Chapter 7
Using an Eye-Tracking Approach to Explain Students' Achievements in Solving a Task About Combustion by Applying the Chemistry Triplet

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Introduction

The application of the macro, submicro and symbolic levels of chemical concept representations (chemistry triplet) at all levels of education is an essential part of teaching and learning chemistry. It is necessary to understand how students can translate the chemistry triplet in solving specific problems. Chemical reaction is one of the fundamental concepts in chemistry education and combustion is a specific example of it. Eye-tracking technology can provide opportunities to monitor cognitive processes based on positive correlations between eye movements and the individual's cognitive process during a specific task. The duration and frequency of gaze fixations are related to the ongoing mental processes associated with fixed information. Research also shows that students who choose an inaccurate animation of a chemical reaction are often attracted by a model that is easier to explain and fits their understanding of the reaction equations.

This chapter aimed to examine students' performance in solving a chemistry context-based task about chemical reactions, more specifically about the combustion of methane. The task displayed on the computer screen included a photograph of the methane combustion, an animated 3D submicron representation (SMR) and chemical equations.

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Understanding Chemical Reaction in the Context of the Chemistry Triplet

Chemical reaction is one of the basic concepts in chemistry education, and combustion is a specific example of it. However, the complexity of teaching and learning chemistry can be explained by the presentation of the concepts on three levels: the macroscopic, the (sub)microscopic and the symbolic level, which could be imagined as the corners of a triangle in which no form of presentation is superior to the others, but rather complements each other (Johnstone, 1982, 1991). The original triangular model, which represents the chemistry triplet, has been further established, and a teaching and learning model for chemistry has been developed (see Fig. 7.1).

Chemical phenomena (macroscopic level) can be explained on the submicroscopic or particulate level; this is where chemistry shows its complexity, which must be dealt with in the learning material if teachers attempt different visualisation methods and adequate language in their lessons (without confusing the macro, submicro and symbolic levels of concepts), and the whole setting of the classroom situation should be situated in the social context (adequate teacher–student and student–student interactions) in the classroom. During this process, students should develop a certain

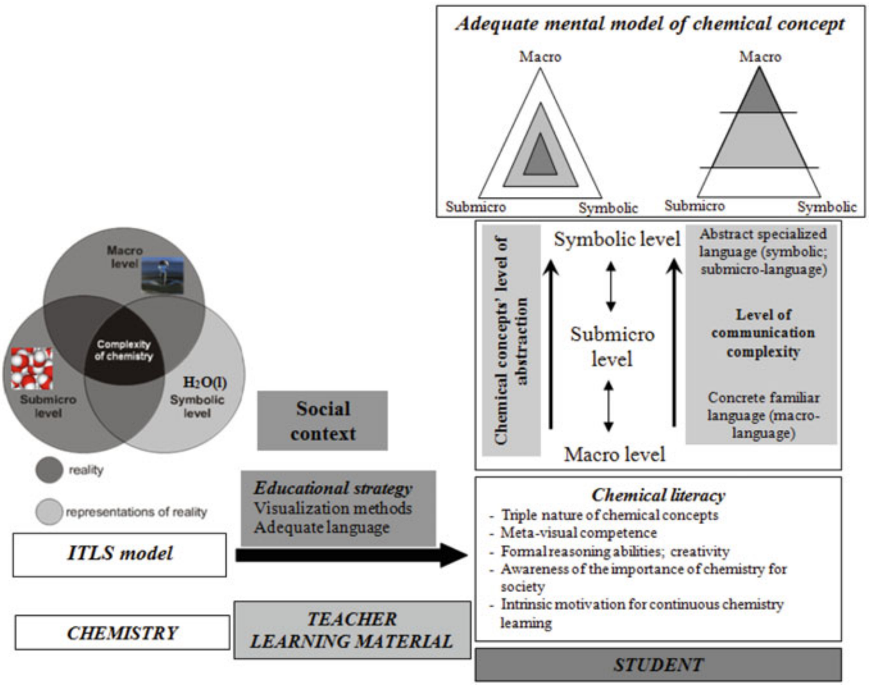


Fig. 7.1 Teaching and learning chemistry model (Adapted from Devetak & Glažar, 2014a; Chittleborough, 2014)

level of chemical literacy, understanding the specific level of complexity of chemical concepts. In this way, a suitable mental model can be created, representing an expanding triangle or a rising iceberg, depending on the students' level of education (Chittleborough, 2014). Submicro representations (SMRs) can be used to represent chemical concepts at the particle level, which can be represented as static or dynamic representations (Devetak & Glažar, 2010). For this study, dynamic 3D SMRs of chemical change (methane combustion) were generated. These SMRs could be translated into established symbols (symbolic level of concept representation), such as symbols of elements, formulas and equations, mathematical equations and various graphical and schematic representations (Levy & Wilinsky, 2009). Johnstone (2001) noted that chemistry concepts are difficult to learn and are often misunderstood by students. The reason for this could be the inability of students to combine the three levels of chemical concepts adequately. Chemistry is inherently conceptual, abstract and difficult to understand without adequate pre-knowledge, which can be understood as a level of chemical literacy adequately embedded in students' long-term memory as specific and adequate mental models.

As Reid (2014) points out, almost by definition, if a concept is to be understood, many facts must be stored simultaneously by the learner in the working memory, whose capacity is very limited. These efforts can lead to learners overloading their working memory capacity (Johnstone & El-Banna, 1986). For this reason, this study also monitored the working memory capacity. Medical research had shown that human memory has several components, one of which is working memory. It is a mental and physical space in the brain in which incoming information is temporarily stored, in which information can be extracted from long-term memory and in which information can be manipulated. The capacity of working memory, the part of the brain that processes information, is quite small. It is known to grow with age, but the final capacity is genetically determined. An average adult (16 years or older) can store seven pieces of information simultaneously, and almost all adults have a capacity between five and nine. It has been found that this part of the brain not only stores information temporarily but is also the location where thinking, understanding information and solving problems takes place, from an educational point of view. It is a "hold thinking" space. However, because it is limited in its capacity and, if there is too much to hold, little space is left for thinking and understanding; therefore, it is a controlling phase for all learning with understanding. Information from the working memory could be transferred to long-term memory, leaving the working space free for further processing (Reid, 2014).

