Review

Using Eye-Movements to Explain Processing Triple Level of Chemical Information: Systematic Review

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Abstract

The focus of this systematic literature review was to examine eye-tracking studies in the chemistry classroom and to evaluate the usefulness of eye-tracking in studying students' learning of complex chemical concepts. The reviewed studies primarily used small samples of students, with undergraduate students being the most studied population, and measured variables such as eye movements, fixation time, pupil dilation, and others. The results show that higher performing students have shorter fixation time and learn better with models, with prior knowledge being an important factor. However, both students rely mainly on the symbolic level of presentations with better performing students being more successful at giving explanations. Problems with the complexity of data analysis were reported in the studies.

Keywords: Chemical education, eye-tracking, cognitive processes, visualisation, triple nature of chemical concepts

1. Introduction

The education sector is one of the priorities of most member states of the European Union.[1] In Slovenia, too, the central national interest is to acquire quality knowledge, in which a quality educational process plays a key role.[2] Learning is a lifelong active social process.[3] Competences also include the understanding of scientific (including chemical) concepts that enable individuals in today's society to develop effective learning strategies and consequently to successfully solve authentic scientific (including chemical) problems.[2] However, content of chemistry education is often abstract for learners in all educational settings and therefore difficult to understand.[4–6] One of the challenges of modern chemistry education is to focus on processes involved in understanding scientific (including chemical) phenomena and their application in solving authentic problems. These processes can be studied through reporting of problem solving or by observing their behaviour during problem solving. Physiological indicators of the cognitive process of individual problem-solving strategies include skin conductance, heart rate, blood pressure, brain waves, blood flow to the brain (monitored by fMRA) and others, as well as eye movements, such as saccades, fixations and pupil size. These eye movements can be measured with an eye-tracking device. These movements play a key role in the study of visual attention and the processing of information, and thus the learning process.[7] Research results show that there are important links between the cognitive of learning (including chemical learning) and eye movements.[8,9]

1. 1. Why is Chemistry Difficult to Learn?

The complexity of teaching and learning chemical concepts can be traced back to their triple nature. Chemical concepts can be taught through experimental work or observation of phenomena – i.e. at the macroscopic level. This level represents the actual state of a chemical process that can be observed and perceived with the senses. At the second level, observations can be explained with theories based on atomic, molecular or ionic – i.e. submicroscopic particle levels. Both levels are represented by the symbolic level, for which it is essential to transform the first two levels into appropriate symbols with a specific meaning.[5,10–12] All three levels of the chemical concept (macroscopic, submicroscopic and symbolic) were thus linked in a so-called triangle of the triple nature of a chemical concept.

It is well known that students have difficulty distinguishing between the description and interpretation of macroscopic phenomena at the submicroscopic level. The submicroscopic level is the basis for understanding chemical concepts that students need to acquire before they can illustrate the concepts symbolically.[5] For students who have not yet developed sufficient abstract thinking skills, such content is difficult to understand and therefore uninteresting and unpopular.[13]

According to constructivist theory, students should initially only be introduced to concepts at the macroscopic level (the concrete level). Later, when they are capable of more abstract thinking, they are expected to move on to submicroscopic interpretations and symbolic representations (abstract level). The model in Figure 1 shows the aspects of students' developing mental model as an expanding triangle (students' depth of knowledge at each corner of the triangle increases), and at the same time the iceberg model serves as an analogy for students moving to higher levels of understanding as more of the symbolic and submicroscopic level can be introduced, the horizontal line moves towards the submicroscopic and symbolic level.[4]

From the model of teaching and learning chemistry (Figure 1), it can also be deduced that for a quality understanding of chemical concepts, it is important that the teacher integrates the threefold nature of chemical concepts into the lesson by using different teaching materials and learning approaches.[14] As already mentioned, inadequate prior knowledge on the basis of which the students cannot build increasingly sophisticated and abstract concepts plays an important role in the lack of understanding of chemical concepts and the creation of incorrect mental models of these concepts. The construction of mental models, including the assimilation of new and challenging concepts, also causes problems at all levels of education.[15] It is argued that in chemistry education in order to properly build mental models of chemical concepts, the triple nature of chemical concepts must be integrated in the classroom using different teaching materials and learning approaches.[5] The gradual transition between the macroscopic and submicroscopic levels of a given phenomenon could facilitate students understanding of the connections between the macroscopic and the submicroscopic levels, which is then added to the symbolic level.[16] It was shown that transition between the macroscopic and submicro-

