Chapter 4
The Role of the Explanatory Key in Solving Tasks Based on Submicroscopic Representations

Vesna Ferk Savec and Špela Hrast

Introduction

Since the building blocks of matter—atoms, molecules and ions—cannot be perceived naturally by our senses, the desire to reveal "the world of the invisible" has inspired philosophers and scientists for many centuries. From Plato, or even earlier, to the present day, people have tried to visualise their ideas about the nature of matter by building mental and concrete models (Gregory, 2000). The important role of using models and modelling in science discoveries to visualise concepts and processes at the particle level has been manifested since the nineteenth century by many leading chemists such as Kekulé, Van't Hoff, Pauling, Watson and Crick (Justi & Gilbert, 2002), often related with corresponding Nobel Prizes awards in chemistry, physics and medicine. In contemporary science, new developments related to the use of models and modelling are supported by the application of computer methods and computer graphics. A recent example of this is the Nobel Prize award in physiology or medicine in 2019, which was awarded to Kaelin, Ratcliffe and Semenza. In particular, the researchers identified molecular machinery that regulates the activity of genes in response to varying levels of oxygen, their discoveries are therefore recognised as paving the way for promising new strategies to combat anaemia, cancer and many other diseases (Nobel Assembly at Karolinska Institutet, 2019).

Models have played an important role not only in science research, but also in science education. The pioneering role in the introduction of models in the teaching of chemistry was attributed as early as 1811 to John Dalton, who used wooden spheres connected by metal pins in his lectures (Francoeur, 1997; Hardwicke, 1995).

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The "golden age" of molecular models began with the spread of commercial molecular model sets based on Stuart's space-filling models after their invention by Stuart in 1934. The first commercially produced set of Stuart-type models, the so-called Fisher-Herschfelder-Taylor models, had accurate bond angles and adequate mechanical stability (Petersen, 1970). The CPK models are named after the initials of the family names of the chemists Corey, Pauling and Koltun, who created the first concrete, space-filling molecular models of amino acids, peptides and proteins, which were painted in different colours to indicate the respective chemical element, e.g. white for hydrogen, black for carbon, red for oxygen and blue for nitrogen (Corey & Pauling, 1953), and patented their improved version in 1965 (Koltun, 1965). The use of colour conventions in these models is known as the CPK colour scheme, which is still the most commonly used colour scheme today.

Computer versions of CPK models have successfully imitated the appearance of their physical analogues and have enabled additional features, e.g. with respect to the possibilities of simultaneous representation of molecules by different model types (e.g. ball-and-stick, space-filling, wire-frame, valence-shell electron pair repulsion model). The use of computer graphics has also considerably extended the possibilities for labelling respective chemical elements in the models with specific colours. An example of a colour convention for computer models is the CPKnew scheme, which applies to Rasmol v 2.7.3. or later ("Jmol Colors", n.d.). One of the most commonly used software packages for the visualisation of molecules today is called Jmol. Jmol has assigned colours (RGB colour and Hexadecimal-Web-Colour) to almost every element likely to be found in a molecule and even to some common isotope colours. These isotopes include deuterium and tritium of hydrogen, carbon-13 and carbon-14 and nitrogen-15 (Helmenstine, 2019).

However, as Francoeur pointed out, the awareness of the limitations of three-dimensional structural representations in physical or computer models remains in its essence: The "gap" between molecular models and other representations of molecules appears particularly obvious when the latter are based on a quantum mechanical understanding of chemistry. "It is clear that a model for a quantum mechanical system like a molecule itself cannot be quantum mechanical" (Francoeur, 1997, p. 17). As a result, a wealth of literature has been collected over the decades to address students' misconceptions about the nature of models as submicroscopic representations (SMR) of phenomena (Barke et al., 2009; Nakhleh, 1992; Slapničar et al., 2014; Van Driel & Verloop, 1999). Johnstone (1991) was the first to point out that the representation of scientific concepts and processes is based on representations on three levels: macroscopic (observable phenomena), submicroscopic or particulate (various representations of atomic, molecular and particle models) and symbolic (mathematical and chemical symbols). In this respect, it has been shown that the integration of three levels of conceptual representations in the learning process enables students to create mental images of the corresponding phenomena, which supports their better understanding (Al-Balushi & Al-Hajri, 2014; Barke & Wirbs, 2002; Ferk Savec et al., 2009; Gilbert et al., 2008).

Although there are several options for technology-enhanced learning in the digital age, textbook sets continue to play a central role in supporting the effective teaching and learning of science. In science teaching, much attention has been paid to the analysis of textbooks, for example, Devetak et al. (2010) examined explanations of states of matter in Slovenian science textbooks; Laçin-Şimşek (2011) studied female scientists in Turkish science and technology textbooks; Majidi and Mäntylä (2011) examined the knowledge organisation in magnetostatics in Finnish textbooks; Mumba et al. (2007) studied inquiry levels and skills in Zambian chemistry textbooks for high schools. It is often assumed that students understand the SMRs and learn efficiently with them because experienced chemists (e.g. textbook authors) can use them simultaneously as part of a triple representation of chemistry concepts (Johnstone, 1991). However, research (Harrison, 2001; Furió-Más et al., 2005; Gkitzia et al., 2011) indicates that the abundant presence of SMRs in a textbook is not a guarantee of efficient learning. It seems that the integration of SMRs in textbook sets by textbook authors and/or editors has often not been given sufficient attention to support the development of students' representational competence through the curriculum topics from the beginning to the end of the textbook (e.g. through the meaningful integration of explanatory keys), and therefore further studies in this area are needed.

Eye tracker has been used in science education to investigate how students process data, e.g. text data, data diagrams, images, photos, etc. (Havanki & Vanden Plas, 2014; Hinze et al., 2013; Mason et al., 2013; Pavlin et al., 2019; Slykhuis et al., 2005; Torkar et al., 2018), because it enables the monitoring of cognitive processes as a consequence of the links between eye movements and cognition (Rayner, 2009; Yen & Yang, 2016). It seems useful to use the eye tracker also for studying selected examples of SMRs and to collect information on eye movements in order to examine the role of an explanatory key in the processing of SMRs by students in relation to the findings from textbook analysis on their integration into textbooks.