Another important aspect of learning chemistry is the attitude of the learner towards the subject to be learned. Reid (2008) reported that attitudes have a powerful and continuous influence on the learning process. Attitudes can influence the filter for information perception and control which information enters the learner's working memory. The research (Jung & Reid, 2009) also confirms that those students who have shown high working memory capacity are more interested in science, try to understand it, and do not intend to learn it by memorising the concepts, as is the case for students with intermediate and low working memory performance.

However, the attitude of the students is an important aspect that guides the learning of chemistry triplets on their abstract level, but the interest and motivation of the students to learn chemistry is also important. As Taber (2014) points out, even if the students have adequately developed formal reasoning abilities, learning abstract chemical concepts will be fairly minimal if a student can see little sense in a lesson and has no interest in being attentive. Stipek (1998) argues that a higher level of intrinsic motivation for learning a specific content has a positive effect on the students' success in understanding new concepts of the specific content. Various research studies (Devetak & Glažar, 2010, 2014b; Devetak et al., 2009; Juriševič et al., 2008; Patrick et al., 2007; Cavas, 2011) have concluded that the motivation of primary and secondary school and university students to learn chemistry or science, in general, is moderately correlated with their performance in chemistry. Concerning the chemistry triplet, it can be concluded that students tend to be more motivated to learn concepts at the macro level and less motivated to learn at the submicroscopic or symbolic levels (Devetak & Glažar, 2014b; Devetak et al., 2009; Juriševič et al., 2008).

Another aspect of students' cognition of the chemistry triplet can be recognised in their formal reasoning abilities. Students need to acquire formal reasoning abilities to understand 3D animated SMRs correctly and to solve context-based exercises (Pavlin et al., 2019). The fact that some students' formal reasoning abilities never reach the formal operational stage must be taken into account (Labinowicz, 1989). Devetak and Glažar (2010) showed that, at the submicroscopic level, there are statistically significant correlations between formal reasoning abilities and students' chemical knowledge. On average, 28% of the students' achievement variance for items requiring reading 2D-SMRs can be explained by the TOLT (Test of Logic Thinking) score. Similar results were reported by Valanides (1996), who found that formal operation scores correlate significantly with performance in chemistry; Lewis and Lewis (2007) reported that TOLT might predict chemistry exam success, based on a large sample study. In this study, students' formal reasoning abilities were also controlled.

The chemistry triplet can be understood if adequate and specific visualisation methods are used in chemistry teaching. The use of particulate representations plays an essential role in chemistry teaching, as they can enable students to visualise phenomena that cannot be directly observed due to the size of the particles (e.g. atoms, ions, molecules and subatomic particles) (Phillips et al., 2010). For this chapter, visualisation abilities, as proposed by Gilbert (2004), are described as students' abilities to recognise and manipulate visual objects. Research shows (Gilbert, 2008) that students have difficulty constructing relevant information from dynamic visual representations when the represented particles move too fast. Students' visualisation abilities correlate with scientific achievement, but this relationship is influenced by exercise requirements and learning strategies (Hinze et al., 2013). However, Raiyn and Rayan (2015) report that there is a positive correlation between students' visuo-spatial abilities and their problem-solving performance, and good 3D visualisation tools improve students' understanding of molecular structures. Ferk Savec et al. (2005) investigated the usefulness of concrete three-dimensional models, virtual computer-molecular models and their combination as tools for students to solve spatial chemical tasks involving three-dimensional perception, rotation and reflection. Students' perception of the three-dimensional structure was better when a stereo-chemical formula was used in comparison to the formula supported by a computer image. The results suggest that both types of molecular models used as auxiliary tools can facilitate the solution of chemical tasks that require three-dimensional thinking.

Animations improved students' conceptual understanding by helping them to create dynamic mental models of particulate phenomena (Williamson & Abraham, 1995). Research also shows that students who select inaccurate animations of chemical reactions are often attracted to a model that is easier to explain and fits their understanding of the chemical equations. Research has also been conducted to identify misconceptions of chemical reactions at three levels of chemical concept representations (e.g. Barker & Millar, 1999; Chandrasegaran et al., 2007; Bergliot Øyehaug & Holt, 2013; Kelly & Hansen, 2017; Cheng, 2018). Robertson and Shaffer (2014) noted that the literature on students' understanding of combustion has reported that students often rely on a descriptive (what they see during combustion) rather than an explanatory (why something happens) characterisation of combustion. Research indicates (e.g. Meheut et al., 1985; Löfgren & Hellden, 2009; Robertson & Shaffer, 2014) that students usually say that oxygen is necessary for combustion and that water and/or carbon dioxide is produced. However, the most significant problem that can be identified is that they are not specifically associated with the presence of carbon and/or hydrogen in the substance being burned (specific reactants). Robertson and Shaffer (2014) summarised research on students' explanations of certain aspects of combustion. They identified three students' misconceptions regarding the production of water vapour during combustion: (1) the water condenses from the air or environment; (2) the water comes out of the flame and (3) the water is displaced from the wood. However, Barker and Millar (1999) speculated that there are different problems in understanding the change (including combustion) when it is explained as a closed or open system. They concluded that students are inconsistent in including the mass of gas in chemical changes, which leads to confusing thinking. They explained the reasons for these misconceptions by saying that many reactions in open systems involve atmospheric oxygen (such as combustion). Although students experience atmosphere constantly, they do not measure its mass, so the authors speculate that many students omit the mass of oxygen that enters the chemical reaction of gasoline combustion in the reaction of the car engine. Furthermore, Bergliot Øyehaug and Holt (2013) argued that the students' idea that oxygen binds to the reactant during combustion reactions is so strong that they use it as a focal point to integrate other ideas. Research (Christian & Yezierski, 2012) also shows that only 17% of 11- and 12-year-old students correctly estimate the gases released when burning wood.

Eye Movement Measurements in Chemical Education Research

Eye-tracking (eyeT) technology can offer opportunities for monitoring cognitive processes due to the links between eye movements and mental processes of cognition. In addition, to understand these mental processes, the eye movements of individuals can be measured and, after careful consideration, used to interpret processes during task completion, since the direction of the human gaze is closely related to the focus of attention when individuals process the observed visual information (Just & Carpenter, 1980; Hyönä et al., 2003). Research (e.g. Slykhuis et al., 2005; Mason et al., 2013; Havanki & VandenPlas, 2014; Ho et al., 2014; Yen & Yang, 2016; Torkar et al., 2018) has shown that the use of eye-tracking technology in various fields, for example, to study how students process text, data diagrams, relevant photos, explanatory keys, SMRs and similar, can provide relevant information on how students learn and solve different tasks and problems. Havanki and VandenPlas (2014) investigated how the previous knowledge of the students and additional indications in the material guide the allocation of attention, since material with scientific content usually consists of several representations (e.g. text, illustrations). Eye-tracking technologies provide real-time information for understanding students' cognitive activities when processing information encoded in different formats. The combination of quantitative methods and eye-tracking technologies can explain how students interact with different presentation formats in multimedia learning environments (Chuang & Liu, 2012).