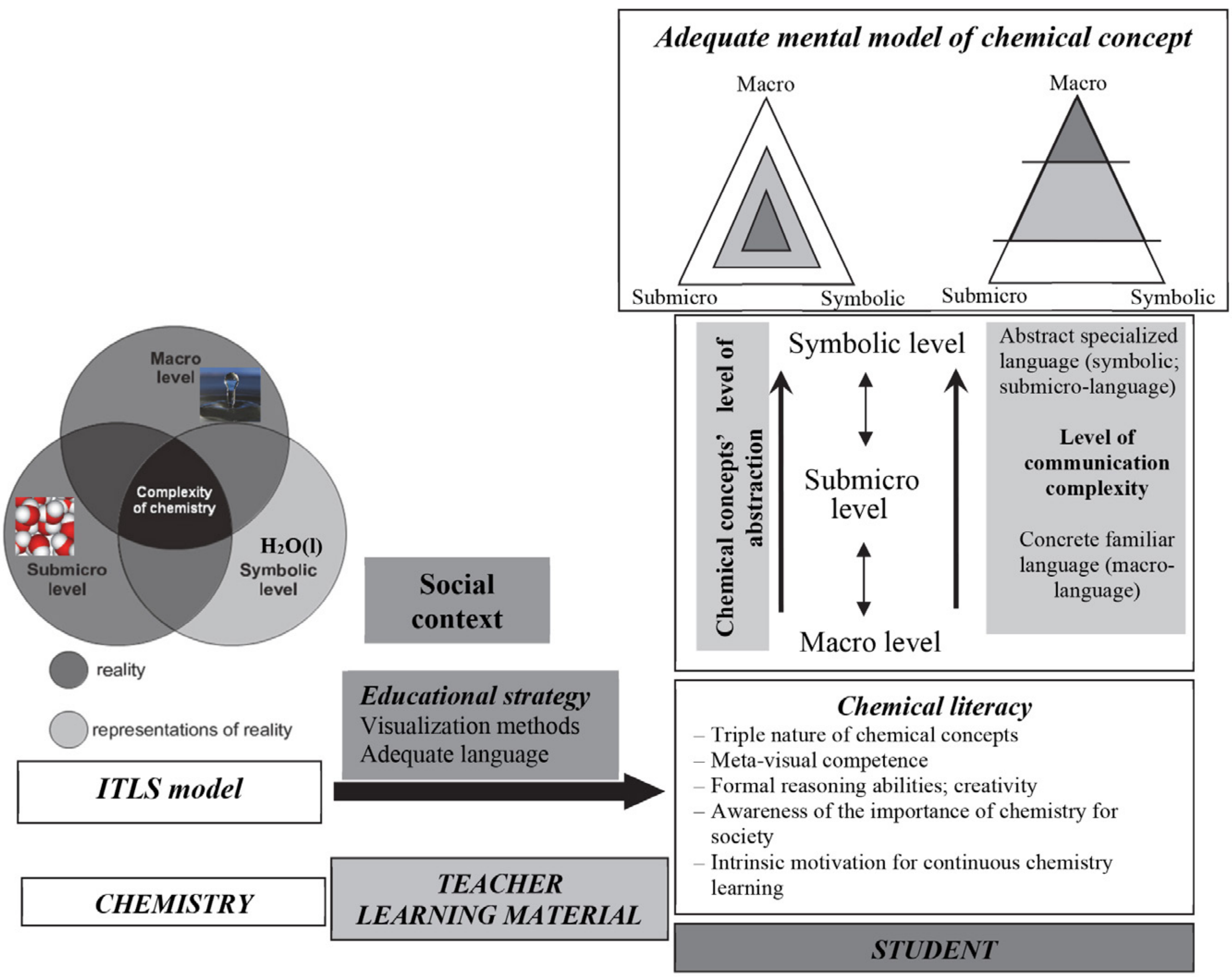

Figure 1. Adapted teaching and learning chemistry model.[4,14]

scopic levels by presenting chemical concepts at the mesoscopic level helps to reduce the occurrence of misconceptions related to the shaping of the mental model of that chemical concept.[17] At the mesoscopic level, different levels of magnification are used until the level of molecules, atoms and ions (submicroscopic level) is reached.

However, research show that the complexity of the triple nature of chemical concepts for students is not so demanding that it could not be understood.[18–22]

1. 2. How Chemistry is Learned – from Processing Chemical Information to Forming Adequate Mental Models

More than 80% of information is received and processed through a visual channel, so the use of different visualization tools is important for the quality of chemical knowledge and the development of problem-solving strategies. Abstract illustrations, especially of chemical concepts at the submicroscopic level, thus support the overall understanding of the concepts presented to students.[8,10] The models used as explanatory and learning tools to represent an actual object, system, phenomenon or process as realistically as possible must be simple, logical and useful. In addition to the use of pre-prepared models, modelling plays an important role, in the classroom, with students creating their own models based on some known laws.[23] This improves students critical thinking and ability to solve chemical problems, which leads to an increase in learning success and situational interest in chemistry lessons.[24] However, in linking the symbolic and submicroscopic level to the macroscopic level of phenomena, the use of visualisation tools can also pose certain dangers and shortcomings due to the way they represent abstract concepts. To avoid further misconceptions of chemical concepts, the teacher should inform students of these dangers when using such tool.[25]

The creation of an appropriate mental model depends to a large extent on interest in the learning content.[26,27] The learning content should be designed to be contemporary and relevant to learning, to increase interest in chemistry and to promote higher order cognitive skills and research skills (e.g. asking research questions, planning research design, selecting appropriate instruments to measure phenomena, knowing how to collect data, understanding the interpretation of results, drawing conclusions and answering research questions).[28]