The Context and the Purpose of the Study

The paper focuses on the integration of SMRs in chemistry learning materials in the higher grades of primary school, with emphasis on the accompanying descriptors that support students' recognition of the informational value of SMRs. Based on their own experience with the simultaneous use of SMRs as part of a triple representation of chemical concepts and processes, experienced chemists, such as textbook authors, could assume that the use of SMRs would enable efficient learning by students even without explaining the meaning of the symbols used in these representations. However, understanding the types of information and conclusions provided by the visualisations in the different learning materials requires explicit guidance and practise (Akaygun & Jones, 2014; Ferk Savec et al., 2005; Jones, 2013). To support the effectiveness of chemistry learning through the use of SMRs, it is useful to include in textbooks and teaching materials tools that help students to recognise the informational value of SMRs. Therefore, as indicated in previous studies (Hrast & Ferk

Savec, 2017a, 2017b), SMRs in textbook sets can be accompanied by different types of descriptors (e.g. pictorial, textual, combined, indirect).

In this paper, the considerations on SMRs descriptors in Slovenian chemistry textbooks are elaborated to reconcile their meaning with the general definition of a legend or key. Merriam-Webster Dictionary (n.d.), states that the legend is "an explanatory list of symbols on a map or diagram" and the key is: "something that gives an explanation or identification or provides a solution" (Merriam-Webster Dictionary, n.d.) In this paper we have used the term SMRs with an explanatory key to address the different possibilities of descriptors that accompany SMRs and allow learners to identify their informational value directly and unambiguously. Given the variety of possible representations of SMRs with descriptors that allow particle recognition, there are many useful options for explanatory keys, such as pictorial, textual, integrated structural or other symbolic notations. When SMRs are used without discussing the meaning of the particles, we refer to them in this paper as SMRs without an explanation key.

The main objective of the first part of the paper is to present the integration of SMRs with/without an explanatory key in Slovenian chemistry textbook sets in relation to the topics of the National Chemistry Curriculum for Primary School (Bačnik et al., 2011).

In the second part of the paper we wanted to investigate whether a certain type of explanatory key accompanying the SMRs provides added value for students in solving certain chemistry tasks. For reasons of clarity of the results, only two types of explanatory keys (pictorial, textual) were selected for the study with eye tracker, and in order to gain additional insight into the students' perception of the added value of the explanatory key, the interview with the students was chosen.

The following research questions (RQ) were specified:

RQ1 How (with/without explanatory key) are SMRs integrated in Slovenian chemistry textbook sets in relation to curriculum topics?

RQ2 Does the type of explanatory key (pictorial/textual) that accompanies SMRs affect students in solving simple chemical tasks?

Method

Sample

SMRs in Slovenian chemistry textbook sets for primary schools (related to RQ1)

In the first part of the paper, we focused on the chemistry textbook sets in primary school (8th and 9th grade), which are obligatory in Slovenia based on the objectives of National Chemistry Curriculum and consequently confirmed by the National Commission for Textbook Approval at the Ministry of Education, Science and Sport. The National Chemistry Curriculum for Primary School (Bačnik et al., 2011) includes general objectives of the school subject Chemistry and specific objectives with suggested contents on how to implement the objectives in chemistry teaching for each of the ten listed chemistry topics. Teachers can distribute the curriculum topics in 70 h in grade 8 and 64 h in grade 9. The list of textbook sets whose use in Slovenian schools is currently confirmed is shown in Table 4.1. These textbook sets were the subject of the textbook analysis in the first part of the paper.

Participants of the study of SMRs with eye tracker, also involved in the final interview (related to RQ2)

In the second part of the paper we describe a study with eye tracker, in which 44 students participated, who were selected from the pool of 118 non-chemistry freshmen of the Faculty of Education of the University of Ljubljana on the basis of their performance in a chemistry knowledge pre-test. Four participants were excluded due to their absence from the eye-tracking session and five participants due to poor eye calibration. The final sample consisted of 35 participants with high overall scores on the Chemistry Knowledge Test (the top third of students with the highest scores). The same 35 students also participated in the final interview.

Instruments

Rubrics for the analysis of the explanatory key accompanying SMRs in Slovenian chemistry textbook sets for primary schools (related to RQ1)

For the study presented in the first part of this paper, a rubric for the evaluation of SMRs in textbook sets was developed on the basis of examples from similar studies (Kahveci, 2010; Devetak & Vogrinc, 2013; Hrast & Ferk Savec, 2017a). The rubric is based on the assumption that in order to recognise the structure of SMRs, the learner can use different information in the role of the explanatory key. To ensure the validity of the rubric, 283 pages (10% of all analysed textbook set pages) were analysed by both authors and the criteria for SMRs with an explanatory key and SMRs without an explanatory key were defined. The main criteria were that SMRs with an explanatory key should enable the learner to identify all particles directly and unambiguously, although this can be achieved through different types of explanatory keys, such as pictorial, textual, integrated structural or other symbolic notations used, etc. On the other hand, SMRs without an explanatory key do not enable the learner to recognise particles directly, although it is possible that different types of related information such as the name of the compound, the description of its properties, etc. are provided. In order to reduce bias issues related to the use of the rubric for categorising SMRs with/without explanatory key through discussion and agreement, a 98% inter-rater reliability of the rubric has been established.