Eye-tracking technology can provide measurements of different eye movements. The most common measurements used in chemical education research are total fixation duration (TFDs) and frequency of fixation or fixation counts (FCs) in the specific area of interest (AOI). Other eye movements are the visit count (VC) to the specific area of interest, the average pupil size (APS) obtained by pupillometry, and the spontaneous blink rate (SBR) associated with the ongoing mental processes associated with the processing of information (see Table 7.1).

The eye tracker was used to measure specific eyeT measurements and also other eye movements for each participant in each area of interest, which were determined in a specific material used to collect research data. Fixations occur when the eye is stabilised over an area of interest. Fixations are separated by saccades or "jumps" between fixations. Research suggests that learners fixate on features that are conspicuous, interesting or important through experience (Goldberg & Kotval, 1999; Henderson, 1992). However, fixation counts (FCs) typically indicate the focus of attention, with areas of high fixation count being the most prominent. It can also be understood that the higher the fixation count, the less efficient the viewer's search for information on the computer screen (Chuang & Liu, 2012). When the eyes fixate on an area with high salience, the duration of fixation (absolute TFD) is determined by the time it takes to process the perceptual and cognitive information in the area. For example, the duration of a subject's fixation within an area of interest is a measure of processing difficulty (Goldberg & Kotval, 1999) or the observer has encountered a

Table 7.1 Eye movement measurements and their correlations to cognitive process

Measure at the specific Area Of Interest (AOI)	Description	Correlation to cognitive process
Absolute total fixation durations (TFD)	The total time someone fixes his/her gaze to a specific AOI	Longer fixation durations are indications that the visual and cognitive information requires more complex processing or it is a measure of processing difficulty
Fixation counts (FC)	The number of fixation of someone's gaze to a specific AOI	Typically indicates the focus of attention on the specific AOI and higher number can indicate less efficiency in searching the relevant information or how important the information in that region is
Visit count (VC)	The number of times someone returns to a specific AOI	Higher number of visits can indicate how attractive/useful a particular AOI is
Average pupil size (APS)	The average size of a pupil while someone is looking at a specific AOI	Greater pupil size indicates higher cognitive load during a specific task
Spontaneous eye blink rate (SEBR)	Frequency of eye blinks per minute while someone is looking at a specific AOI	Higher blink rate is related to lower distractibility on tasks that place higher demands on working memory

more difficult element of the task (Chuang & Liu, 2012). Therefore, longer fixation times are usually an indication that the visual information requires more complex processing (Cook et al., 2008).

A visit begins when the eyes first fixate on a particular AOI and ends when it moves away. Visit count (VC) is a measure of how often the person returns to a particular AOI, which can indicate how attractive a particular AOI is, how useful or confusing this AOI can be for the person (Cullipher & VandenPlas, 2018).

Average pupil size (APS) has long been used to identify the cognitive load or mental effort when a person performs various tasks. Pupil dilation increases when the task being performed is cognitively demanding (Beatty, 1982; Dionisio et al., 2001). The larger pupil size when solving specific tasks of wind formation over land or sea suggests that pupil size has been a useful indicator for measuring the cognitive load of learners (Chuang & Liu, 2012). The fact that pupil diameter scales with task requirements makes it a valuable tool for objectively measuring the intensity of cognitive processing in participants of all ages (Eckstein et al., 2017). Research also shows that adults with higher scores on intelligence tests had lower pupil dilation for a range of cognitive tasks (mental multiplication, digit span, sentence comprehension) than those with lower scores (Beatty, 1982), suggesting that more skilled participants exerted less effort to complete the task. This study demonstrates the relationship between pupil response and individual differences in cognitive processing (Ecksteina et al., 2017).

The last eye movement used in this chapter to examine student activity in working memory is the spontaneous eye blink rate (SEBR), which indicates the number of blinks per minute. Spontaneous blinking is one of the most common human movements, with 14,000 spontaneous eye blink per day and an average rate of 14 eye blink per minute when looking straight ahead (Kaminer et al., 2011). Blinking fulfils various functions ranging from maintaining eye health to non-verbal communication. There are three main types of blinking: voluntary, reflexive and spontaneous. Spontaneous blinking occurs without choice and is characterised by a highly synchronised and temporary closing and reopening of the eyelids, a movement that helps to distribute the tear film evenly across the eye (Cruz et al., 2011, cited in Eckstein et al., 2017). It has been suggested that the spontaneous eye blink rate or the frequency with which the eyelids open and close can serve as a non-invasive, indirect measure of dopamine activity in the central nervous system (Eckstein et al., 2017), since dopamine regulates eyelid blinking (Jongkees & Colzato, 2016). Dopamine is an important neurotransmitter involved in learning, working memory functions and goal-oriented behaviour (Kaminer et al., 2011). These functions keep a person focused until a solution is found. Functions related to the frontal lobe, including working memory, are responsible for maintaining a high degree of concentration on a task (Duncan et al., 2000). The basal ganglia, which are connected to the cerebral cortex (Bostan et al., 2013), have a critical function for memory, attention and consciousness. They regulate the release of dopamine in the striatum and thus influence spontaneous eye blinking (Evinger et al., 1993). The basal ganglia also control the input of working memory and have the ability to manipulate information in short-term memory and use it to control actions (Baddeley, 1998). They also filter what enters working memory and modulate its focus by modifying dopamine levels (Schroll & Hamker, 2013), acting as perception filters. In fact, dopamine is released in the prefrontal cortex during higher executive functions such as learning, remembering and recalling memories (Puig et al., 2014), which indicates the importance of dopaminergic mechanisms for cognitive performance (Paprocki & Lenskiy, 2017).

However, eyeT, pupillometry and spontaneous blink data can be misinterpreted. For example, a long fixation on a particular area of interest may be caused by a variety of factors: (1) the participants find that the information in that region is important or relevant to the problem; (2) the material in the area is interesting; (3) the material is difficult or (4) the participants simply stared at the location or object without any associated mental activity (Knoblich et al., 2001).

