

Chapter 11

The Impact of Students' Educational Background, Formal Reasoning, Visualisation Abilities, and Perception of Difficulty on Eye-Tracking Measures When Solving a Context-Based Problem with Submicroscopic Representation



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Introduction

Science and technology continue to develop rapidly, which leads to the need for all-encompassing science education, starting in the early years (Lloyd et al., 1998; Millar, 2006). All students should benefit from the science education provided, which includes an understanding of the scientific dimension of phenomena and events, critical recognition of the possibilities and limitations of science, its role in society and its contribution to citizenship, as well as the development of critical thinking, oral communication, and writing skills (BSCS, 2008; ICSU, 2011; Vieira & Tenreiro-Vieira, 2014). In addition, Harlen (2010) suggested that science education should enable everyone to make informed choices and take appropriate action that will affect their well-being and the well-being of society and the environment. A school curriculum that develops an understanding of fundamental science concepts, ideas about the nature and limits of science, ethical reasoning, as well as the skills of argumentation, and opportunities for students to apply them in a range of novel contexts, is appropriate preparation for future work on social issues arising from the application of science (Lewis & Leach, 2006). The content that students learn in primary school is defined, usually consisting of living beings and their interactions with the environment, materials and their properties, and forces and their effects. However, no preparatory course can cover all the science content that teachers have to teach. The courses must also promote independent learning and enable in-service

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teachers to recognise the further knowledge they need when confronted with new challenges in teaching.

Representations are basic tools that help students to take advantage of the quality of learning in various scientific disciplines such as mathematics, chemistry, and physics (Mozaffari et al., 2016). The term 'representation' has several interpretations; mostly, it only refers to concrete, external descriptions used by a problem solver. Some examples include pictures or sketches, physics-specific descriptions (e.g., free body diagrams, field line diagrams, ray diagrams, or energy bar diagrams), animations, concept maps, diagrams and equations or symbolic notation, and similar. Some researchers further distinguish between general and physics-specific representation (Docktor & Mestre, 2014).

However, the complexity of teaching and learning concepts of physics, and more often of concepts of chemistry, can be explained on three levels: the macroscopic, the submicroscopic, and the symbolic level, which can be imagined as the corners of a triangle in which no form of representation is superior to the others but rather complements them (Johnstone, 1982, 1991). The macroscopic level of chemical concepts is illustrated by the observation of chemical phenomena. The interpretation of the observations is explained by the interaction of particles at the submicroscopic level. To illustrate chemical concepts at the particle level, static or dynamic submicroscopic representations (SMRs) can be used (Devetak & Glažar, 2010). It is also important to note that, at lower stages of chemical education, SMRs can be represented as a particle even if a represented molecule is more complex, while SMRs illustrate the actual structure of molecules at higher stages of chemical education. At the symbolic level of concept representation, these SMRs could be translated into established symbols, such as symbols of the elements, formulae and equations, mathematical equations, and various graphical, schematic representations (Johnstone 2001; Levy & Wilinsky, 2009; Devetak, 2012; Taber, 2013). Students often have difficulties in understanding SMRs, and teaching about the world of particles is challenging, since particle theory is abstract. Therefore, the use of visualisation material is necessary for classroom presentation (Johnstone, 2001; Exerciseer & Dalton, 2006; Kautz et al., 2005; Lin et al., 2016; Cheng & Gilbert, 2017).

In addition, the use of SMRs plays a crucial role in the teaching of chemistry, as it can enable the visualisation of phenomena that cannot be directly observed due to the size of the entities in these processes (e.g., atoms, ions, molecules, and subatomic particles) (Phillips et al., 2010). Visualisation abilities might be considered as the students' ability to recognise and manipulate visual objects (Barnea, 2000; Gilbert, 2005). The study by Wu and Shah (2004) introduced the role of visualisation in chemistry teaching and learning and suggested that one of the main features of visualisation tools should be to provide multiple representations (e.g., static 2D or 3D SMRs, computer animations of particles, physical models, etc.) that should be implemented in the classroom in such a way that students can visualise the connections between representations and relevant concepts.

The relationship between the students' perception of task or problem difficulty and the actual difficulty, measured by the successful completion of a task, is low. Students are not in a position to predict which tasks are difficult. Nunan and Keobke

(1995) cited three factors: lack of familiarity with the nature of the task, confusion on the part of students over the purpose of the task, and cultural knowledge that might justify students' views on the difficulty of the task. In addition, Andrzejewska and Stolińska (2016) investigated the comparison of task difficulty using eye-tracking in combination with subjective and behavioural criteria. They found that there was no correlation between the activity of eye movement parameters, which are considered indicators of mental effort, and a student's opinion about the difficulty of the task. On the basis of the theoretical background of the paper, it can be concluded that the average fixation time can be considered as an index of the difficulty of the problem or task to be solved. However, an analysis of the data obtained made it possible to observe discrepancies in the categorisation of the difficulty of the tasks according to subjective and behavioural criteria. A significant and strong correlation was found between the difficulty of the task, determined by the percentage of correct answers, and the fixation parameters, although no such relationship was found with the blinking parameters.