Materials and apparatus of the study of SMRs with eye tracker (related to RQ2)

Chemistry knowledge pre-test

With the aim of recruiting participants with a highlevel of prior knowledge for the eye tracker study, 118 students completed the chemistry knowledge paper- and-pencil pre-test developed by Ferk Savec et al. (2016). The pre-test with $\alpha = 0.62$, consists of 30 multiple-choice chemistry questions based on SMRs (M = 12.38; SD

Table 4.1 The list of the analysed textbook sets

Textbook set* title	Author(s)	Publisher	Year of publication (Edition) Textbook/ workbook	Number of Pages Textbook/workbook	Grade/ Learner's age
Kemija danes 1	Gabrič, A., Glažar, S. A., Graunar, M., Slatinek-Žigon, M.	DZS	2014 (1st Ed.)/ 2013 (1st Ed.)	125/106	8/13
Kemija 8, i-učbenik	Sajovic, I., Wissiak Grm, K., Godec, A., Kralj, B., Smrdu, A., Vrtačnik, M., Glažar, S.	Zavod RS za šolstvo	2014	264	8/13
Moja prva kemija	Vrtačnik, M., Wissiak Grm, K. S., Glažar, S. A., Godec, A.	Modrijan	2015 (1st Ed.)/ 2014 (1st Ed.)	240/92, 61	8, 9/13, 14
Peti element 8	Devetak, I., Cvirn Pavlin, T., Jamšek, S.	ROKUS KLETT	2010 (1st Ed.)/2010 (1st Ed.)	103/71	8/13
Pogled v kemijo 8	Kornhauser, A., Frazer, M.	MK	2003 (1st Ed.)/ 2004 (1st Ed.)	140/126	8/13
Od atoma do molekule	Smrdu, A.	JUTRO	2012 (2nd Ed.)/2012 (2nd Ed.)	128/160	8/13
Kemija danes 2	Graunar, M., Podlipnik, M., Mirnik, J. (textbook) Dolenc, D., Graunar, M., Modec, B. (notebook)	DZS	2016(1st Ed.)/ 2016 (1st Ed.)	152/96	9/14
Kemija 9, i-učbenik	Jamšek, S., Sajovic, I., Wissiak Grm, K., Godec, A., Boh, B., Vrtačnik, M., Glažar, S.	Zavod RS za šolstvo	2014	271	9/14

(continued)

Table 4.1 (continued)

Textbook set* title	Author(s)	Publisher	Year of publication (Edition) Textbook/ workbook	Number of Pages Textbook/workbook	Grade/ Learner's age
Peti element 9	Devetak, I.,Cvirn Pavlin, T., Jamšek, S.	ROKUS Klett	2011 (1st Ed.)/2011 (1st Ed.)	77/79	9/14
Pogled v kemijo 9	A. Kornhauser, M. Frazer	MK	2005(1st Ed.)/ 2006 (1st Ed.)	140/115	9/14
Od molekule do makromolekule	Smrdu, A.	Jutro	2013 (2nd Ed.)/2013 (2nd Ed.)	128/152	9/14

The term "textbook set (*)" refers to all materials for students in the written or electronic form

= 4.52). Based on the results of the pre-test, 44 participants with a highlevel of prior knowledge were included in the eye-tracking sub-sample with an average score of over 16.71 points (SD = 2.86).

Eye tracker

For monitoring students' eye movements when solving chemistry tasks based on SMRs with different types of explanatory key, we used the screen-based Tobii Pro X2-30 eye tracker. Gaze data were captured at 30 Hz with an accuracy of 0.4 degrees of visual angle at distances ranging between 40 and 90 cm.

Problem set

The original problem set (Ferk Savec et al., 2016) consisted of 8 tasks based on SMRs, but for the purposes of the present study only 4 tasks were selected to investigate in detail the value of pictorial versus textual explanatory keys accompanying SMRs. Intentionally, all tasks were at the same taxonomy level (application) and the models of simple common compounds were used in all tasks. All tasks are comparable in terms of complexity and type of visual representation. The tasks were displayed one after the other on the computer screen. There was no time limit for solving the task, and the tasks were presented in random order.

The four examined tasks in the problem set can be viewed in full text (including the English translation of the Slovenian instructions) in the results section of this paper through print screens of the heat maps.

Eye-movement measures

In order to determine the visual attention of students for different elements of the tasks they solved, we focused on the total amount of time (total fixation duration, TFD; in some studies also referred to as dwell time) and the number of fixations (fixation count, FC) spent in particular areas of interest (AOI). For this purpose, the tasks displayed on the computer screen were divided into several AOIs (see Fig. 4.1).

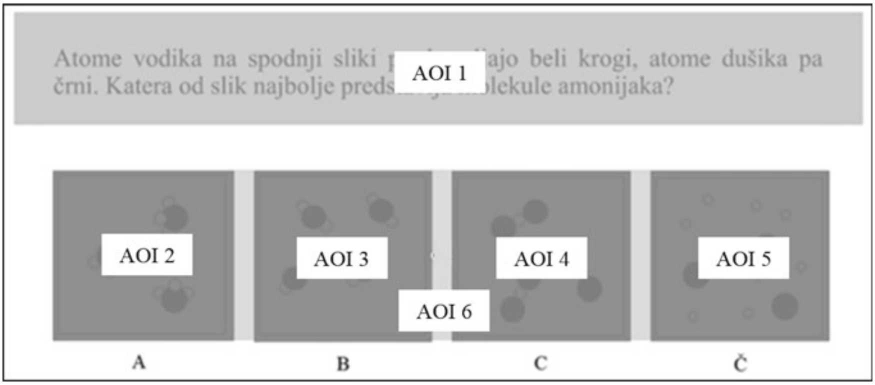

Fig. 4.1 Example of a task divided into AOIs [AOI 1 = Instructions and explanatory key; AOI 2 to AOI 5 = Model 1 (choice A) to Model 4 (choice Č); AOI 6 = All presented models]

A fixation was determined as a process when the participant held his eye for at least 60 ms at a specific AOI.

Since the data from eye movements were collected as part of the information processing during task solving, the total time spent in a given AOI was interpreted as a reflection of the relative amount of attention and consequently reliance paid towards each AOI was given in the service of task solving.