Research Problem and Research Questions

The main purpose of this chapter was to present the students' achievements in solving the context-based exercise on chemical reaction, more specifically methane combustion and the use of the chemistry triplet in the process. This study aims to show the differences between the students who chose the correct chemical equation to represent methane combustion (G1) and those who had not (G2) in specific eye movement measurements on the specific AOIs (e.g. absolute total fixation duration (TFD), fixation counts (FC), visit count (VC), average pupil size (APS) and spontaneous eye blink rate (SEBR)) and their pre-knowledge, formal reasoning abilities, level of motivation to learn science, working memory capacity and visualisation abilities.

According to the research problem, four research questions can be addressed:

1. Do students who correctly applied the symbolic level of the natural gas combustion process in solving the context-based exercise show statistically significantly different levels of pre-knowledge, motivation to learn the science and some mental abilities (such as formal reasoning abilities, working memory capacity and visualisation abilities) than those who incorrectly applied the symbolic level?
2. Do students who have correctly applied the symbolic level of the natural gas combustion process in solving the context-based exercise describe methane combustion at the submicroscopic level more successfully than those who have misapplied the symbolic level?
3. Do students who correctly applied the symbolic level of the natural gas combustion process in solving the context-based exercise differ statistically significantly in the eye movement measurements on-screen Images 1 and 2 from those who misapplied the symbolic level?
4. Do students who correctly applied the symbolic level of the natural gas combustion process while solving the context-based exercise differ statistically significantly in the eye movement measurements in the macro, submicro and symbolic representations from those students who misapplied the symbolic level?

Method

In this study, a cross-sectional and non-experimental pedagogical research design with a quantitative approach was used.

Participants

The non-random sample of this study comprises 49 participants. All participants came from the Ljubljana Region and participated in this study voluntarily. Secondary school students ($n = 29$) were on average 15.6 years old ($SD = 8.4$ months) and two subject pre-service teachers in bachelor's degree programmes studying biology or physics and chemistry ($n = 20$) at the Faculty of Education of the University of Ljubljana (at the age of $M = 23.18$ years, $SD = 12.0$ months). The consent for secondary school students was obtained from school authorities, teachers and parents, according to the opinion of the Ethics Committee for Pedagogy Research of the Faculty of Education of the University of Ljubljana. 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, such as pre-knowledge achievement test, eye-tracking apparatus with context-based natural gas combustion exercise on three levels of presentation of chemical concepts (Figs. 7.2 and 7.3 presenting screen images), a Test of Logical Thinking (TOLT) for the students' formal reasoning abilities, a Science Motivation Questionnaire (SMQ) for the students' motivation to learn science, a test of working memory capacity and a Pattern Comparison Test (PCT) for the students' visualisation abilities.

Pre-knowledge Achievement Test

Nine items (with 22 sub-items) pre-knowledge achievement test was developed by the researchers. The construct validity of the instrument was confirmed by three independent experts in science and chemical education. The items include concepts related to chemical and physical changes, as context-based exercises include these concepts.

The Context-Based Natural Gas Combustion Exercise

The selected context-based combustion exercise was presented on a computer screen in the form of a text describing the environment, visualisations of the combustion process of natural gas at all three levels of the presentation of chemical concepts and six tasks on two PowerPoint slides (Figs. 7.2 and 7.3). Both slides showed the same photo of a blue natural gas flame burning, as well as a dynamic 3D animation created specifically for this study. For on-screen Image 1 (Fig. 7.2), the students had to answer three questions and provide a justification for the second question. Three specific areas of interest (AOIs) were defined, representing the combustion of methane, as shown in Fig. 7.3, with green rectangles displayed: macro level, submicroscopic dynamic 3D-SMR, and the symbolic level. The symbolic level was used either for the correct selection of the chemical equation or for the wrong selection of the equations (more specific aspects of selecting different wrong chemical equations were not discussed).

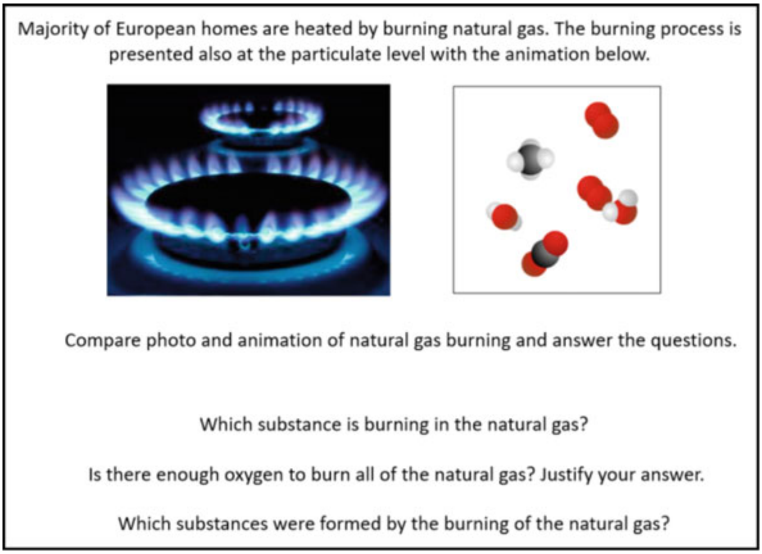


Fig. 7.2 Screen Image 1 of the burning contextual task, which includes macro and submicro level of representations of chemical concepts