Cognitive processes cannot be observed directly during learning, but only indirectly, through students' answers (in achievement tests), observation of behaviour during learning (e.g. how quickly questions are answered, in what order tasks are solved) and other methods of self-reporting about the learning process. Due to the indirect measurement of cognitive processes and to methodological limitations of the procedures for collecting data on cognitive processes during learning, questions often arise about the validity of the data obtained. Therefore, different research methods are needed to represent learning and problem-solving processes from different perspectives.[29] One of the techniques that has recently been used in the chemistry didactics research is the use of eye-tracking. There are important links between the cognitive process and eye movements.[7,30–32] The use of eye-tracking allows us to indirectly monitor the basic mechanisms of information encoding and integration.[7] Eye-tracking technology has been used in chemistry education research to investigate students' understanding of the phenomena while they are working on a task as it provides information of students' cognitive processes while working on activity.[33,34] The main question was how eye movements can be related to students' understanding of chemistry. The eye tracker measures the number of fixations in the region of interest (i.e. periods of relatively stable gaze on the observed object during which visual information is processed), the total duration of fixations in the region of interest, number of visits on a particular source, which is useful in problem-solving, and also some other measures of eye movements (such as pupil size). A typical fixation lasts 200–300 milliseconds. Successive fixations are separated by saccades (i.e., the rapid movement of the eyes to the centre of interest that provides new visual information).[35] A higher number of fixations and their longer duration on a particular area of interest indicate which area in the visual field was of most interest to the person and where attention was directed. Eye-tracking system also allows measurements of pupil dilation which is related to person's cognitive load. Eye-tracker measurements provide objective data about a person's covert attention and offer additional support in the measuring the person's cognitive activity and in studying the process of problem solving with visual stimuli.[8,9]

Previous studies on eye-tracking have shown that unsuccessful problem solvers have problem distinguishing between relevant and irrelevant factors also, they have a problem focusing on relevant factors.[36]

2. The Purpose of this Research

The aim of this study was to examine the findings from eye-tracking studies on cognitive processes during chemistry learning and solving chemistry problems. A review paper that examined papers which were published by recognized scientific journals from 2000 to 2012 and which employed eye-tracking method in studying learning in a general context were already published. Seven areas were examined in this study: patterns of information processing, effects of instructional design, review of existing theories, individual differences, effects on learning strategies, patterns of decision making, and conceptual development.[37] Another review focusing on the use of eye-tracking method in chemistry education research analysed six studies (two of which were unpublished dissertations by the authors). Authors examined various aspects of this method in chemistry education research, such as research questions, study type, sample size, protocol, and stimuli.[32]

A more detailed analysis of published research in the field of problem solving in chemistry is needed, covering the complexity of chemical concepts, their influence on the processing of chemical information and learning chemistry, and different methods for investigating cognitive processes in the performance of tasks in chemistry. Therefore, this review examines four themes in the analysed papers: (1) participants, (2) supported methods, (3) chemical content, and (4) basic outcomes applicable in a school context. In addition, the reference lists of analysed papers were examined to identify further studies that could be considered for analysis. The results could help determine what aspects teachers should consider when teaching more abstract concepts at all levels of chemistry education.

3. Method

The focus of this paper was to review eye-tracking studies in the chemistry education and evaluate the utility of eye-tracking in examining how complex chemical concepts (e.g. triple nature of chemical concepts) are learned by students.

In conducting the systematic review of the published literature, the Preferred Reporting Items for Systematic Reviews (PRISMA) approach was followed in accordance with the definition of a systematic review.[38,39] Evidence from multiple studies were combined by identifying relevant research and assessing the quality of the studies.

3. 1. Search Strategy

Papers from two databases Web of Science (WoS) and Scopus were identified using Boolean operators (Table 1) created for each database to identify published papers.

Table 1. Search strings.

Database	Search string
Web of Science	(TI=(eye-tracking) OR AB=(eye-tracking) OR AK=(eye-tracking) OR TI=(eye AND movements) OR AB=(eye AND movements) OR AK=(eye AND movements)) AND (TI=(chemical AND education) OR AB=(chemical AND education) OR AK=(chemical AND education))
Scopus	(TITLE(eye-tracking) OR ABS(eye-tracking) OR KEY(eye-tracking) OR TITLE(eye AND movements) OR ABS(eye AND movements) OR KEY(eye AND movements)) AND (TITLE(chemical AND education) OR ABS(chemical AND education) OR KEY(chemical AND education))

To ensure that the references are current, and the results of this study are up to date, papers from 2010 to 2024 were included in this systematic review.

3. 2. Study Selection

The inclusion criteria (IC) were established for the inclusion of a particular paper identified in both databases in this review. These criteria are: (1) the paper was published between the year 2010 and 2024; (2) the paper is written in English; (3) it is not review study or meta-analysis; (4) the paper has been published in peer reviewed journal; (5) the study is not listed in another database; (6) the full text paper is available; (7) the study used eye-tracking technology for data collection; (8) the study was conducted with primary, secondary or university students and (9) the study was conducted in chemistry education.