Docktor and Mestre (2014) prepared the paper *Synthesis of discipline-based education research in physics* in which they present various aspects of research in physics education in detail. They mentioned that eye-tracking has attracted the attention of the science community, including the research community for physics education (Han et al., 2017; Yen & Yang, 2016) and that several studies have been conducted (Pavlin et al., 2019). Otherwise, in cognitive psychology, eye-tracking methods (tracking eye gazes by capturing or recording position and duration during cognitive tasks) are quite common and are used to study what people pay attention to without disturbing their thought processes. It is generally agreed that the place where the eyes are looking indicates what people are looking for, so by tracking eye fixations one can inconspicuously observe what is being looked for during a cognitive task and thereby draw conclusions about what the mind is processing (Hoffman & Rehder, 2010; Rayner, 1998; Stuart et al., 2019).

Problem-solving is of significant interest in physics education research. There are many different definitions of what problem-solving means (Maloney, 2011). In order to uncover the students' approach, problem-solving has also been studied using the eye-tracking method in recent years (Tai et al., 2006). Smith et al. (2010) investigated which aspects of problem solution students look at while studying the examples. The results show that while students spent a large amount of time reading conceptual, textual information in the solution, their ability to remember this information later was poor. The students' eye-gaze patterns also showed that they often jumped back and forth between textual and mathematical information when attempting to integrate these two sources of information. The fact that performance is affected by the representation format is confirmed by studies that show that some students give inconsistent answers to the same problem-solving question when presented in different representation formats (Kohl & Finkelstein, 2005; Meltzer, 2005).

Carmichael et al. (2010) and Madsen et al. (2012) have used eye-tracking to examine how expert and novice learners allocate visual attention to physics diagrams in cases in which information critical to answering a question was contained in the diagram. They found that experts spend more time looking at thematically relevant

areas of diagrams than novice learners did. Similarly, Pavlin et al. (2019) showed that the total fixation duration is longer for animations containing examples of novel stimuli (e.g., air pump), but that the percentage of fixation duration spent by students of different age groups on the area of interest with correct animations is significantly different. These results suggest that students' age and, therefore, the number of years of chemistry studies turn novices into experts and influence the fixation duration in the area of interest with the correct animation.

Several other studies including eye-tracking were conducted regarding physics education, for example, investigations of the trouble-shooting of malfunctioning circuits were done by Van Gog et al. (2005); comprehending malfunctioning mechanical devices was the topic of the study carried by Graesser et al. (2005); Hegarty (1992) on how mechanical systems work; Kozhevnikov et al. (2007) studied the relationship between spatial visualisation and kinematics problem-solving abilities; Smith et al. (2010) explored what novices look at while studying example problem solutions in introductory physics, comparing the time spent on mathematical information (equations) to the textual or conceptual information, and similar. The study by Klein et al. (2020) showed that graphical representation can be beneficial for data processing and data comparison. In addition, graphical representation aids in visualising data and thus reduces the cognitive load on students when performing measurement data analysis, so students should be encouraged to use it (Susac et al., 2014).

Furthermore, eye-tracking can make unique contributions to the validation of concept inventories at the behavioural level without using interview or survey data. While simple measures of time (length of visit durations on the question or options) are well suited to differentiate between different confidence levels of test-takers, they do not distinguish between the correct from the incorrect performers for this type of question (Viiri et al., 2017).

As shown, the eye movements of individuals can be measured and, after careful consideration, used to interpret processes during solving the tasks, since the direction of the human gaze is closely related to the focus of attention as individuals are processing the observed visual information, as indicated by Just and Carpenter (1980) and Rayner (2009). An eye-tracker device can be used to measure eye movements, such as fixations of the gaze on a specific area of the computer screen during a certain activity and saccades (i.e., eye movements between fixations) (Havanki & VandenPlas, 2014). The total time (total fixation duration [TFD]) spent in specific areas of interest (AOI) can be measured to capture students' visual attention to different elements of the context-based problem on the computer screen, which is also known as the 'visual attention' or 'attention allocation' of the student (Tsai et al., 2012).

According to Hyönä et al. (2002), a longer total fixation duration (TFD) on an AOI could indicate the salience, meaning deeper and more complex information processing, difficulties in processing this area, or less efficiency in finding the information on the computer screen (Green et al., 2007). Research has shown that experts had shorter fixations on task-irrelevant information than novices did, and longer fixations on relevant information (compared to novices) (Gegenfurtner et al., 2011). However, to ensure a proper fixation allocation, the problem or task displayed on

the computer screen must be divided into several wisely chosen AOIs according to the placement elements that are of interest with regard to the research problem (Ferk Savec et al., 2016).