Data Collection and Analysis

Application of the rubrics for the analysis of the explanatory key accompanying SMRs in Slovenian chemistry textbook sets for primary schools (related to RQ1)

The rubric described in the section on instruments was used in the analysis of the chemical representations of the entire sample of chemistry textbook sets, which are presented in Table 4.1. The textbook sets were analysed individually. The SMRs were categorised with respect to the curriculum topics of the National Chemistry Curriculum for Primary School. The core topics in which SMRs were categorised are as follows: (1) Chemistry is a World of Matter (orig. Kemija je svet snovi); (2) Atom and the Periodic System of Elements (orig. Atom in periodni sistem elementov); (3) Compounds and Bonding (orig. Povezovanje delcev/gradnikov); (4) Chemical Reactions (orig. Kemijske reakcije); (5) The Elements in the Periodic Table (orig. Elementi v periodnem sistemu); (6) Acids, Bases and Salts (orig. Kisline, baze in soli); (7) Hydrocarbons and Polymers (orig. Družina ogljikovodikov s polimeri); (8) Organic Compounds Containing Oxygen (orig. Kisikova družina organskih snovi); (9) Organic Compounds Containing Nitrogen (orig. Dušikova družina organskih spojin) and (10) The Mole (orig. Množina snovi). Finally, the number of SMRs in each of the topics were counted and the frequencies calculated.

Collection of data in the SMRs study with eye tracker followed by an interview with students and their analysis (related to RQ2)

The data collection took place in two parts. In the first part of the study, the participants solved the group from the chemistry knowledge test under standard conditions that were the same for all participants. This part lasted up to 45 min. In the second part, in which the cognitive processes of the students were monitored using eye-tracking technology and an interview, the students were selected based on their performance in the chemistry knowledge test, and they participated individually. After calibrating the eye tracker, the students were introduced to a pre-task to avoid any impact due to difficulties in understanding the type of the tasks or the process of recording the answers and moving on to the next task before starting the main testing. Participants were asked to write down one answer for each task on a piece of paper and then press the space bar to move on to the next screen. Afterwards, the students completed eight tasks for the problem set displayed on the computer screen at their own pace, while eye movements were recorded. Each task was presented on the computer screen without time limit and in random order.

After the eye-tracking data were collected, the participants were interviewed and asked to compare tasks with different explanatory keys (textual versus pictorial explanatory key) with the following question: "When you compare these two tasks, was there a difference in difficulty between them? If there was a difference, please explain possible reasons". The oral answers of the participants were transcribed. The collection of eye- tracking and interview data took 30–55 min.

In order to investigate the role of the explanatory key in solving tasks based on submicroscopic representations, the collected eye movement data was first analyzed with Tobii Studio Enterprise. A further analysis was conducted using the Statistical Package for the Social Sciences (SPSS), version 21. The nonparametric test Wilcoxon Ranks Test (Z) was used to evaluate significant differences in the absolute and relative total fixation duration (TFD) and fixation count (FC) within particular areas of interest (AOIs) with respect to the pictorial versus textual explanatory key accompanying the SMRs.

The interview responses of the participants were coded using a coding table. The coding table was derived from a qualitative analysis of 25% ($n = 9$) of the interviews; the reliability of the coding was ensured by independent coding by two researchers (the two authors of this paper). Subsequently, the two evaluations were compared at the points where differences occurred and the more appropriate one was selected after consideration. Overall a reliability of 98% was achieved.

Results and Discussion

The results in paper are presented with regard to the stated research questions.

The integration of SMRs with/without explanatory key in Slovenian chemistry textbook sets with respect to curriculum topics (related to RQ1)

Table 4.2 The proportion of SMRs in the particular topics of the textbook sets with regard to the presence of explanatory key

The topics of the National Chemistry Curriculum for Primary School (8th and 9th Grade)	All SMRs		SMRs with explanatory key		SMRs without explanatory key	
	N	f (%)	N	f (%)	N	f (%)
1—Chemistry is a World of Matter	179	12.61	50	3.52	129	9.09
2—Atom and the Periodic System of Elements	29	2.04	12	0.85	17	1.20
3—Compounds and Bonding	150	10.57	31	2.18	119	8.39
4—Chemical Reactions	69	4.86	22	1.55	47	3.31
5—The Elements in the Periodic Table	16	1.13	2	0.14	14	0.99
6—Acids, Bases and Salts	160	11.28	49	3.45	111	7.82
7—Hydrocarbons and Polymers	407	28.68	32	2.26	375	26.43
8—Organic Compounds Containing Oxygen	287	20.23	12	0.85	275	19.38
9—Organic Compounds Containing Nitrogen	116	8.17	0	0.00	116	8.17
10—The Mole	6	0.42	0	0.00	6	0.42
SUM	1419	100.00	210	14.80	1209	85.20

The number of SMRs in the Slovenian chemistry textbook for the 8th and 9th grade of primary school varies from one curriculum topic to another. SMRs with an explanatory key represent 14.80% of all SMRs integrated in analysed chemistry textbook sets, which means that the majority (85.20%) of SMRs in all chemistry curriculum topics are not accompanied with an explanatory key (Table 4.2).

Table 4.2 also shows that the SMRs were most frequently used in the Topic 7—Hydrocarbons and Polymers (407 SMRs; 28.68%) and Topic 8—Organic Compounds Containing Oxygen (287 SMRs; 20.23%). The lowest frequency of use of SMRs was found in the Topic 10—The Mole (6 SMRs; 0.42%) and Topic 5—The Elements in the Periodic Table (16 SMRs; 1.13%) and Topic 2—Atom and those Periodic System of Elements (29 SMRs; 2.04%). However, the SMRs with explanatory key were most frequently found in the Topic 1—Chemistry is a World of Matter (50 SMRs; 3.52%) and Topic 6—Acids, Bases and Salts (49 SMRs; 3.45%). In contrast, in the Topic 9—Organic Compounds Containing Nitrogen (0 SMRs; 0.00% of SMRs with explanatory key) and Topic 10—The Mole (0 SMRs; 0.00% of SMRs with explanatory key) no SMRs with an explanation key were found.