Papers were selected in four phases. In each phase papers were excluded from the review based on the exclusion criteria.

Forty-one papers were identified that explored concepts for science education using eye-tracking technology. The main reason for excluding the papers from this systematic review was that they were duplicates and did not meet the inclusion criteria IC7, IC8 and IC9. A total of twenty-two papers were included in this systematic review. In the analysed period, most articles (3) in the field of chemical education were published in 2015, 2019, 2020 and 2024. Ten papers were published in the *Journal of Chemical Education*, followed by the journal *Computers in Human Behaviour* with two papers. On average, the analysed papers referred to about 60 units of literature. Papers included in this review were cited on average 25 times in WoS and 18 times in Scopus by the end of 2024, this shows that that using eye tracking technology in chemical education is trending internationally.

4. Results and Discussion

4. 1. Characteristics of the Analysed Studies

The research problem, the number of participants, the eye-tracker model and the data collection technique were analysed in the articles examined (Table 2).

It can be seen from Table 2 that all the papers analysed investigated similar problems, related to different types of visualisation materials that students can use when learning certain chemical concepts or solving problems. Most of the papers focused on students' fixation time, gaze and eye movements when viewing static/dynamic 2D/3D representations or simulations. The attention was also measured when using stick and ball models and when making connections between different representations. The different fixation times, gaze and eye movements of the students on the different models were also compared

Table 2. Research problems and methods used in the analysed papers.

Authors (year)	Research problem	Participants	Eye-tracker	Data collection technique; instruments
Stieff et al. (2011)[40]	What are the students' abilities to coordinate representations using multi-representational displays (i.e. a molecular model, a general equation, a numerical equation and a graph). What are the complementary contributions of eye fixation data.	10 undergraduate chemistry students	SMI EyeLink	Eye-tracking system; interview, videotape-audiotape
Tang and Pienta (2012)[41]	How students use online tools for problem-solving. Effect of problem difficulty and cognitive processes on solving gas law word problems (i.e. the differences in problem-solving time and number of fixations between two groups of students).	12 high-school students	Tobii T120	Eye-tracking system; questionnaire
Williamson et al. (2013)[42]	How students use ball-and-stick images versus electrostatic potential maps when asked questions about electron density, positive charge, proton attack, and hydroxide attack with six different organic molecules.	9 undergraduate chemistry students	SMI EyeLink	Eye-tracking system; interview
Hinze et al. (2013)[43]	How students use ball-and-stick images versus electron potential maps to solve specific questions about electronegativity, molecule polarity, and identification of oxidations states.	30 undergraduate chemistry students	Tobii T60	Eye-tracking system; tests (pre-test basic chemical knowledge test; cognitive ability test; five spatial ability tests), interview, audiotape
Tang et al. (2014)[44]	What are students' chemistry problem-solving abilities. Which cognitive activities students use when solving gas law stoichiometry word problems.	High-school students; number not reported.	Tobii T120	Eye-tracking system; interview;
O'Keefe et al. (2014)[45]	How learners construct knowledge when learning environments that include multiple representations of ideal gas laws, as well as transition between them, are applied using a computer-based model.	26 high-school students	SMI RED250	Eye-tracking system; tests, interview
Chen et al. (2015)[46]	What is the effectiveness of mental (spatial) abilities to construct mental models of atomic orbitals after learning with 3D static or dynamic representations. Can eye movements predict students' achievements on constructing the mental models of these concepts.	60 high-school students	EyeLink 1000	Eye-tracking system; pre-post multiple-choice test, mental model construction test; spatial ability test
Cullipher and Sevian (2015)[47]	How students' eye gaze patterns correlate with their implicit assumptions about structure property relationships using IR spectroscopy.	25 undergraduate and graduate chemistry students	Tobii X2-60	Eye-tracking system; interview, audiotape
Rau et al. (2015)[48]	How students' visual attention behaviours relate to their sense-making abilities and their reasoning about chemistry? Furthermore, identify specific concepts that Chem Tutor should target because helping students make connections between representations with respect to these concepts might lead to significant learning gains.	26 undergraduate and graduate chemistry students	SMI RED250	Eye-tracking system; online test
Topczewski et al. (2016)[49]	How do students in organic courses use data to solve NMR spectral problems and how do these students develop effective strategies.	27 undergraduate and graduate chemistry students	Tobii T120	Eye-tracking system; test
Herrington et al. (2017)[50]	How students understand solution process for ionic and covalent compounds? How and where do students allocate attention while interacting with a simulation, as compared to a screencast, when coupled with a guided assignment?	12 undergraduate students	Tobii T60	Eye-tracking system; pre- and post-knowledge tests