Visit count is another frequently used key figure and can be informative when examining participant interest or ease of understanding. The measure used to count the number of visits provides information on the number of individual returns to an AOI and is an indicator of its attractiveness, usefulness, or lack of clarity (West et al., 2006). Mean pupil dilation is a measure for identifying cognitive load (Bassok, 1990). As reported by Beatty and Lucero-Wagoner (2000), it is a common eye-tracker measure. However, Just et al. (2003) report that mental effort is reflected in the enlargement of the pupil diameter and showing the difficulty of the task. Lang et al. (2020) report that the pupil is demonstrably enlarged when individuals are confronted with cognitively challenging tasks, proving that autonomic pupil response can be used as a marker of mental effort (Korbach et al., 2018). Eye-tracking technology makes it possible to precisely measure pupil dilation, resulting in the real-time measurement of mental effort during task processing. Compared to retrospective self-reports, this measure of mental effort has the added value of providing more spontaneous and unbiased answers. Karch (2018) notes that research has shown that pupil responses can be correlated with higher processing loads. If a stimulus is carefully designed and the data are carefully recorded, the task defined by the stimulus can be correlated with a change in processing load.

Accordingly, the purpose of this paper is to investigate the total fixation duration, the average pupil dilation, visit count of students of different age groups to the AOI with macro- and submicroscopic representations and the perception of the difficulty of context-based problems, and to identify correlations between eye-tracker measures and the level of logical thinking/visualisation ability.

Aims and Research Questions

The present research aims to study the eye-tracker measurements of Slovenian students at different levels of education (primary school, upper secondary school, and undergraduate education level), in a context-based problem with SMR on AOI with macroscopic and submicroscopic representation. The context-based problem used in this study covers only the macroscopic and submicroscopic levels of concept representation; the symbolic level was not used. Emphasis is also placed on examining the differences between specific groups of students, including perceived problem difficulty, level of formal reasoning, and visualisation abilities in eye-tracker measures on AIOs.

With regard to the research aims, the following research questions can be addressed:

- RQ1: Does educational level influence eye-tracker measures of AOIs at the macro- and submicroscopic levels?
- RQ2: Are there significant differences between students of different levels of perception of the difficulty of eye-tracker measures on AIOs with macro- and submicroscopic levels of representation?
- RQ3: Is there a relationship between the level of thinking ability or visual ability and eye-tracker measures at the macroscopic and submicroscopic levels of representation?

Method

In this research, a quantitative research approach with descriptive and non-experimental methods was used.

Participants

Seventy-nine students of three different age groups (primary education, upper secondary education, and university education levels) took part in this study, which was conducted in their native language, Slovenian. The group of primary school students comprised 30 12.0-year olds (*IQR* = 0.0 years); 29 upper secondary school students aged 16.0 years (*IQR* = 1.0 years) were in the second group; the group of university students had 20 pre-service teachers for two subjects (chemistry and biology) aged 23.0 years (*IQR* = 2.0 years). The students came from the Ljubljana region and participated in the study on a voluntary basis. For the students of primary and upper secondary education, the consent of school authorities, teachers, and parents was obtained, in accordance with the judgement of the Ethics Committee for Pedagogy Research of the Faculty of Education of the University of Ljubljana. The students were selected from a mixed urban population. All participants had normal or corrected-to-normal vision, and all were competent readers. To ensure anonymity, each student was assigned a code.

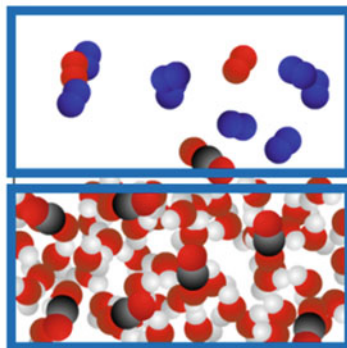
Instruments

Various instruments were used to collect data to answer the research questions, e.g., a context-based problem, a test of logical thinking, a test of visualisation ability, and eye-tracking apparatus.

Context-Based Problem About the Process of Opening a Bottle of Mineral Water

The problem consists of the macroscopic, submicroscopic representation and the text. The specific context-based problem is one of 11 science problems studied in the research funded by the Slovenian Research Agency (ARRS) entitled 'Explaining Effective and Efficient Problem Solving of the Triplet Relationship in Science Concepts Representations' (J5-6814) (Pavlin et al., 2019). The SMRs were designed by science educators; according to the ideas they developed, they were completed by the computer expert with expertise in creating chemistry animations. There was no limit to the time in which the participants viewed the animations. If the participants needed more time to solve the problem, the animations started again. However, the participants could not control the animations. The text of the context-based problem was written in Slovenian (Fig. 11.1). The problem starts with a photo from everyday life (closed and open bottle of mineral water) and SMR of the process. In the part of the study with the eye-tracker, the focus is on macroscopic and submicroscopic representations. The screen image was divided into seven AOI, four of which were the focus of our interest: two photos (Photo 1—closed bottle, Photo 2—open bottle) and two parts of the animation (upper and lower part).

