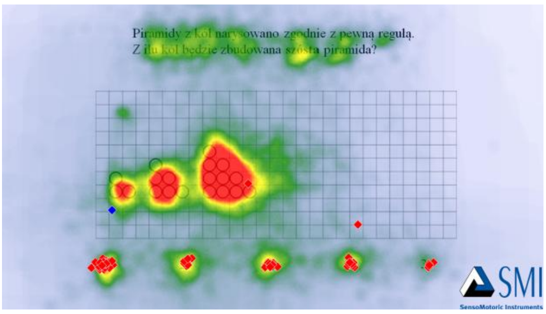

Fig. 8. Heat Map – All

Source: own elaboration.

The white spots on the Focus Map and the yellow colour on the Heat Map corresponding to the words “how many” and “sixth”, indicate that these words emerged as the key words for the subjects and were not omitted by them during reading the textual instruction.

In the article (Rożek 2014), the way of searching for the task solution was characterised based on the analysis of the sight paths for the group of subjects indicating answer A and answer D. Similar conclusions can be drawn while analysing the differences in the arrangement of the fixation points shown as the heat maps prepared separately for the people indicating answer A (Figure 9) and answer D (Figure 10):

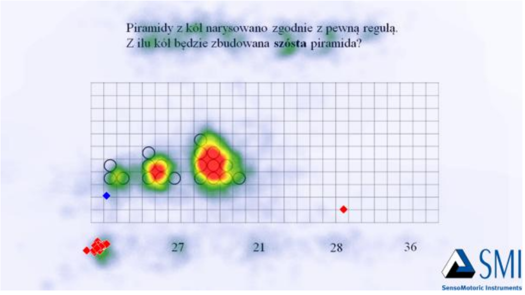

Fig. 9. Heat Map for answer A

Source: own elaboration.

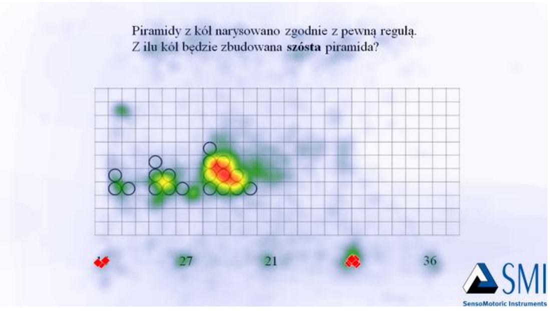

Fig. 10. Heat Map for answer D

Source: own elaboration.

Both on the map with answer A and answer D there is an apparent increase of visual attention to the textual information: to the words “how many” and “**sixth**”. Another feature common to both the maps is the dominating sight fixation on the consecutive pyramids of the figure, especially on the third pyramid. **Such** visual analysis of the third pyramid allows to discover the way of forming the consecutive pyramids and calculate the number of circles. It demonstrates that in most cases answer A was not selected at random but was the result of the analysis of the figure – perhaps an analysis which was completed too soon.

Similar conclusions can be found in the article (Tsai et al. 2011, p. 384), where the author states that one of the reasons for incorrect answers is: “finding that some students need more fixations to process information in the zone of problem statements or title descriptions”.

While comparing both the maps however, we find a noticeable difference in the way of tracking the figure in the search for a solution. This coincides again with the conclusions drawn by Tsai, Hou, Lai, Liu andYang (2011, p. 383), pointing out different approach of the students. “Successful problem solvers tend to shift their visual attention from irrelevant factors to relevant factors, while unsuccessful problem solvers tend to shift their visual attention from relevant to irrelevant factors and to the problem statement”.

With the correct answer D, the searching area exceeds distinctly the third pyramid. This might be the proof of searching by the subjects for the number of the circles in the consecutive pyramids: the fourth, the fifth, to eventually gain the number of the circles of the sixth pyramid.