Authors (year)	Research problem	Participants	Eye-tracker	Data collection technique; instruments
Karch et al. (2019)[51]	Can gaze data and pupil measures be used to identify students' solving strategies? How different tasks influence students' level of cognitive load?	22 students before the beginning of first semester general chemistry	Tobii X2-60	Eye-tracking system; chemical concepts inventory, retrospective interviews
Connor et al. (2019)[52]	To identify invalid assumptions of students when interpreting the results of IR and ^{1}H NMR synthesis. What invalid assumptions severely constrain organic chemistry students' reasoning?	18 undergraduate organic chemistry students	SMI RED	Eye-tracking system; semi-structured retrospective think-aloud interviews
Baluyut and Holme (2019)[53]	How students obtained and used information from particulate nature of matter diagrams as well as balanced chemical equations when asked questions about stoichiometry concepts such as limiting and excess reagents, and yield.	29 chemistry students of a two-semester general chemistry sequence	SMI RED	Eye-tracking system; online test
Nehring and Busch (2020)[54]	To find out, whether students tend to observe demonstrations from left-to-right manner and to test if there is any difference in setting up the demonstration from left to right or not.	146 students, on lower and upper secondary school	Eye gaze Edge Eye-Follower 2.0 with NYAN	Eye-tracking system; tests
Rodemer et al. (2020)[55]	To find out to what extent do beginner and advanced students differ in in their visual processing behaviour in case-comparison tasks and to what extent does task characteristics influence beginner and advanced students' visual processing behaviour.	37 undergraduate chemistry students	Tobii Pro X3-120	Eye tracking system; tests
Slapničar et al. (2020)[56]	To determine if the justifications of successful and unsuccessful students differ according to their level of education and their age. Also, to check if successful students fix their gaze on correct 3D presentation for longer time.	30 seventh grade primary school students, 29 first year upper secondary school students and 20 students of the double-majors study programme of chemistry and biology/physics	Eye-Link1000	Eye-tracking system; tests, think-aloud interviews
VandenPlas et al. (2021)[57]	How learning with PhET simulation effect students' conceptual understanding, can screencast be most effective method for students' learning outside of the class, and where do students allocate attention when using screencast or simulation.	302 undergraduate students overall, 16 students using eye-tracker	Tobii T60	Eye-tracking system; pre-test and follow-up test
Tóthová et al. (2021)[58]	To examine students' problem-solving skills by examining their visual attention (fixation duration time). Are students capable of using periodic table of elements (do they use it as an inductive tool, are they able to orient in the periodic table of the elements, what factors affect their use of the table). What strategies do students use when solving the tasks and what problems they face during their activity?	139 non-chemistry vocational school students overall, 8 of them were selected to participate in eye-tracker study	Gaze Point eye camera GP3	Eye-tracking system; think aloud interviews
Sun et al. (2024)[59]	The research problem is related to the questions of whether it can a microcomputer-based laboratory effectively promote the chemical triple representation of a preservice chemistry teacher and what cognitive mechanisms are demonstrated by students at different academic achievements.	35 second-year preservice chemistry teachers	Eye-Link 1000 Plus	Eye-tracking system; video experiment, knowledge test, semi structured interview

Authors (year)	Research problem	Participants	Eye-tracker	Data collection technique; instruments
Hamerská et al. (2024)[60]	The pedagogical challenges in teaching chemical equations, focusing on the ability to balance chemical equations and understanding related basic chemical concepts among chemistry teacher students.	24 chemistry teacher students	Tobii Fusion Pro	Eye-tracking system; retrospective think-aloud interviews
Huangfu et al. (2024)[61]	How displayed teacher enthusiasm in video lectures affect students' positive emotions, visual attention, cognitive load, and learning outcomes?	128 eighth-grade middle school students	Eye Link 1000 Plus	Eye-tracking system; experimental videos, self-report questionnaire, post-test; PAS questionnaire; cognitive load questionnaire

with the different learning outcomes, e. g. between low and high achieving students. In addition, the students' learning strategies were determined based on their eye movements.

In most (18) of the examined studies, the sample was relatively small, with the exception of four studies in which the sample comprised more than 100 participants. On average, 43 participants were exposed to the eye-tracking procedure. In one study, there were only 9 students[42] and the highest number of participants using an eye-tracker device was included in the study by Nehring and Busch.[54] In one of the analysed papers no information was provided on the number of participants. It can therefore be concluded that the number of participants in eye-tracking studies in chemistry education is generally low, and the results of these studies should therefore be interpreted with caution. As far as the educational level of the participants in the studies examined is concerned, university students were represented in most of the studies. Only five papers included high school students, and three papers included graduate students (Masters and PhD students) in the sample. Primary and secondary school students were least likely to be included in the research sample in the papers examined, with two studies including secondary school students and one study including primary school students in their research sample. Two studies were conducted with pre-service chemistry teachers. It can be therefore concluded that further eye-tracking studies should be conducted with secondary school students and pre-service chemistry teachers to gain a more comprehensive understanding of the effects of using visual elements in learning chemical concepts at all educational levels. It is also important to obtain information about how future chemistry teachers understand chemical concepts and how this understanding develops as teachers' knowledge influences their future teaching.