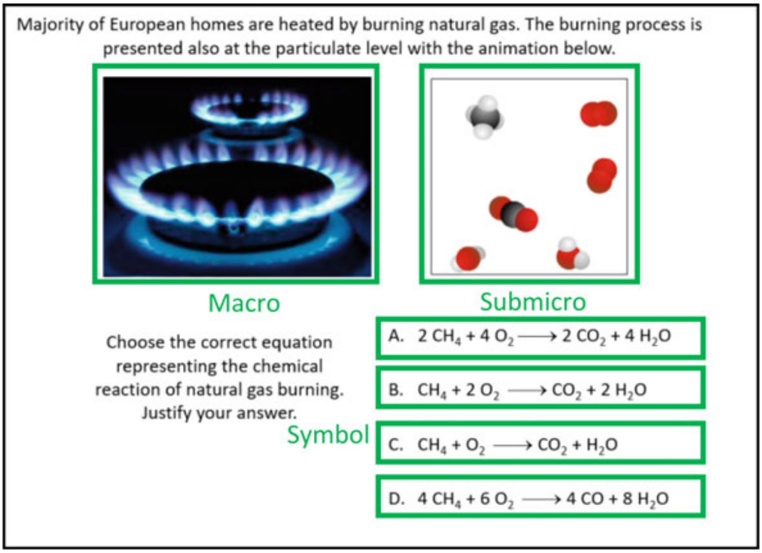
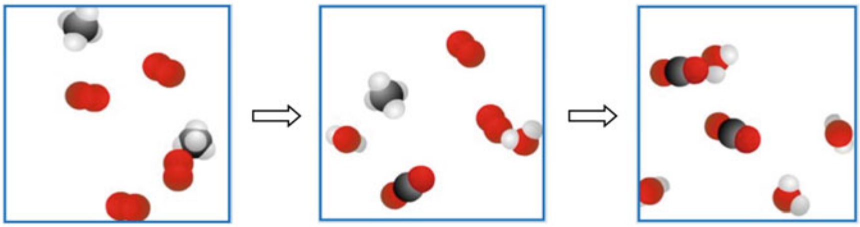


Fig. 7.3 Screen Image 2 of the contextual task with areas of interest (green squares), which includes macro-, submicro and symbolic levels of representations of chemical concepts (equation B is correct)



Phase 1 – Only methane and oxygen molecules were represented.

Phase 2 – Methane and oxygen molecules are present, but combustion products (water and carbon dioxide molecules) are also present.

Phase 3 – The combustion of methane is completed; only products of the chemical reaction are shown.

Fig. 7.4 Phases of the 3D animation of natural gas combustion on both slides

The particulate level of natural gas combustion is shown in the animation in three stages (see Fig. 7.4). The students had to analyse the course of the animation so that a correct symbolic representation (chemical equation) and a correct justification of the choice were provided.

For this chapter, eye movement measurements were used for screen Image 1 and 2. The screen-based EyeTracker (eyeT) device EyeLink 1000 (35 mm lens, horizontal orientation) and associated software (Experiment Builder to prepare the experiment and connect to EyeLink; Data Viewer to collect data and basic analysis) to measure and analyse the eye movements of the participants while solving context-based exercises was used. Data were collected at 500 Hz in the right eye (monocular data acquisition following corneal reflection and pupil responses) (Torkar et al., 2018).

Test of Logical Thinking

The test of logical thinking (TOLT) test is a multiple-choice test which assesses five skills of logical reasoning relevant for science teaching. 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 added to an overall score (maximum 10 points), which was used as the main result of the test. The students had 38 min to solve the test (Tobin & Capie, 1984).

Science Motivation Questionnaire

To measure motivation for science in our study, we used an adapted Slovenian version of the self-assessment of science motivation questionnaire (SMQ) (Glynn et al., 2009). The term "science" included chemistry, biology and physics. Participants answered each of the 30 items of the SMQ on a five-point Likert scale ranging from 1-never to 5-always. The questionnaire consists of six five-item scales: (1) intrinsically motivated science learning, (2) extrinsically motivated science learning, (3) relevance of learning science to personal goals, (4) responsibility (self-determination) for learning science, (5) confidence (self-efficacy) in learning science and (6) anxiety about science assessment. The students were given 35 min to complete the questionnaire. We calculated the average answers in all six scales and overall (anxiety was coded in reverse) in order to compare and differentiate all aspects of motivation for science.

Visualisation Ability Test

The pattern-based approach was used to assess students' visual processing (visualisation) skills using the Visual Pattern Comparison Test (VPCT) 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 equal and 30 different. The participants had to compare the stimuli in pairs and answer as quickly as possible whether the patterns were the same or different. The reaction time and the correctness of the answers were measured. The maximum score was 100 and participants had 15 min to complete the test (Perez et al., 1987).

Test of Working Memory Capacity

A simple digit span task (DST) from the PEBL test battery was used to measure the participants' working memory capacity. This test stores and processes lists of digits that are visually displayed on a screen and spoken through headphones, providing both visual and auditory stimuli. Participants were shown a series of digits, presented one by one on the screen and instructed to enter (recall) items on the next screen. The participants had to recall the numbers in the order in which they were presented. This variable indicates the participants' working memory capacity. However, participants were also instructed to recall the numbers in reverse order, and this mental reversal of the numbers requires both the storage and processing of information in working memory. If the participants were successful in recalling a three-digit list (first step), the list was extended by one digit in the next step (up to a maximum of 10 digits). The number of steps depends on the number of successful attempts until the participant unsuccessfully recall the list of digits without success (Averett, 2017; Croschere et al., 2012).

Research Design

This research was conducted from November 2016 to March 2017. The data were collected in the Department of Psychology Laboratory, at the Faculty of Arts, University of Ljubljana. The participants were informed about the purpose of the study and the methods used before the data collection. The participants had no time limit to solve 11 context-based tasks, but they spend approximately 30 min to solve them. Their eye movements were measured with the eye tracker apparatus. One (natural gas combustion) context-based task was selected for this chapter. The participants sat about 60 cm away from the computer screen on which the context-based tasks were displayed. They placed their heads in a special head-supporting stand to ensure stability and to record the most optimal eye movement data. Prior to recording eye movement data, each participant's gaze had to be calibrated and validated using a nine-point algorithm. Participants solved the context-based exercises using the method (in the same order for all participants). The researcher collected the data by writing down the participants' answers.

TOLT, SMQ, DST and VPCT were applied to all participants in the group before participating in the eye-tracking study. All data were collected in the Slovenian language.

All collected data were statistically processed in SPSS (Statistical Package for the Social Sciences). Basic descriptive statistics (median *Md* and an interquartile range *IQR*) of the numerical variables were determined. EyeLink Data Viewer was used to draw specific heat maps. The text of the heat maps shown in Figs. 7.5 and 7.6 is in Slovenian, since the data were collected in Slovenian, as it is usually appropriate that the data are analysed in the language in which they were collected (Taber, 2018).

The participants were divided into two groups according to their correct choice of the chemical equation: correct chemical equation (G1) and incorrect chemical equation (G2).

The Mann-Whitney U test was used to explain the differences between students who chose the chemical equation of natural gas combustion correctly or incorrectly and their formal reasoning abilities, visualisation abilities, motivation, working memory and eye movement measurements (e.g. absolute total fixation durations (TFD), fixation counts (FC), frequency of returning back (FRB), average pupil size (APS) and spontaneous eye blink frequency rate (sEBR)). The frequency distribution of students' responses to different questions on-screen Fig. 7.1 (Fig. 7.2) on two levels (i.e. the correct response and application of the triple nature of presenting chemical concepts) was also analysed.