The above considerations lead to the conclusion that the subjects' ignoring the condition included in the word “**sixth**”, had a crucial impact on the type of the given answer – omitting this condition suggested providing answer A, which is the number of circles of the consecutive, fourth pyramid. For this reason, it was decided to carefully analyse some chosen areas of the slide. The following 13 Areas of Interest (AOI) were defined (Figure 11):

A 01 – textual formulation of the task;
A 02 – key word of the task;
A 03, A 04, A 05 – graphical formulation of the task;
A 06, A 07, A 08 – imaginary areas of creating consecutive pyramids;
A 09, A10, A11, A12, A13 – optional solutions of the task.

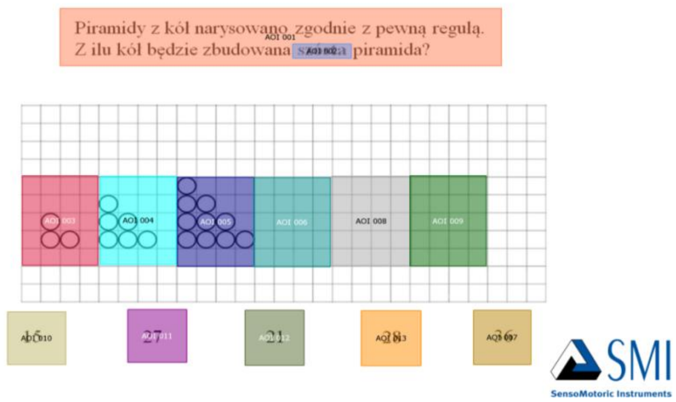

Fig. 11. Areas of Interest

Source: own elaboration.

Defining the Areas of Interest allowed to generate the results as the Key Performance Indicators (KPI) such as: Sequence, Entry time, Dwell time, Hit Ratio, Revisits, Revisitors, Average Fixation, First Fixation, Fixation Count and to compare the behaviour of the participants giving answer A and D within the relevant areas. Figure 12 shows the KPI (Key Performance Indicators) for the people who chose answer A.

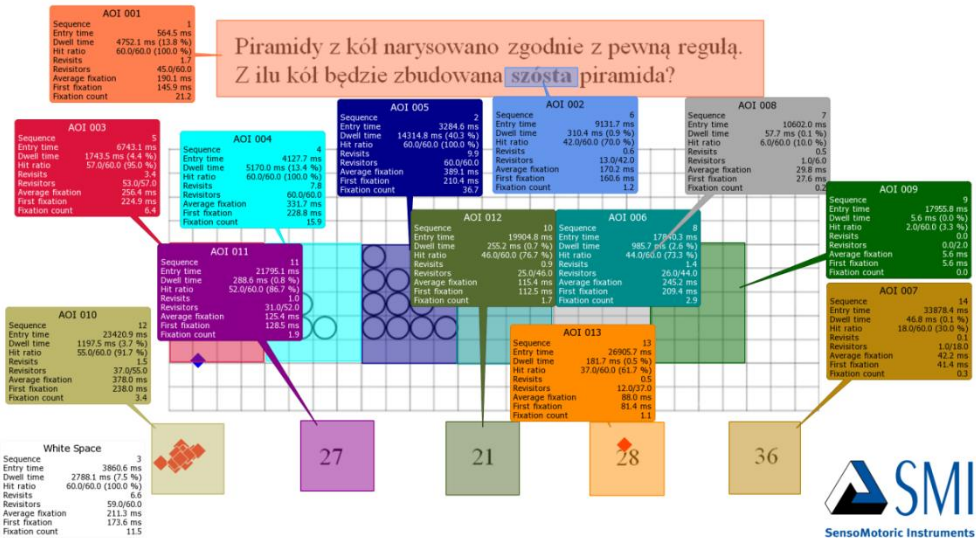

Fig. 12. Key Performance Indicators – answer A

Source: own elaboration.

Based on the KPI for answers A and D, the parameters within the defined area AOI 002 containing the key word "**sixth**" were compared which allowed for the precise analysis of this area. Given below, the table for this area (Table 1) combines the parameters connected with the participants' sight fixation:

Table 1. Average fixation, first fixation and fixation count for answer A, B, C, D, E

	Answer A	Answer B	Answer C	Answer D	Answer E
Average fixation [ms]	**170**	141	219	**152**	169
First fixation [ms]	**160**	138	188	**133**	161
Fixation count	**1,2**	1,2	2,9	**1,9**	2

Source: own elaboration.