Regarding to the instruments used in addition to eye-tracking technology, the results of the analysis showed that ten studies used interviews with the participants. Twelve of the studies analysed also used achievement tests to determine the participants' level of knowledge of the specific chemical concepts used in the study. In addition, the majority of the papers analysed used different tests in a pre- and post-test research design to differentiate between pre- and post-activity knowledge levels. In three analysed papers, audio or video recordings of the participants solving tasks the with the eye-tracking device were also used. In addition, a specific mental ability test, a spatial ability test and a cognitive load questionnaire were used to measure some independent variables that were part of the research problem. The data suggest that researching an individual's cognitive activities requires the inclusion of additional instruments, such as interviews, questionnaires, mental ability tests, spatial ability tests, knowledge tests, in addition to the use of eye-tracking technology, to obtain a more comprehensive picture of the processes occurring during the chemical activities under investigation.

4. 2. Major Conclusions from Studies Using Eye Tracking in the Field of Chemistry Education

Table 3 summarises the most important results of the studies examined. The most important results are printed in bold.

As shown in Table 3, eye-tracking was used in most studies to provide visual feedback to students when they used models or different levels of representation when learning certain chemical content. Results show that students were better able to answer the questions with models than with diagrams. However, the mathematical equations posed the greatest problems for the students when they tried to solve the problem.[40] These results are consistent with the findings that students do best with models when solving chemistry problems.[41] In addition, students spend less time solving the problem when using models. Therefore, teachers should use models in classroom learning as they allow students to form appropriate mental models.[24] Students' prior knowledge and educational level are identified as important factors influencing the effectiveness of teaching with models and presentations, which indicates that the use of models in the classroom learning needs consideration and needs to be appropriate to the prior knowledge of the students in the group. Students with a higher level of knowledge were more successful in using representations for learning and had a longer fixa-

Table 3. The main conclusions of the included studies.

Study	The main conclusions
Stieff et al. (2011)[40]	– Students rely primarily on visual-spatial representations in the display and do not make use of accompanying mathematical representations. – Results support the complementary validity of verbal protocols and eye-tracking data; both data sets were highly correlated; both data sets provide insight into students' problem-solving with multiple representations, supporting the validity of both data sets for measuring students' use of representations. – Students did not rely primarily on the visual representation of the molecules, which were rendered with bolder colours and included more striking animations of multiple atoms; they placed equal importance on the model and the diagram and switched frequently transitions between these two representations. – Participants performed well on questions that could be answered using the model and diagram and performed poorly on questions that required integration of information from the model, diagram, and mathematical equation.
Tang and Pienta (2012)[41]	– The unsuccessful students spent more time thinking about their solutions and focusing more on the questions than they did trying to solve the gas law problem. – The gas law problem represented a greater cognitive load for the unsuccessful students. – Both successful and unsuccessful participants spent the same amount of time on the initial reading, but the unsuccessful students spent more time on the problem planning phase. – Students with varying degrees of success in solving the gas law problem showed different eye movement patterns that corresponded with their cognitive effort.
Williamson et al. (2013)[42]	– Students spent significantly more time with the ball-and-stick image than with the potential map when asked questions about proton attack or hydroxide attack, but same amount of time with both images when asked about electron density or positive charge. – Students who spent more time with the ball-and-stick image when asked about positive charge were less likely to be correct, while those who spent more time with the potential map were more likely to be correct.
Hinze et al. (2013)[43]	– Eye-tracking and explanation measurements showed that attention to and explicit use of EPMs (electron potential maps) was associated with higher accuracy. – When answering questions that required identifying the format and features of a representation, participants were more likely to adopt the novel visualizations than when answering questions that required drawing inferences. – Students' adoption or avoidance of EPMs was caused, in part by the difficulty of understanding unfamiliar visualizations, although their designs was explicitly specifically intended to promote learning and was often praised by the designers. – Prior knowledge facilitated successful use of EPMs, as reflected in accuracy and eye-tracking data, but not in explanations. – Experts tended process external representations more efficiently than did novices. – Even when the features of a representation were clear, expertise played a necessary supporting role in understanding the relevance of these features to the domain of interest. – The development of representational competence during early learning and comprehension experiences depended not only on practice with visualizations, but also on task and learner characteristics. – Interestingly, participants with greater prior knowledge began to use EPMs effectively in inference problems with some practice; participants with little prior knowledge, on the other hand, stuck with their ball-and-stick representations and were more likely to answer questions incorrectly.
Tang et al. (2014)[44]	– Students were able to find and interpret relevant information needed to solve the tasks (the reading phase in the eye-tracking experiment), but their working memory load was increased by the subsequent procedures (post-reading phases). – Almost all students applied or attempted to apply dimensional analysis (step-by-step procedure) to solve the stoichiometry problem.
O'Keefe et al. (2014)[45]	– Students can integrate multiple representations through sequential fixations over related elements of a simulation, and transitions between different simulation elements are associated with different learning outcomes.
Chen et al. (2015)[46]	– Learning with dynamic 3D representations leads to a better understanding of atomic orbitals. – The construction of correct mental models is positively predicted by the number of saccades and rereading and negatively predicted by the number of fixations. – Students spent similar amounts of time on 3D representations.