It was assumed that the authors systematically plan the integration of SMS into the textbook sets and that the explanatory keys are also meaningfully integrated with SMRs and continuously upgraded through the curriculum topics from the 1st topic towards 10th topic in order to support the development of the representational competence of the learner. From the Fig. 4.1 it can be derived that in order to support the learners' representational competence, the introduction of SMRs accompanied by their explanatory keys into the textbook sets could probably have been more systematic, since the majority of SMRs are not accompanied by the explanatory key and the number of SMRs with explanatory key is zero in some cases (Topic 9—Organic Compounds Containing Nitrogen; Topic 10—The Mole) or very low, e.g. Topic 5—The Elements in the Periodic Table (2 SMRs; 0.14% of the SMRs with an explanatory key).

Figure 4.2 also indicates, that SMRs without an explanatory key are used quite often in the text book sets, especially in the second part of the curriculum topics (topics: 6—Acids, Bases and Salts; 7—Hydrocarbons and Polymers; 8—Organic Compounds Containing Oxygen; 9—Organic Compounds Containing Nitrogen). The high number of SMRs used in these topics could be explained through prepositions in general curriculum objectives, which require students to systematically develop an understanding of the relationship between structure, properties and application of the substances (Bačnik et al., 2011, p. 5), in addition these topics are elaborated with specific curriculum objectives. For example, in the curriculum topic 7—Hydrocarbons and Polymers, which has the largest number of SMSs (out of 407 SMRs: 32 SMRs with explanatory key; 375 SMRs without explanatory key),

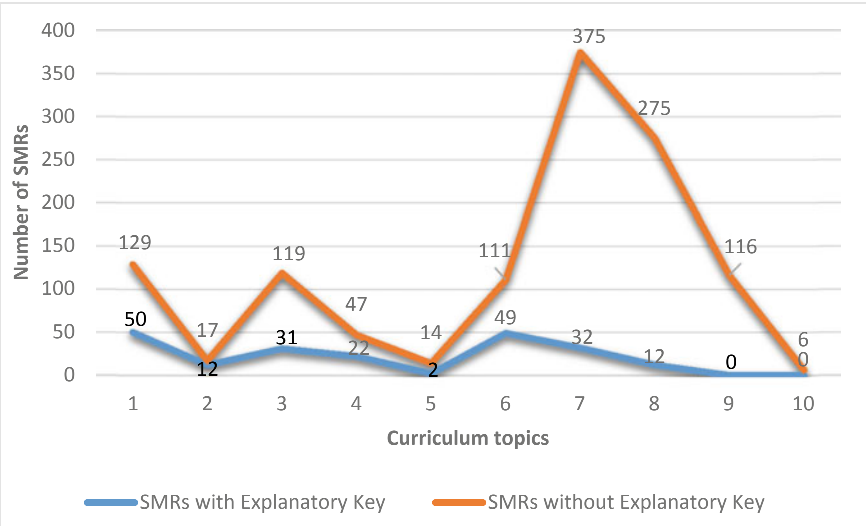

Fig. 4.2 The number of SMRs with/without Explanatory key within the curriculum topics in the textbook sets [Explanation of abbreviations: 1—Chemistry is a World of Matter; 2—Atom and the Periodic System of Elements; 3—Compounds and Bonding; 4—Chemical Reactions; 5—The Elements in the Periodic Table; 6—Acids, Bases and Salts; 7—Hydrocarbons and Polymers; 8—Organic Compounds Containing Oxygen; 9—Organic Compounds Containing Nitrogen; 10—The Mole]

the specific objectives indicate that students should learn that carbon and hydrogen are the fundamental elements of organic compounds, that students should be able to recognise the reasons for the abundance and diversity of organic compounds, the isomerism and that students should know the basic properties of hydrocarbons, correlate them with their use and act accordingly (Bačnik et al., 2011, pp. 11–12). On the other hand, it is not easy to find a reason for a high number of SMRs without an explanatory key, as they do not provide additional information to support the learner's recognition process. It may be that textbook authors assume that learners are already able to recognise the meaning of SMRs without explanation, because their representational competence has been adequately developed in previous topics, or that authors integrate SMRs into textbook sets without considering how correct recognition of SMRs by learners might affect the learning process based on them. The latter assumption is consistent with Johnstone's assertion that experienced chemists make the transition between levels of representation very easily, and they assume that learners can do this as easily as they do themselves (Johnstone, 1991).

The value of the pictorial versus textual explanatory key accompanying SMRs for the learners (related to RQ2)

In order to better understand the potential added value of the explanatory key accompanying SMRs for students, in the second part of the paper we present a study based on four simple cases of SMRs accompanied by pictorial versus textual explanatory keys, which were examined with the help of an eye tracker, followed by a short interview with the students.

First, based on the study with eye tracker, Figs. 4.2 and 4.3 present examples of eye movements using a heat map for the task in which SMRs were accompanied by

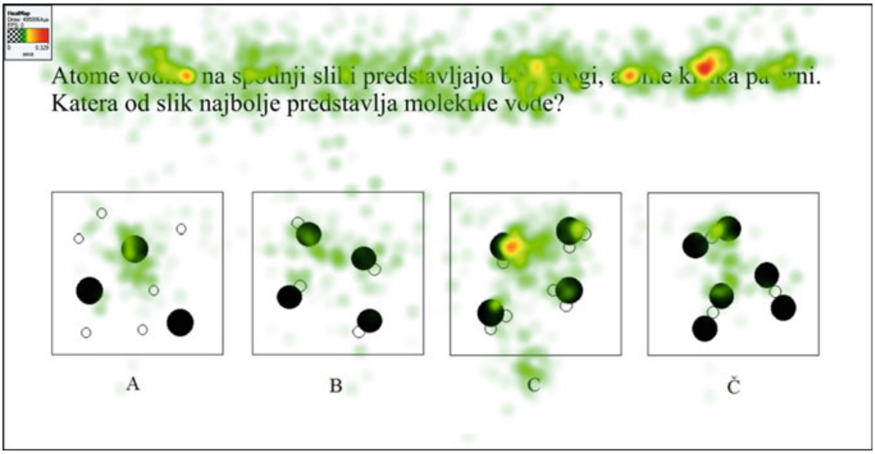

Fig. 4.3 A heat map for Task 1, which includes textual explanatory key, shows the relative density of fixations using a colour gradient [Task 1 Instruction (above): On the pictures bellow, the hydrogen atoms are represented by white circles, oxygen atoms are represented by black circles. Which of pictures best presents the water molecule?]

textual explanatory key (Task 1 and Task 2). Figures 4.4 and 4.5 show tasks in which SMRs were accompanied by pictorial explanatory key (Task 3 and Task 4). In heat maps, the red colour stands for a high relative density of fixations and green for a low relative density of fixations by students.