Pri odpiranju steklenice mineralne vode sprva opazimo meglico, ki hitro izgine.
Dobro si oglej predstavitev na nivoju delcev.



2. stopnja

Pojasni dogajanje ob odprtju steklenice mineralne vode. Pri razlagi upoštevaj obe stopnji (1 in 2) predstavitve.

Fig. 11.1 Screen image of the mineral water context-based problem with four labelled areas of interest with blue rectangles

Test of Logical Thinking

The Test of Logical Thinking (TOLT) is a multiple-choice paper-pencil test that assesses five skills of logical reasoning relevant for science teaching (Tobin & Capie, 1984). The test contains ten problems that require some consideration and the use of problem-solving strategies in different areas (i.e., controlling variables as well as proportional, correlational, probabilistic, and combinatorial reasoning). Participants were given a point for a correct answer and its explanation (in Exercises 1–8) and for the correct combinations and their correct number (in Exercises 9–10). These points were combined into a total score (maximum 10 points), which was used as the main result of the test (Devetak & Glažar, 2010).

Visualisation Ability Test

The pattern-based approach was used to assess students' visual processing skills (visualisation ability) with the application of the Pattern Comparison Test (PCT) from the Psychology Experiment Building Language (PEBL) test battery, a series of psychological tests for researchers and clinicians. In the PCT, there were 60 pairs of two grid patterns, 30 of which were the same and 30 different, displayed on the computer screen (Mueller & Piper, 2014). The participants individually had to compare the stimuli in pairs and respond as quickly as possible by pressing a specific key on a keyboard, regardless of whether the patterns were the same or different. Reaction time and the correctness of the answers were measured.

Eye-Tracking Apparatus

An eye-tracking device can be used to measure eye movements (i.e., fixations of the gaze on a specific area of the computer screen during a certain activity) and saccades (i.e., eye movements between fixations). To capture students' visual attention to different elements of the task on the computer screen, the eye-tracker measures the TFD, the average pupil size, the visit count to particular areas of interest (AOI) can be measured. This is also defined as the visual attention or attention allocation of the participant (Havanki & VandenPlas, 2014; Tsai et al., 2012). To ensure proper fixation allocation, the task displayed on the computer screen must be divided into several carefully and clearly divided AOIs, according to the placement elements that are of interest from the perspective of the research problem (Ferk Savec et al., 2016). The identification of saccades/fixations is based on the motion of gaze during each sample collected. If both velocity and acceleration thresholds (in our case: 30 degrees per second and 8000 degrees per second squared) are exceeded, a saccade begins; otherwise, the sample is labelled as a fixation. The screen-based eye-tracker

apparatus EyeLink 1000 (35 mm lens, horizontal orientation) and associated software (Experiment Builder to prepare the experiment and connect to EyeLink; Data Viewer to collect the data and basic analysis) to record and analyse the students' eye movement when solving context-based problems was used. Data were collected at the right eye (monocular data collection that followed corneal reflection and pupil responses) at 500 Hz (Torkar et al., 2018).

Data Collection

TOLT was applied to the groups of participants in the standard environment one week before the eye-tracker study. The eye-tracker study was conducted from November 2016 to March 2017 at the Laboratory of the Department of Psychology at the Faculty of Arts, University of Ljubljana. Each participant completed the PCT study from the PEBL individually on the same day, but in a different room of the laboratory. After completing the PCT, participants entered the eye-tracker room. There was no time limit for the participants to solve eleven context-based problems; they needed about 30 min to complete them. Prior to the test, each participant was individually informed about the purpose of the study, the method used, and their role in the study. They sat about 60 cm from the screen (distance to the eyes) and had to place their head in a special headrest stand to ensure stability and gather the most optimal recordings. After the initial calibration and validation (through the nine-point algorithm), the participants solved all problems aloud: they gave oral answers (in the same order for all participants) while the experimenter wrote down their answers. To exclude distorting influences on pupil dilation, the lighting conditions were kept constant. The same procedure was performed with participants of each age group. The eye movements were measured with the eye-tracker. All data were collected in the Slovenian language (Pavlin et al., 2019).