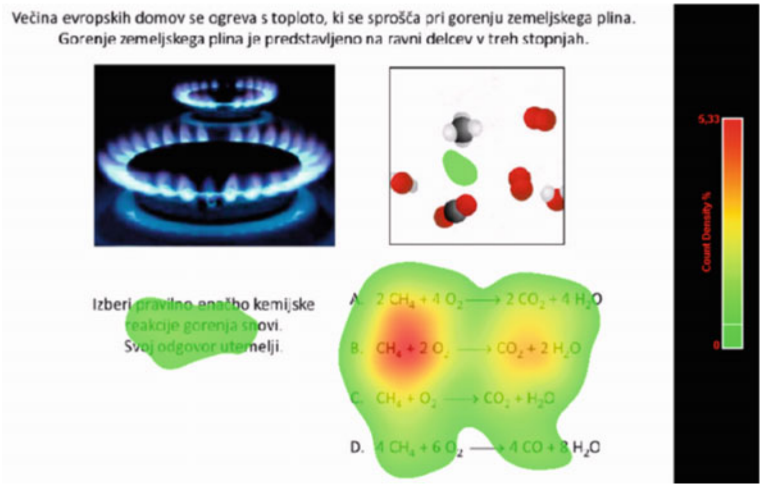


Fig. 7.5 Average heat map for students who correctly solve the context-based natural gas-burning exercise (G1)

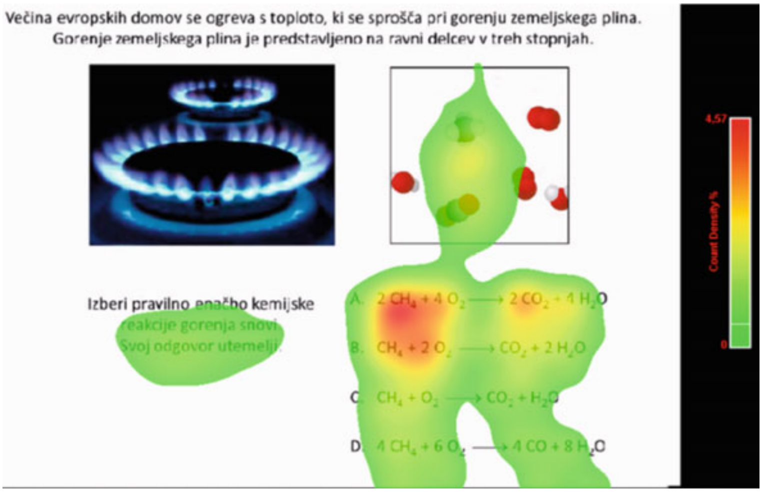


Fig. 7.6 Average heat map for students who incorrectly solve the context-based natural gas-burning exercise (G2)

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. Benchmarks for defining small (.01), medium (.06) and large (.14) effect sizes were provided by Cohen (1988).

Results and Discussion

The purpose of this chapter is to show the differences in the students' achievements and information processing in solving the context-based natural gas combustion exercise, depending on their success in choosing the correct chemical equation: the symbolic level of chemical concepts related to natural gas combustion on the screen image 2; the correct chemical equation (G1) and the wrong chemical equation (G2) (see Fig. 7.3). The results are presented according to the research questions; 65.3% of all participants correctly applied the symbolic level of the natural gas combustion process when solving the context-based natural gas combustion exercise (G1 students), but 34.7% of the participants (G2 students) were not successful in choosing the correct equation.

The first research question deals with control variables so that students' achievements in identifying the correct equation of methane combustion is influenced by the macro picture or dynamic submicro-representation.

The differences in controlling variables, such as pre-knowledge (G1 (*Md* = 79.0; *IQR* = 73.0–88.0); G2 (*Md* = 75.0; *IQR* = 62.0–83.5); *Mann-Whitney U* = 191.0; *p* = .088), motivation (G1 (*Md* = 3.7; *IQR* = 3.3–4.0); G2 (*Md* = 3.4; *IQR* = 2.8–3.7); *Mann-Whitney U* = 184.5; *p* = .066), formal reasoning abilities (G1 (*Md* = 8.0; *IQR* = 6.0–7.6); G2 (*Md* = 7.0; *IQR* = 6.0–8.0); *Mann-Whitney U* = 246.0; *p* = .578) and visualisation abilities (G1 (*Md* = 57.0; *IQR* = 55.0–58.0); G2 (*Md* = 57.0; *IQR* = 56.5–59.0); *Mann-Whitney U* = 205.5; *p* = .155) and working memory capacity (G1 (*Md* = 6; *IQR* = 5–6); G2 (*Md* = 5; *IQR* = 4–6); *Mann-Whitney U* = 215.5; *p* = .221), between the two groups are not significant.

The second research question is about the students' description of methane combustion at the submicroscopic level. Table 7.2 shows the students' (for groups G1 and G2) achievements in answering the questions about screen Image 1 regarding the combustion of natural gas. It also shows what kind of explanations triplet they used regarding the chemistry when answering the questions or justifying their answer.

It can be concluded from Table 7.2 that those students who correctly chose the chemical equation of methane combustion also generally achieved better results in

Table 7.2 Students' achievements in answering the questions for screen Image 1 (see Fig. 7.2) according to the correctly (G1) or incorrectly (G2) selected symbolic representation (chemical equation) on-screen Image 2 (see Fig. 7.3)

Question about screen Image 1		G1 students' answer [%] (*n* = 32)		G2 students' answer [%] (*n* = 17)	
		Correct	Incorrect/No. answer	Correct	Incorrect/No. answer
1. Which substance is burning in the natural gas?		53.1	46.9	47.1	52.9
2. Is there enough oxygen to burn all of the natural gas?		93.8	6.3	94.1	5.9
a. Justify your answer for Question 2.		56.3	43.8	41.2	58.8
3. Which substances were formed by the burning of the natural gas?	CO_2	96.9	3.1	70.6	29.4
	H_2O	100	0	88.2	11.8

answering the questions about screen Image 1. Both groups of students responded similarly, stating that there is enough oxygen to react with methane, but the group that chose the chemical equation correctly better justified its answer. The major difference between the two student groups (G1 and G2) was the prediction that carbon dioxide is the product of this chemical reaction. More than 26% of the students in G1 also correctly predicted both products of the chemical reaction.