Study	The main conclusions
Cullipher and Sevian (2015)[47]	– Analysing fixation sequences during eye-tracking can provide useful information about what students are thinking when they associate molecular structures with spectroscopic reactions, and that this information goes beyond what can be learned from thinking aloud. – Viewing patterns differed depending on students' implicit assumptions about how spectroscopic reactions relate to molecular structures. – The initial results provide partial validation of a newly developed methodology for analysing eye tracking data to uncover reasoning patterns that appear to correspond to identifiable underlying assumptions.
Rau et al. (2015)[48]	– Sensory perception ability: Students have a higher sense-making ability than fluency. It can be assumed that the chemical instructions do not provide sufficient support for making the connection. – Sense-making ability: difference-connections were associated with significantly more inferences. However, there were no correlations between surface-connections and inferences, or between similarities-connections and misconceptions or between differences-connections and misconceptions. The Frequency of switching was significantly related to surface connections. However, no significant correlations were found between eye-tracking and similarity connections. There were also no correlations between eye-tracking and misconceptions. – Difficult concepts: Students with a university degree mentioned colour coding, bond angles, atomic radii, etc. more frequently than students without a university degree. Graduate students were more likely to use these concepts to describe the behaviour of electrons, atoms, bods, etc. Undergraduate students were more likely to describe the differences between the concepts as shown in the animations without going beyond what the presentation shows. Graduate students were more likely to present complementary features of the representation.
Topczewski et al. (2016)[49]	– Two groups: Statistically significant differences were found between experts and novices in the correctness of their responses to the NMR tasks. Experts had a much shorter fixation time than novices. – Three groups: Statistically significant differences were also found between advanced and early beginners and experts in answering the NMR tasks. In addition, statistically significant differences in fixation time were found between all three groups. Experts have a longer fixation time for the last three items.
Herrington et al. (2017)[50]	– Student responses: Most students were able to recognise the differences between sugar and NaCl dissolving in water. However, further analysis shows that students who used the screencast were better able to identify electrolytes and recognise how water interacts with covalent compounds. The pre- and post-test analysis revealed statistically significant differences between the groups of students. The students who used screen-cast were able to significantly improve their understanding. – Eye-tracking: Significant differences were found between the students in the screencast and simulation groups. The number and duration of fixations were significantly different in the two groups. In addition, the screencast group focused significantly more on the electronic resource.
Karch et al. (2019)[51]	– Pupil dilatation and gaze: In complex multiple-choice tasks, pupil dilation fluctuated while solving the task. In a simpler true/false task, there was a clear difference in pupil signal between participants who answered the question correctly and those who answered it incorrectly. Those who answered the question correctly had linearly increasing pupillary signals, while those who answered the question incorrectly had pupillary signals more like those observed in the multiple-choice tasks.
Connor et al. (2019)[52]	– Invalid assumptions: 20 invalid assumptions were identified as part of the research. In addition, eight heuristic reasoning strategies were identified (1) basic associative processes, (2) inductive judgments and (3) affective judgments.
Baluyut and Holme (2019)[53]	– Statistically significant differences were found between the visual behaviours of high-achieving and low-achieving students. – High-achieving students spent more time examining diagrams of the nature of matter and switched between parts of the diagrams and other areas of interest more frequently than low-achieving students. – The study is an example of how the underlying strategies students use when answering conceptual stoichiometry questions can be triangulated using quantitative and qualitative techniques related to visual eye-tracking behaviour.
Nehring and Busch (2020)[54]	– Student observations: Students who look at an object more often tend to look further at the object on the left side. The left-to-right setting reduces right-to-left eye movements, but the right-to-left setting does not reduce left-to-right eye movements. The effects found were small. Thus, the results indicate that setting the demonstration from left to right may reduce eye movements and support the reaction flow.