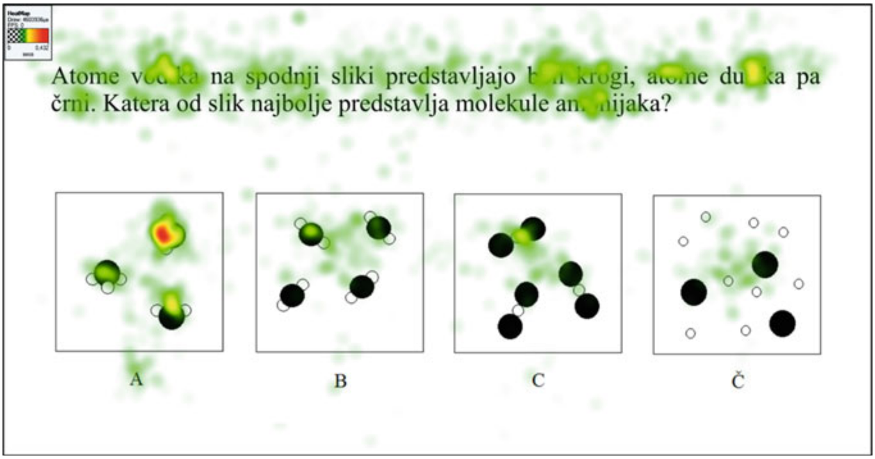

Fig. 4.4 A heat map for Task 2, which includes textual explanatory key, shows the relative density of fixations using a colour gradient [Task 2 Instruction (above): On the pictures bellow, the hydrogen atoms are represented by white circles, nitrogen atoms area represented by black circles. Which of pictures best presents the ammonia molecule?]

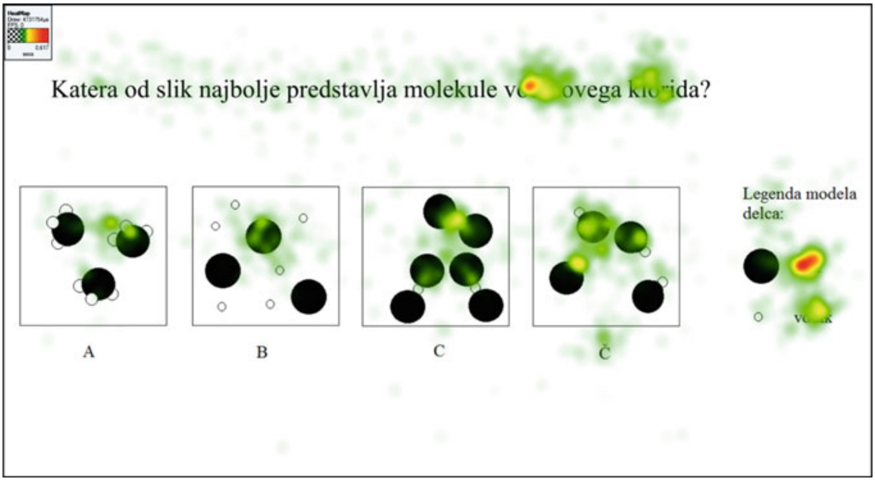

Fig. 4.5 A heat map for Task 3, which includes pictorial explanatory key, shows the relative density of fixations using a colour gradient [Task 3 Instruction (above): Which of pictures best presents the hydrogen chloride molecule? Task 3 Instruction (right): Legend of the particles in the model: bigger black circle—chlorine, smaller white circle—hydrogen]

In addition to the heat maps, Table 4.2 shows the corresponding mean values of the absolute and relative TFD and FC for the areas of interest of particular models. The Spearman correlation coefficients ($r = 0.777 – 0.969$, $p < 0.001$) indicate that there is a strong correlation between absolute and relative TFD and FC in all tasks (Task 1–Task 4).

From Fig. 4.3 it can be seen that the AOI of choice B and choice C of Task 1 have a higher relative density of fixations compared to other choices, since the students' gaze was more often fixed on these representations when solving a task at particle level. This can also be seen from Table 4.3, which shows the mean values of the absolute and relative TFD and FC are presented. The choice C, which attracted the attention of the majority of students (TFD 13.90%; FC 13,12%), is also the correct answer of the Task 1, where the accuracy of the students' answers is 100%.

Figure 4.4 shows that the AOI of choice A and choice B have a higher relative density of fixations. The same student focus can also be seen from Table 4.3, where the choice A attracted the most student attention (TFD 16.93%; FC 12.18%), as it is the correct answer of Task 2, with a student response accuracy of 97.01%.