Data Analysis

Participants' think-aloud responses were obtained during their solving of the context-based problem. To determine how students allocate attention to the macroscopic and submicroscopic areas of interest, eye movement measures were obtained (recorded and analysed) with an EyeLink 1000 device and associated software. Experiment Builder software was used to prepare the experiment, and a connexion to the EyeLink Data Viewer was used to obtain the data for the basic analysis.

All data were collected in Excel and statistically processed in SPSS (Statistical Package for the Social Sciences). Basic descriptive statistics (median Mdn and an interquartile range IQR) of the numerical variables were determined. Spearman's Rank Order Correlation (ρ , r) is used to calculate the strength of the relationship between two continuous variables. The Kruskal–Wallis nonparametric test was used

to explain the relationship between eye-tracker measures on macroscopic and submicroscopic areas of interest among students of different groups and perceived problem difficulty due to the small sample size and non-normal distribution (Pallant, 2011). The Kruskal–Wallis test enables the comparison of results on a continuous variable for three or more groups. Post hoc Dunn tests are used to determine the differences between different pairs of groups (Pallant, 2011). Statistical hypotheses were tested at an alpha error rate of 5%. To describe whether the effects have a relevant magnitude, the effect size measure eta squared η^2 was used to describe the strength of a phenomenon. Cohen (1988) provided benchmarks to define small (.01), medium (.06), and large (.14) effects.

Results and Discussion

The results and discussions are presented according to the research questions.

Eye-Tracker Measures Among Students of Different Levels of Education

The first research question is related to the identification of eye-tracker measures of AOIs with macroscopic and submicroscopic representation level among students of different education level. Tables 11.1, 11.2, and 11.3 show whether the eye-tracker measures (TFD, VC, and APS) differ statistically significantly between students of different age groups.

The results in Table 11.1 show that students in all three educational levels spent more time on submicroscopic than on macroscopic representations. The TFDs on Photo 2 account for about half of the TFDs on Photo 1, which could indicate that familiar data represent stimuli that are processed more quickly (Topczewski et al., 2016).

However, there are statistically significant differences in TFDs between students of different age groups among AOIs with macroscopic representations (Photo 1 and Photo 2). The post hoc tests to test the pairwise comparisons were performed to show which group differs statistically from which group. Primary school students spent more time on AOIs with macroscopic representations than upper secondary school students or university students did. However, there are no statistically significant differences in TFDs on 3D dynamic SMR (divided into upper and lower parts) between students of different educational levels. This confirms the fact that primary school students spend more time observing AOIs with macroscopic representation than students of other educational levels and are more familiar with macroscopic imaging than with submicroscopic ones. As educational levels increase, students are less and less focused on the macroscopic level when solving a new context-based

Table 11.1 TFD on different AOIs in context-based problem related to a context-based problem of the processes occurring during the opening of a bottle of mineral water

AOI	Primary school students (Group 1)		Upper secondary school students (Group 2)		University students (Group 3)		Kruskal–Wallis test		
	<i>Mdn</i> [s]	<i>IQR</i> [s]	<i>Mdn</i> [s]	<i>IQR</i> [s]	<i>Mdn</i> [s]	<i>IQR</i> [s]	χ^2	<i>p</i>	η^2
Photo 1	8.894	7.449	3.124	3.889	2.186	3.654	22.975	.000 ¹	.276
Photo 2	4.894	6.969	1.726	3.631	1.080	1.970	21.734	.000 ²	.260
3D SMR upper part	18.182	16.166	13.034	9.985	12.810	18.192	5.625	.060	–
3D SMR lower part	27.352	22.896	16.640	15.963	18.592	13.162	3.005	.223	–

Results of post hoc Dunn's tests:

¹Group 1–2: *p* = .004; group 2–3: *p* = .288; group 1–3: *p* = .000; 1 > 2, 2 = 3, 1 > 3

²Group 1–2: *p* = .020; group 2–3: *p* = .096; group 1–3: *p* = .000; 1 > 2, 2 = 3, 1 > 3

Table 11.2 VC on different AOIs in a context-based problem about the processes occurring during the opening of a bottle of mineral water

AOI	Primary school students (Group 1)		Upper secondary school students (Group 2)		University students (Group 3)		Kruskal–Wallis test		
	<i>Mdn</i>	<i>IQR</i>	<i>Mdn</i>	<i>IQR</i>	<i>Mdn</i>	<i>IQR</i>	χ^2	<i>p</i>	η^2
Photo 1	15.00	9.00	8.00	3.50	7.00	9.00	17.194	.000 ¹	.200
Photo 2	11.00	9.50	4.00	5.00	4.00	5.00	15.441	.000 ²	.177
3D SMR upper part	21.00	16.50	12.00	9.50	16.00	11.00	9.645	.008 ³	.101
3D SMR lower part	31.00	18.00	23.00	8.00	24.00	19.00	7.536	.023 ⁴	.073

Results of post hoc Dunn's tests:

¹Group 1–2: *p* = .005; group 2–3: *p* = .944; group 1–3: *p* = .000; 1 > 2, 2 = 3, 1 > 3

²Group 1–2: *p* = .049; group 2–3: *p* = .283; group 1–3: *p* = .000; 1 > 2, 2 = 3, 1 > 3

³Group 1–2: *p* = .007; group 2–3: *p* = .173; group 1–3: *p* = 1.000; 1 > 2, 2 = 3, 1 = 3

⁴Group 1–2: *p* = .036; group 2–3: *p* = 1.000; group 1–3: *p* = .106; 1 > 2, 2 = 3, 1 = 3

problem (Chittleborough, 2014). However, research has shown that experts spent less time on task-irrelevant information than novices do (Gegenfurtner et al., 2011). This is also evident from Table 11.1, since university students who could be labelled experts have shorter TFDs, on AOIs with macroscopic levels of representation, than novices—primary school students do (Slapničar et al., 2017; Slapničar et al., 2018).

Table 11.3 APS on different AOIs in context-based problem about the processes occurring during the opening of a bottle of mineral water

AOI	Primary school students (Group 1)		Upper secondary school students (Group 2)		University students (Group 3)		Kruskal–Wallis test		
	<i>Mdn</i> [10 ⁵ a.u.]	<i>IQR</i> [10 ⁵ a.u.]	<i>Mdn</i> [10 ⁵ a.u.]	<i>IQR</i> [10 ⁵ a.u.]	<i>Mdn</i> [10 ⁵ a.u.]	<i>IQR</i> [10 ⁵ a.u.]	χ^2	<i>p</i>	η^2
Photo 1	1.78	.87	1.54	.77	1.04	1.41	10.285	.006 ¹	.109
Photo 2	1.60	.76	1.42	1.70	.14	1.30	13.894	.001 ²	.157
3D SMR upper part	1.78	.59	1.51	1.02	1.35	.83	4.610	.100	–
3D SMR lower part	1.74	.64	1.67	.92	1.42	.79	2.601	.272	–

Results of post hoc Dunn's tests:

¹Group 1–2: $p = 1.000$; group 2–3: $p = .064$; group 1–3: $p = .005$; 1 = 2, 2 = 3, 1 > 3

²Group 1–2: $p = .310$; group 2–3: $p = .060$; group 1–3: $p = .001$; 1 = 2, 2 = 3, 1 > 3

Table 11.2 presents VC on four different AOIs. Repeated visits to an area of interest (AOI) may indicate characteristics that the observer considers important or interesting (West et al., 2006). It is obvious that statistically significant differences in VC occur between students of different stages of education. AOIs with macroscopic representation were more frequently revisited by primary school students than by students of upper secondary school and university. The differences are statistically significant. However, VCs on AOIs with submicroscopic representation among students of different educational levels are also statistically significant. Differences occur between primary and upper secondary education, while there are no statistically significant differences between primary and university students and between upper secondary and university students.

Table 11.3 shows that there are differences between students at different levels of education in APS on AOIs with macroscopic representations. The APS decreases with increasing age of the students. The results suggest that mental effort decreases with the levels of education due to pupil diameter if the results of the study by Just et al. (2003) are taken into account. Furthermore, pupil dilation could be used to identify mental effort during problem processing (Korbach et al., 2018). The results show that there are statistically significant differences in APS at the macroscopic level. However, there are no statistically significant differences in APS at submicroscopic levels among students at different levels of education. It could be interpreted that the SMR represents a similar cognitive load for students of all ages.

Eye-Tracker Measures Among Students' Perceived Task Difficulty

The second research question relates to the identification of differences between students of different levels of their perception of context-based problem difficulty in eye-tracker measures on AIOs with macro- and submicroscopic representation levels. According to Nunan and Keobke (1995), one of the three factors is the lack of familiarity with the type of task, which could justify students' perception of task difficulty as moderate on average ($Mdn=3.00$, $IQR=2.00$).

Nevertheless, Tables 11.4, 11.5, and 11.6 show whether the eye-tracker measures (TFD, VC, and APS) differ statistically significantly among students who self-assess the difficulty of the context-based problem differently. The results show that there are no statistically significant differences in the eye-tracker measures among the students who assessed the context-based problems at the given difficulty level. However, the context-based problem including the process of opening the bottle of mineral water is new to the students, as it has never occurred before in the existing curricula and textbooks (Bačnik et al., 2009, 2011; Balon et al., 2011; Planinšič et al., 2009; Skvarč et al., 2011; Verovnik et al., 2011). Therefore, it might turn out that the self-assessment of a context-based problem according to the specifics of the participants is complex, and it is difficult to conclude anything if the deeper analysis is missing.