Although the average fixation count of the people choosing answer D (1,9) is higher than the average fixation count of those giving answer A, the average fixation time on the area containing the word "sixth" is slightly longer than with the people choosing answer A. However, these are not significant differences. The conclusions following the data in the table are that the fixation time and fixation count on the area with the word "sixth" were not the only factors having a decisive significance for indicating the correct answer by the participants.

The list of the other parameters connected with the revisits to the area AOI 002 was given in Table 2:

Table 2. Revisits and revisitors for answer A, B, C, D, E

	Answer A	Answer B	Answer C	Answer D	Answer E
Revisits [count]	**0,6**	0,6	1,8	**1,4**	1,7
Revisitors [count]	**13,0/42,0**	3,0/7,0	9.0/12.0	**8.0/12.0**	1.0/3.0

Source: own elaboration.

The average number of revisits to the discussed area for answer D is 1,4, which is more than double for revisits in the case of answer A. It can also be seen from the table that for answer D, 8 people out of 12 , i.e. more than half "eye dwelling" on area AOI 002, returned to this spot during solving the task, while for answer A, out of the 42 people looking at the word "sixth" only 13 people (i.e. less than one third) returned to the same area. These facts let us draw the conclusion that what turned out to be important for indicating the correct answer was not the fixation count and time – much more significant were the revisits to the area containing the word "sixth".

5. Summary

The initial analysis of the discussed task presented in (Rożek 2014), pointed to the fact that a large number of incorrect answers might have been caused by the specific type of task which brought about a certain type of "trap". Answer A might be regarded as the correct one in a task where the word "sixth" would not appear. In other words, the deletion of the textual information "sixth" causes the implication that the task concerns the number of circles of the next immediate pyramid, and so the correct answer to such a modified question would be answer A. Such a quality could not have been applied to other incorrect answers because answers C and E would have become the correct ones in modified sentences in which the word "sixth" would be **replaced** with other words: for answer C it is the “fifth” pyramid made of 21 circles, and for answer E the “seventh” pyramid is formed of 36 circles.

However, further analyses brought a surprising result: regardless of their mathematical experience, the selected experimental groups of *Pupils, Students* as well as *Experts*, had given over 50% of incorrect answer A. This pointed to a certain kind of regularity of the subjects’ behaviour not linked to the level of their substantive mathematical knowledge. Thus the hypothesis arose that the subjects choosing answer A had overlooked the key word “sixth” and gave the rational answer concerning the number of circles in the fourth pyramid. However, based on the data analysis generated as KPI, a significant new conclusion appeared: omitting the (textual) task condition **was not** caused by omitting by sight the textual area with the given task condition (there are no visible significant differences in the average fixation time and fixation count). An even more important influence on giving the correct answer resulted from the numbers of returns to the field with the word “sixth”.

Those subjects who noted that the word “sixth” was important (this was the crucial condition of this task) – revisited it frequently to confirm that it should be “the sixth” and not e.g. the fifth pyramid – as demonstrated by the higher count of revisits to the area with the word “sixth” for the people indicating the correct answer (the number of the revisits is nearly two and a half times bigger than the people who chose the answer A; the fraction of the revisits is two times bigger).

A cognitivist view on the research results suggests a certain hypothesis: while solving such type of mathematical test tasks the mind sometimes by suggesting a way “to reach quickly a reasonable answer “ e.g. by omitting a certain condition.

However, confirmation of this hypothesis requires further studies and it seems that eye-tracking research is the best method which allows verification of the given hypothesis.

Suggestions made in this article show that using the eye-tracking method in research on didactics of mathematics carries new cognitive possibilities. It may prove particularly useful to understand the mental processes of people tested during solving mathematical tasks requiring the analysis of an image.

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