Most students (84.4%) who correctly chose the chemical equation used the macro level to explain what the substance that burns in natural gas is. Similar results (82.4%) were obtained by students who did not choose the chemical equations correctly; others did not provide any explanation. Only one student mentioned methane molecules and two used the methane formula to express their reasoning. In explaining whether there is enough oxygen to burn all the natural gas, 65.6% of the students used only macroscopic explanations and 41.2% of those who chose the wrong symbolic representation. In total, 25.1% of the students explained sufficient amount of oxygen using the submicroscopic level or the combination of the submicroscopic and macroscopic levels, and 41.2% of those who chose the wrong chemical equation. Others did not provide any information or explanation. More students explained that the combustion of methane produces carbon dioxide molecules (34.4%) and water molecules (28.1%).

In contrast, no student who was unsuccessful in choosing the correct chemical equation for methane combustion explained that carbon dioxide and water molecules are formed. They provided their explanations at the macro level, stating that carbon dioxide (76.5%) and water (82.4%) are formed as substances. Others used the formula of these substances (CO_2 and H_2O, 11.8 and 5.8%, respectively) or did not provide an explanation.

The third research question relates to the differences in specific eye movement measurements (e.g. absolute total fixation durations (TFD) (in sec.), fixation counts (FC), average pupil size (APS) (in arbitrary units), spontaneous eye blink rate (SEBR)) for screen Images 1 and 2 of the context-based natural gas combustion exercise as between those who chose the chemical equation incorrectly and those who did not.

From Table 7.3, it can be concluded that there were no significant differences between the two groups of students, which may indicate that those students who were more successful in selecting the correct chemical equation were generally (the entire screen Image 1 or 2) less successful in focusing their attention or processing visual information than those who were less successful. Similar results were also obtained by comparing the students in both groups in terms of the cognitive load that the task imposed on the students, which is also consistent with the non-significant difference in blinking rate between the students who were correct in choosing the symbolic level representing methane combustion and those who were not successful.

The final research question focuses on the differences in student eye movement measurements for macro, submicro and symbolic representations between those who correctly and incorrectly chose the chemical equation. A more detailed data analysis of eye movement measurements between the two groups of students is presented in Table 7.4.

Table 7.3 Differences in eye movement measurements between students according to the correctly (G1) or incorrectly (G2) selected symbolic representation (chemical equation) on the screen image 1—SE1 (see Fig. 7.2) and 2—SE2 (see Fig. 7.3)

Eye movement measurement		G1 students' answer [%] ($n = 32$)		G2 students' answer [%] ($n = 17$)		*Mann-Whitney U test*	
		Mdn	*IQR*	*Mdn*	*IQR*	*U*	*p*
TFD	SE1	75.2	65.9–104.4	76.4	49.7–108.6	256.0	.737
	SE2	57.6	4.6–82.4	80.5	56.7–93.7	199.0	.125
FC	SE1	281	250.8–375.8	290.0	214.0–397.5	266.0	.900
	SE2	234	179.3–278.0	251.0	222.5–319.5	212.5	.211
APS	SE1	1643.7	1340.1–2006.9	1416.4	1271.0–1761.1	216.0	.240
	SE2	1482.1	1275.7–1893.4	1330.0	1161.3–1625.6	225.0	.324
SEBR	SE1	28.0	12.0–41.0	20.0	14.5–55.0	265.0	.883
	SE2	19.5	7.0–34.8	17.0	13.5–48.5	263.0	.449

TFD—absolute total fixation durations (in sec.), FC—fixation counts, APS—average pupil size (in arbitrary units), SEBR—spontaneous eye blink rate

In the screen Image 2 (see Fig. 7.3), three significant elements were covered in the analysis of the eye movement measurements of the participating students. The absolute total fixation durations (TFD) indicate that the 3D animation of the chemical change (combustion of methane) requires statistically significantly more complex processing of the presented visual information at the SMR for low-performance students. In contrast, students who correctly selected the chemical equation (underlined symbol B in Table 7.4) also find the correct symbolic representation of methane combustion more complex when processing visual stimuli, which is understandable: they must analyse the chemical equation to ensure that it is correct. The duration of visual information processing is also consistent with the second eye movement measurement, the number of fixation (FC) on the specific area of interest. It is clear that more successful students paid more attention to the correct chemical equation than to the other areas of interest identified by the researchers on the second screen image. Both significant differences in the average total absolute fixation durations and the fixation counts for both AOIs (3D-SMR and correct equation) show medium effect size, which means that about 10% of the variability in the TFD and FC for both AOIs is accounted for successfully selected the correct chemical equation in the context-based natural gas combustion exercise. Those students who chose the wrong chemical equation spent the longest time (longest average TFD and highest average fixation count) on the first (incorrect) chemical equation.

The number of visits (VC) to the specific AOI can be an indication of how attractive or useful a particular AOI is for students in solving a particular task. Students who chose the wrong chemical equation to represent methane combustion visit the 3D animated submicron representation of the chemical reaction statistically significantly more often than students who have chosen the right equation do. A higher number of visits to 3D-SMR by low-performing students may indicate that this animation

Table 7.4 Differences in eye movements between students according to the correctly (G1) or incorrectly (G2) selected symbolic representation (chemical equation) on specific AOIs at the screen image 2 (see Fig. 7.3)