Viiri et al. (2017) report that simple measures of time (visit durations on the question or options) are well suited to distinguish between different confidence levels of test participants. However, this was not at the forefront of the present study. Furthermore, Andrzejewska and Stolińska (2016) found that there was no correlation between the activity of eye movement parameters, which are considered indicators of mental effort, and the opinion of a student about the difficulty of the task, as confirmed in the presented study.

Eye-Tracker Measures Among Students of Different Levels of Logical Thinking and Visualisation Abilities

The third research question relates to the relationship between the level of logical reasoning or visual ability and eye-tracker measures at the macroscopic and submicroscopic levels of representation. The relationship between eye-tracker measures on AOIs with macroscopic and submicroscopic representations and first TOLT and then PCT was investigated using the Pearson product-moment correlation coefficient (Tables 11.7 and 11.8).

There is a medium, negative correlation between VC on macroscopic representations and TOLT between TFD on macroscopic representations and TOLT, which means that the student with greater formal thinking skills spends less time on AOIs with macroscopic representations and returns less often to the AOIs mentioned. There is a medium, negative correlation between APS on submicroscopic representation

Table 11.4 TFD on different AOIs in a context-based problem related to the process of opening a bottle of mineral water

AOI	Very easy (N=1)		Easy (N=20)		Moderate (N=34)		Difficult (N=18)		Very difficult (N=6)		Kruskal–Wallis test		
	<i>Mdn</i> [s]	<i>IQR</i> [s]	<i>Mdn</i> [s]	<i>IQR</i> [s]	<i>Mdn</i> [s]	<i>IQR</i> [s]	<i>Mdn</i> [s]	<i>IQR</i> [s]	<i>Mdn</i> [s]	<i>IQR</i> [s]	χ^2	<i>p</i>	η^2
Photo 1	2.620	–	4.196	6.650	6.532	6.634	7.118	7.933	4.359	8.066	2.977	.562	–
Photo 2	1.026	–	1.738	3.814	4.680	7.460	2.710	3.465	2.948	3.578	.750	.945	–
3D SMR upper part	9.830	–	12.794	8.056	18.182	15.948	14.550	13.387	10.440	15.370	8.892	.064	–
3D SMR lower part	12.218	–	16.690	16.962	25.356	20.828	24.728	15.887	15.448	37.144	3.979	.409	–

Table 11.5 VC on different AOIs in context-based problem related to the process of opening of a bottle of mineral water

AOI	Very easy (N=1)		Easy (N=20)		Moderate (N=34)		Difficult (N=18)		Very difficult (N=6)		Kruskal–Wallis test		
	Mdn	IQR	Mdn	IQR	Mdn	IQR	Mdn	IQR	Mdn	IQR	χ^2	p	η^2
Photo 1	9.00	–	9.00	6.00	12.00	13.00	10.00	9.00	10.00	15.50	1.106	.893	–
Photo 2	2.00	–	5.00	6.00	9.00	10.00	6.00	6.50	8.50	8.75	1.580	.812	–
3D SMR upper part	10.00	–	15.00	8.00	21.00	18.00	15.00	15.00	18.00	14.50	7.913	.095	–
3D SMR lower part	16.00	–	23.00	12.00	27.00	12.00	28.00	16.50	28.50	20.00	4.277	.370	–

Table 11.6 APS on different AOIs in context-based problem related to the process of opening of a bottle of mineral water

AOI	Very easy (N=1)		Easy (N =20)		Moderate (N=34)		Difficult (N=18)		Very difficult (N=6)		Kruskal-Wallis test		
	Mdn [10 ⁵ a.u.]	IQR [10 ⁵ a.u.]	Mdn [10 ⁵ a.u.]	IQR [10 ⁵ a.u.]	Mdn [10 ⁵ a.u.]	IQR [10 ⁵ a.u.]	Mdn [10 ⁵ a.u.]	IQR [10 ⁵ a.u.]	Mdn [10 ⁵ a.u.]	IQR [10 ⁵ a.u.]	χ^2	p	η^2
Photo 1	1.71	-	1.41	1.19	1.33	1.03	1.71	.66	1.64	1.18	1.106	.893	-
Photo 2	.18	-	1.60	1.43	1.20	1.51	1.34	1.65	1.67	1.17	1.580	.812	-
3D SMR upper part	1.61	-	1.67	.87	1.47	.89	1.70	.69	1.94	1.10	7.913	.095	-
3D SMR lower part	1.71	-	1.54	.89	1.47	.80	1.76	.59	1.99	.71	4.277	.370	-

Table 11.7 Spearman's rho correlations between TFD, VC, or APS in AOIs with macroscopic representations for a context-based problem related to the process of opening a bottle of mineral water and TOLT or PCT (N=79)