From Fig. 4.5 it can be seen that the AOI of choice C and choice Č have a higher relative density of fixations, since the students' gaze was more often fixed on these representations when solving the task. The observation is also evident from Table 4.3,

Table 4.3 Mean values of absolute and relative TFD and FC for tasks 5 to 8 with the focus on AIO for particular possible choices of answers in tasks

Type of explanatory key	Task	Eye-movement measures	Area of interest (AOI)				
			Model 1 (choice A)	Model 2 (choice B)	Model 3 (choice C)	Model 4 (choice Č)	All presented models
Textual	5	TFD [s]	0.51	0.59	1.44	0.56	3.11
		TFD [%]	4.94	5.71	13.90	5.42	29.96
		FC [count]	2.73	3.84	7.14	2.73	16.44
		FC [%]	5.02	7.06	13.12	5.02	30.22
	6	TFD [s]	2.07	0.88	0.82	0.54	4.29
		TFD [%]	16.93	7.17	6.68	4.39	35.16
		FC [count]	7.21	4.35	3.91	2.47	17.94
		FC [%]	12.18	7.35	6.60	4.17	30.30
Pictorial	7	TFD [s]	0.79	0.87	1.48	2.03	5.18
		TFD [%]	6.85	7.54	12.81	17.57	44.77
		FC [count]	3.33	4.03	6.00	8.24	21.59
		FC [%]	6.42	7.77	11.57	15.89	41.64
	8	TFD [s]	1.95	0.85	3.12	0.64	6.54
		TFD [%]	18.01	7.82	28.84	5.88	60.56
		FC [count]	6.94	4.44	11.65	3.24	26.26
		FC [%]	15.03	9.61	25.23	7.01	56.88

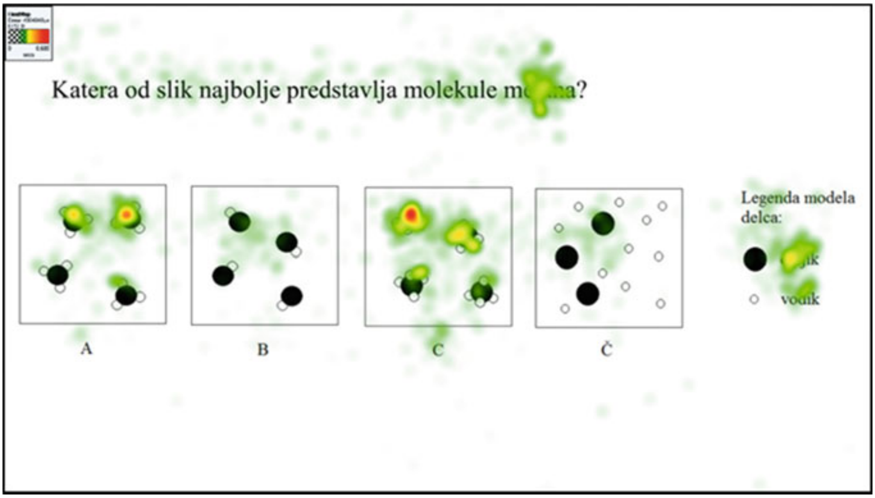

Fig. 4.6 A heat map for Task 4, which includes pictorial explanatory key, shows the relative density of fixations using a colour gradient [Task 4 Instruction (above): Which of pictures best presents the methane molecule? Task 4 Instruction (right): Legend of the particles in the model: bigger black circle—carbon, smaller white circle—hydrogen]

where the choice Č as the correct answer of the Task 3, achieved the attention of most students (TFD 17.57%; FC 15.89%) with a response accuracy of 94.61%.

Figure 4.6 shows that the AOI of choice A and choice C have a higher relative density of fixations, since the students' gaze was more often fixed on these representations when solving the task. The observation is also evident from Table 4.3, where choice C as the correct answer of the Task 4 received the most attention from the students (TFD 17.57%; FC 15.89 with a student response accuracy of 87.45%.

Table 4.3 shows that the highest mean values of relative TFDs and FCs for the explanatory key were achieved in the task with a textual key (Task 1: TFD = 70.04%; FC = 69.78%), and the lowest mean values of relative TFDs and FCs were achieved in the task with a pictorial representation (Task 4: TFD = 39.44%; FC = 43.12%). This is also consistent with the highest response accuracy of students in Task 1 (100.00%) and the lowest response accuracy of Task 4 (87.45%).

To further examine how textual and pictorial explanatory key influence students' task solving the AOI for *All presented models*, AOI for *Instructions and explanatory key* and AOI for *Models, instructions and explanatory key* (Table 4.4) were examined by the use of the Wilcoxon Ranks Test. Thereby, AOI for the pictorial explanatory key in Tasks 7 and Task 4 also included task instruction in order to equalise the AOI with the textual explanatory key where the task instructions and key were jointly presented (Task 1 and Task 2). The common AOI for both kinds of tasks is therefore named *Instructions and explanatory key.* The analogical reasoning was used with AIO *Models, instructions and explanatory key.*

Table 4.4 Mean values of absolute and relative TFD and FC for tasks 5 to 8 with the focus on AOI for All presented models, Instructions and explanatory key and Models, instructions and explanatory key

Type of explanatory key	Task	Eye-movement measures	Area of interest (AOI)		
			All presented models	Instructions and explanatory key	Models, instructions and explanatory key
Textual	5	TFD [s]	3.11	7.27	10.38
		TFD [%]	29.96	70.04	100.00
		FC [count]	16.44	37.97	54.41
		FC [%]	30.22	69.78	100.00
	6	TFD [s]	4.29	7.91	12.20
		TFD [%]	35.16	64.84	100.00
		FC [count]	17.94	41.26	59.20
		FC [%]	30.30	69.70	100.00
	SUM	TFD [s]	7.40	15.18	22.58
		TFD [%]	32.77	67.23	100.00
		FC [count]	34.38	79.23	113.61
		FC [%]	30.36	69.74	100.00
Pictorial	7	TFD [s]	5.18	6.39	11.57
		TFD [%]	44.77	55.23	100.00
		FC [count]	21.59	30.26	51.85
		FC [%]	41.64	58.36	100.00
	8	TFD [s]	6.54	4.26	10.80
		TFD [%]	60.56	39.44	100.00
		FC [count]	26.26	19.91	46.17
		FC [%]	56.88	43.12	100.00
	SUM	TFD [s]	11.72	10.65	22.37
		TFD [%]	52.39	47.61	100.00
		FC [count]	47.85	50.17	98.02
		FC [%]	48.82	51.18	100.00

With regard to AOIs of ***All presented models*** (Table 4.4) the Wilcoxon Ranks Test indicated significant differences in the sum of the relative mean values of TFD and FC (TFD: $Z = -3.958$, $p < 0.001$; FC: $Z = -3.405$, $p < 0.001$). The significant differences in the sum of the mean values of TFD as well as the sum of the mean values of FC indicate, that students spent more time glancing on the AOIs of models that were accompanied by pictorial explanatory key in comparison to the AOIs of models accompanied with the textual explanatory key. Thereby, students also fixated on particular spots of the AOIs of models accompanied with the pictorial explanatory key more often than on AOIs of models accompanied with the textual explanatory key while solving the tasks.