Eye movement measurement		G1 students' answer [%] (n = 32)		G2 students' answer [%] (n = 17)		*Mann-Whitney U test*		
		Mdn	*IQR*	*Mdn*	*IQR*	*U*	*p*	η^2
TFD	Macro	.413	.266–.983	.594	.398–1.458	200.0	.130	
	Submicro	**2.1**	**.518–5.1**	**14.0**	**1.7–27.0**	**163.0**	**.022**	**.107**
	Symbol A	10.3	4.4–18.6	18.3	7.6–24.2	209.0	.186	
	Symbol B	**19.5**	**11.4-26.7**	**5.7**	**3.6–28.1**	**165.0**	**.025**	**.103**
	Symbol C	6.8	3.7–12.6	5.1	1.6–7.6	199.0	.125	
	Symbol D	2.4	1.2–4.5	2.8	1.3–7.2	252.0	.674	
FC	Macro	2.0	1.0–5.0	4.0	2.0–8.0	195.0	.101	
	Submicro	**9.0**	**3.0–12.0**	**50.0**	**4.5–68.5**	**171.5**	**.034**	**.091**
	Symbol A	36.0	21.5–65.3	67.0	31.0–85.0	200.0	.130	
	Symbol B	**63.5**	**47.3–97.3**	**20.0**	**16.5–87.0**	**162.0**	**.021**	**.109**
	Symbol C	24.5	16.3–48.8	18.0	7.5–29.5	183.0	.061	
	Symbol D	10.0	5.3–19.5	13.0	6.0–28.5	244.0	.556	
VC	Macro	2.0	1.0–3.0	3.0	1.0–4.5	197.5	.107	
	Submicro	**5.0**	**2.3–6.8**	**18.0**	**3.0–28.5**	**174.5**	**.040**	**.086**
	Symbol A	12.0	7.0–20.5	19.0	9.0–22.5	205.0	.159	
	Symbol B	**18.0**	**12.0–29.5**	**11.0**	**6.5–21.5**	**167.5**	**.028**	**.098**
	Symbol C	11.5	5.0–17.0	7.0	4.0–11.0	195.0	.105	
	Symbol D	5.0	2.0–8.3	6.0	3.0–7.5	236.5	.451	
APS	Macro	1490.9	1155.4–1817.0	1373.5	1219.2–1508.1	240.0	.612	
	Submicro	1603.0	1221.0–2072.2	1536.6	1272.0–1660.1	245.0	.690	
	Symbol A	1675.8	1252.7–1916.1	1517.9	1250.9–1747.4	233.0	.413	
	Symbol B	1612.6	1324.3–1930.5	1483.8	1235.6–1777.9	241.0	.515	
	Symbol C	1583.5	1189.9–1927.4	1523.7	1216.4–1748.7	259.0	.785	
	Symbol D	1637.9	1264.6–2050.5	1477.9	1256.1–1812.3	249.0	.629	

TFD—absolute total fixation durations, FC—fixation counts, VC—visit count, APS—average pupil size [in arbitrary units]
Underlined alternative indicates a correct symbolic representation
Significant differences are written in bold

was more attractive or useful to them than to high-performing students. However, high-performing students found the correct chemical equation more attractive than students who did not choose the correct equation. For these students, again, the first equation (see above) was most attractive. Both significant differences on average VC show medium effect size, which means that about 9% of the variability in VC 3D-SMR and the correct chemical equation is due to the fact that the correct chemical equation was successfully selected in the context-based natural gas combustion exercise. The final eye movement measurement indicates the cognitive load of the students during a given task, which means that a larger pupil size indicates a higher cognitive load. The results show that both groups of students experienced similar cognitive load during the context-based natural gas combustion exercise. However, when comparing the pupil size, it can be speculated that students who solved the exercise correctly experienced higher cognitive loads, but this is due to the greater effort required to solve the exercise correctly.

These results are also supported by the visual attention distribution (on average) between the two groups of students (see Figs. 7.5 and 7.6).

The average heat map for both groups of students shows that the macro level does not sufficiently draw their attention for them to choose the correct chemical equation; although the flame of methane combustion can indicate the chemical reaction with oxygen, this was obvious to the students after reading the text of the task (Translation: Choose the correct chemical equation representing the burning of the substance) and by looking at (G1) or processing (G2) the visual information represented by the animated 3D submicro-representation. Overall, the students showed little interest in the macro level, which is consistent with other research, as it can be assumed that students are less focused on the macro level when they are familiar with the task context (Chittleborough, 2014). For those students who chose the chemical equation correctly, other levels of conceptual representations (macro and submicro levels) were less relevant. Other studies described similar findings that experts spend less time on information that is irrelevant for the successful solution of the task (Gegenfurtner et al., 2011).

Conclusions

The main purpose of this chapter was to present the students' achievements in solving the context-based exercise on chemical reaction, more specifically, methane combustion and the use of the chemistry triplet in the process. This research aims to determine the differences between the students who chose the correct chemical equation and those who were unsuccessful in certain eye movement measurements in the specific area of interest, on two screen images where the context-based task was presented.

The differences between the two groups of students in pre-knowledge, motivation for learning science, formal reasoning abilities, visualisation abilities and working memory are not significant, which means that these variables do not statistically significantly affect the solving of the context-based combustion exercise, but the ability of the students to solve the exercise correctly may be due to their ability to process and determine relevant information presented in the two screen images and how familiar they were with the task.

Students' explanations, regardless of whether they are attending an upper secondary school or university, remain at the macro level.

It can be summarised that students who were more successful in selecting the correct chemical equation do not focus their attention overall or process visual information displayed on the whole screen Image 1 or 2 as less successful.

From this, it can be concluded that students who chose the correct chemical equation when solving the context-based natural gas combustion exercise spent less time processing 3D animations and photos representing methane combustion. However, more successful students spend more time mentally analysing the correct chemical equation without searching for much information at the macro or submicro levels. They also find it more relevant to the solution of the task, but for both groups of students, the context-based natural gas combustion exercise presents similar cognitive load while solving the task.

Some implications for chemistry teaching can be suggested. Teachers should stimulate students to provide explanations using correct language at the submicroscopic level and describe chemical phenomena not only at the macroscopic level. Poorly performing students should be encouraged to use all three levels of presentation of chemical concepts when attempting to solve the specific chemical exercise or problem successfully. In addition, the results can enable teachers to encourage students to develop successful problem-solving strategies, which means that teachers could focus on the analysis of those textual or visual elements of the exercise or problem that could lead the students to effectively use all three levels of chemical concept representations in finding the right solution.

There are some limitations to the research presented in this chapter. The sample size is relevant for this type of research, but it is difficult to obtain a large number of participants. It is also important to emphasise that students solve different tasks during eyeT measurements (some of which are also used in the chapters of this book), so it can be speculated that some students may not have made enough effort to solve the tasks. The eye-tracking technology can provide useful data, but we should be aware that this is not a standalone research method and that a triangulation of methods should be applied to a similar research design, which may also reduce the possibility of misinterpretation of eyeT, pupillometric and spontaneous blink data, as this can be a major problem when attempting to draw conclusions from eyeT research.

The conclusions of this study also suggest some further research. More attention should be paid to the analysis of eye movement measurements as a function of the abilities of certain students, which may influence learning and solving specific tasks. In addition, complex chemical problems involving the chemistry triplet should be used in similar studies to determine students' strategies for solving these tasks.

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