	VC Photo 1		VC Photo 2		APS Photo 1		APS Photo 2		TFD Photo 1		TFD Photo 2	
	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
TOLT	-.341	.003	-.345	.002	-.192	.097	-.121	.324	-.362	.129	-.334	.003
PCT	.079	.490	.005	.964	-.014	.903	.147	.221	.001	.258	-.019	.866

Table 11.8 Spearman's rho correlations between TFD, VC, or APS in AOIs with submicroscopic representations for a context-based problem related to the process of opening a bottle of mineral water and TOLT or PCT ($N=79$)

	VC 3D SMR upper		VC 3D SMR lower		APS 3D SMR upper		APS 3D SMR lower		TFD 3D SMR upper		TFD 3D SMR lower	
	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
TOLT	-.066	.570	-.135	.246	-.312	.006	-.147	.206	-.026	.823	.076	.515
PCT	.119	.296	.124	.277	.147	.199	-.015	.898	.061	.591	.029	.802

and TOLT. It could be interpreted that this representation represents a lower cognitive load for students with higher intellectual capacity, considering that it has been shown that the pupil becomes larger when individuals are confronted with cognitively challenging tasks, which proves that the autonomic pupil response can be used as a marker for mental effort (Korbach et al., 2018; Lang et al., 2020).

However, the ability to visualise refers to the recognition and manipulation of visual objects by the students (Barnea, 2000). The results from Tables 11.7 and 11.8 show that there are no correlations between PCT and eye-tracker measures of AOIs with both macroscopic and submicroscopic representations, which means that the visualisation ability identified by the PCT (i.e., a test of visual processing and pattern recognition) did not come to the fore in solving a new context-based problem with SMR (Phillips et al., 2010). However, the study by Pavlin et al. (2019) also shows that visualisation abilities do not play a significant role in choosing the correct one from among the three animations. It may, therefore, seem logical that visualisation ability is not reflected in the degree of cognitive load identified by pupil dilation.

Conclusions

This paper aimed to investigate and explain the eye-tracker measures (total fixation duration, average pupil dilation, visit count) of students of different age groups at the AOIs with macroscopic and submicroscopic representation and context-based problem difficulty perception and to identify correlations between eye-tracker measures and the level of logical thinking as well as visualisation ability.

When we conclude that educational level affects the decreasing time spend on the macroscopic representation, we find that older students process familiar stimuli faster, while the influence on submicroscopic stimuli is not significant. The number of visits to the macroscopic representations as well as to the submicroscopic representations varies among students of different age groups. In addition, in the upper part of the animation, which was crucial in answering the question, differences in pupil dilation, which identifies cognitive load, are found in students of different age groups.

However, the students found the context-based problem to be from very easy to very difficult. The self-assigned difficulty level of the context-based problem is not reflected in eye-tracker measures for AOIs with macroscopic and submicroscopic representations.

Visualisation abilities are not significant when observing, returning to, and processing the information on AOIs with macroscopic and submicroscopic representations over time. Furthermore, the results of the test of logical thinking correlate with the time spent and the number of returns on AOIs with macroscopic representations. Its results correlate with pupil dilation, which represents the effort of students solving problems.

Limitations of This Research

The main limitation of this research is the limited number of characteristics of the participants that allow for in-depth analysis. A second limitation results from the measurement of pupil dilation; despite ample evidence that pupil dilation is associated with complex cognitive processing, there may be other factors that affect pupil diameter. While physical factors, such as light conditions and screen distance, were kept constant, we did not consider other variables on the participant side that might affect pupil dilation, such as emotional arousal and autonomic activation (Bradley et al., 2008; Lang et al., 2020). Furthermore, the triple nature of science concepts should be integrated into the context-based problem where appropriate; the problem discussed in this research was not designed to require the symbolic level. The screen image should be developed so that eye-tracking measurements are clearly defined. An additional limitation of this study is the breadth of students' knowledge.

Implications for the Educational Process

The research suggests that more emphasis should be placed on teaching context-based problems of varying difficulty levels and that submicroscopic representations should be presented as simply as possible so that they do not require too much cognitive effort to the student. When designing teaching materials, the teacher must ensure that a sufficient number of carefully selected visualisation elements are included to arouse the interest of the student.

Further Research Guidelines

One possible area for future research would be to examine how students' self-esteem and visualisation skills are reflected in their problem-solving abilities. In addition, the number of repeat visits provides information on how often a participant returned his gaze to a specific location defined by an AOI. The participant may be attracted to a certain AOI because it is attractive, because it is confusing, or even because it is frustrating. From the eye-tracking measures, it is not evident how someone felt while looking at something; this issue should be further investigated. Further work is needed to determine whether the symbolic level of science concepts influences context-based problem-solving from an information processing perspective. The question of the role of teachers in the presentation of particle animations in class about specific science concepts is an interesting question that could be usefully investigated in further research.

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