The Wilcoxon Ranks Test showed also significant differences in the sum of the relative mean values of TFD and FC on AOIs of ***Instructions and explanatory key*** (Table 4.4) of the pictorial and textual explanatory key (TFD: $Z = -3.838$, $p < 0.001$; FC: $Z = -4.626$, $p < 0.001$). The significant differences in the sum of the mean values of TFD as well as the sum of the mean values of FC could be interpreted with the postulation, that students not only spent more time on the textual explanatory key in comparison with the pictorial explanatory key, but also fixated on particular spots (words) of the textual explanatory key more often while solving the task in comparison to a pictorial key.

On the other hand, Wilcoxon Ranks Test indicated, that the sum of the relative mean values of TFD on AOIs of ***Models, instructions and explanatory key*** (Table 4.4) of the pictorial versus textual explanatory key was not significantly different (TFD: $Z = -0.445$, $p = 0.657$). However interestingly, the number of FC on these AOIs was significantly different (FC: $Z = -2.360$, $p = 0.018$), which points to a difference in number of fixations on particular spots of AOIs. This could be interpreted with assumption, that the students in overall used the comparable amount of time for solving tasks either with a pictorial or textual explanatory key, but during the process of task solving students fixated their attention on more spots, when solving tasks with textual explanatory key. It would be interesting to further examine these results, especially with taking into consideration that the students' response accuracy in tasks with textual explanatory key yielded slightly higher (Task 1: 100% and Task 2: 97.01%) then tasks with pictorial explanatory key (Task 3: 94.61% and Task 4: 87.45%).

As the final part of the consideration about possible added value of a certain type of explanatory key to the SMRs, the attention was payed to students' perception of their value. Therefore, in the **interviews**, students were asked to compare two tasks (one having the textual other the pictorial explanatory key) and explain if there was any difference in difficulty between them. If students would observe differences, they would be asked to explain possible reasons from their perspective.

The majority of the students (91.43%; $N = 32$ from 35 students) claimed that from their perspective there was no difference in difficulty between task with various explanatory key (in terms of textual versus pictorial) accompanying the SMRs:

Typical students' comment:

"There are no differences, if you know the molecular formula, they're all easy".

"They are similar; the procedure of solving is the same".

Some students ($f = 8.57\%$; $N = 3$ from 35 students) explicitly pointed out that their difficulties in solving such tasks are due to their lack of chemistry knowledge.

Typical student's comment:

"The one with the methane was the hardest. I didn't know, if it was CH_3 or CH_4".

Conclusion

In recent decades, submicroscopic representations (SMRs) have been integrated into textbook sets, as research in chemistry education has shown that their meaningful integration can facilitate learning chemistry with understanding. The paper focuses on two perspectives of the explanatory key accompanying SMRs in chemistry learning, and attempts to combine the findings from both perspectives to provide recommendations that could be useful in the school practise of chemistry teaching. The paper firstly examines the state-of-art with respect to the presence of explanatory key accompanying SMRs in Slovenian chemistry textbook sets for the 8th and 9th grade of primary school, and secondly it aims at the role of the explanatory key in the processing of SMRs in solving chemistry tasks in which they are involved using the Eytracker method, followed by a short interview with the students.

The results of the first part indicate, that the number of SMRs in the Slovenian chemistry textbook for the 8th and 9th grade of primary school varies from curriculum topic to curriculum topic. SMRs with an explanatory key represent 14.80% of all SMRs integrated in analysed chemistry textbook sets, which means that the majority (85.20%) of SMRs in all chemistry curriculum topics are not accompanied with an explanatory key. It can be assumed that in order to support the representational competence of learners, the introduction of SMRs with their explanatory keys into the textbook sets from the beginning to the end of the textbook sets could probably have been more systematic.

In the second part, which examined the possible added value of the explanatory key that accompanies the SMRs, it was found that students use the explanatory key efficiently in solving chemistry tasks both in the pictorial and textual form of the explanatory key. Overall, the students spent the same amount of time solving tasks that were solved with the pictorial or textual explanatory key. However, the students spent more time glancing on the AOIs of models that were accompanied by pictorial explanatory key compared to the area of interest AOIs of models accompanied with the textual explanatory key. In solving the tasks, the students also fixated on particular spots of the AOIs of models that were accompanied by the pictorial explanatory key than on AOIs of models that were accompanied by the textual explanatory key. In the cases studied, the students not only spent more time on the textual explanatory key compared to the pictorial explanatory key, but also fixed themselves more often on particular spots (words) of the textual explanatory key compared to a pictorial key when solving the task. Despite the observed differences in the use of certain forms of the explanatory key, it can be concluded from the results that both forms of the explanatory key supported the students' ability to perceive SMRs correctly when solving tasks and enabled them to solve the tasks with approximately the same amount of time.

From the results it can be concluded that the explanatory key accompanying the SMRs plays an important role in information processing and that it should be an integral part of the SMRs in chemistry textbook sets. It would be beneficial for students if the SMRs were more systematically included in textbook sets from beginning to end to facilitate the development of their representational competence and to support students' learning.

In order to support the efficient use of SMRs by students, additional parts (e.g. annexes) of chemistry textbooks could also be proposed by textbook authors and/or editors, in which the possibilities to support students in the use of different types of SMRs, both in traditional and computer-based form (e.g. ball-and-stick, space-filling, wire-frame, valence-shell electron pair repulsion model) are elaborated, the colour conventions used to label the respective elements are presented and didactic explanations aimed at possible misunderstandings in the use of SMRs are addressed (e.g. the type of models, the rigidity of particles and bonds in models, the role of colours in labelling particles, the speed of processes at particle level).

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