Study	The main conclusions
Rodemer et al. (2020)[55]	– Test results: No statistically significant differences were found between advanced students and beginners in their test scores at the baseline. This could be due to the small sample size. However, the effect size was .32, – Visual processing behaviour: Advanced students require less time and fewer fixations for each task than beginners. Both groups of students did not differ in their attention distribution. – Task characteristics: Task duration and number of fixations are significantly influenced by the task. No significant effect was found for advanced students. Advanced students also work more homogeneously through the task than beginners. Beginners appear to be more strongly influenced by the task characteristics. Overall, the tasks appear to have a significant influence on visual behaviour. It was also shown that viewing behaviour is much more influenced by the amount of information a presentation contains than by the type of information.
Slapničar et al. (2020)[56]	– Justification of correct presentation: Students' successful justification of correct 3D presentation increased with educational level. Students have problems describing the submicroscopic level with the macroscopic level. Primary school students have problems with understanding 3D presentations and with the transition between them. The number of students who use macroscopic presentation to describe different states of water decreases with age. – Differences between successful and unsuccessful students in terms of total fixation duration (TFD) and area of interest (AOI): It can be concluded that successful and unsuccessful students of the same age group look at 3D presentations for a similar amount of time.
VandenPlas et al. (2021)[57]	– Learning gains: In all participant groups (simulation, screencast and extended screencast), statistically significant differences were found between the results of the pre-test and post-test. Furthermore, no statistically significant differences were found between the students who used using simulation and screencast. it can therefore be assumed that the simulation did not significantly reduce the students' cognitive load. The extended screencast proved to be the best presentation to improve students' knowledge and understanding. – Eye-tracking: Students using the simulation spend more time on the task than students using the screencast. This suggests that student do not need as much time to decipher the meaning of the simulation. However, students using screencasts spend less time reading and responding to the tasks, proving that screencasts can reduce students' cognitive load.
Tóthová et al. (2021)[58]	– Use of periodic table: The students tried to use the periodic table of the elements to solve the task. The same applies to high-achieving and low-achieving students. There are statistically significant differences between the students' fixation on the table and on the text. However, success in solving the task was not related to the use of the periodic table, but to several other factors. It was also found that students spent less time on the legend, which could indicate that students did not understand the reason for the table. – Factors influencing students' engagement with the periodic table: Understanding the task proved to be the main reason why students could not successfully complete the task. Their motivation, unfamiliarity with the content and unfamiliarity with the basic concepts also proved to be important factors in solving the task. – Students' strategies for solving the tasks: The main problem in unsuccessfully solving the task was not the strategies they used but the problems they faced. In addition, the students used extensive strategies when solving the tasks.
Sun et al. (2024)[59]	– The comparison of the results of the triple representations test and the eye-tracking indicators of the two groups shows that a microcomputer-assisted laboratory has a positive effect on triple representation. – Students in the experimental group showed significantly better performance in the recording of image information under the influence of the microcomputer-assisted laboratory.
Hamerská et al. (2024)[60]	– The students could be divided into four different groups based on their total score and solution time: efficient, persistent, impulsive, and inefficient solvers. – The results of an eye-tracking study show that students predominantly rely on symbolic representations, with additional sub-microscopic representations provided by digital applets not significantly improving equation solving skills. This reliance potentially hinders students' ability to conceptualize reactions at the particle level, impacting their overall understanding of chemistry. – The study highlights the need for a pedagogical shift toward integrating multiple representations into chemistry education to bridge the gap between procedural skills and deep conceptual understanding.
Huangfu et al (2024)[61]	– The results show that an enthusiastic teacher positively influences students' positive emotions, reduces students' cognitive load and makes students focus more on the content learning. – More enthusiasm shown by the teacher improved the learning outcomes of the students.

tion time on these models. [43,45,48,53] This was also the case in the study where graduate students paid much more attention to the models than undergraduate students. They are also better able to use these models when explaining certain chemical concepts than undergraduates and also understand the background of the presentation.[48] More successful students are also able to focus on different parts of the diagram when analysing them, than less successful students and are therefore able to complete the task successfully.[53] These results are also consistent with the findings that higher performing students were more likely to be able to choose the correct representation than lower performing students.[56] Low-performing students also spend more time on questions than on models.[41] There were no statistically significant differences between high-performing and low-performing students in terms of their fixation time on a particular model.[56] These results contradict to the findings, that there were statistically significant differences between high-performing and low-performing students in terms of fixation time, with low-performing students spending more fixation time on a particular model than high-performing students.[55,57,51] Successful students also spend less time fixating on the symbolic level of presentation.[58] However, successful and unsuccessful students rely on this level of representation.[60] Results in the analysed papers support the idea, that all levels of representation need to be implemented in the classroom learning alongside with different learning approaches.[5]

When using different models, students spend an equal amount of time focusing on all models and that using these models improves their knowledge.[46] However, results also show that fixation duration does not predict the correctness of the mental models that students formed when using static and dynamic 3D presentations,[46] but using of specific models can show how students think.[47] In addition, the correctness of students' mental model can be predicted by the number of cascades when working with physical models of chemical structures[46] and the use of a computer-based laboratory also improves students' understanding of the triple nature of chemical concepts.[59]

In some papers, the authors examined students' eye movements in relation to their level of cognitive load. In these studies, more eye movements and thus shorter fixation time were found in low-performing students, which is likely due to the higher cognitive load resulting from a more difficult task for the low-performing students.[40,44] Cognitive load can also be correlated with students' pupil dilation during solving specific tasks and research showed that it varied in multiple-choice tasks. In tasks where students had to decide whether the statement was correct or incorrect pupil size changed linearly when students answered correctly.[51]

The analysis of 22 papers published in respected peer review journals on the topic of using eye tracking technologies in chemical education has shown that eye-tracking can provide important insights into students' use of visual models in chemistry. Students' fixation patterns vary with their performance level, cognitive load and task complexity. Eye-tracking metrics, such as fixation time and pupil dilation can provide clues to cognitive processes and understanding in chemistry learning.

5. Conclusion

The focus of this paper was to review eye-tracking studies in chemistry education and evaluate the usefulness of eye-tracking methodology in investigating how complex chemical concepts are learned by students at different educational levels. The results could help determine which aspects teachers should consider when teaching abstract chemistry triplet concepts at all levels of chemistry education.

Among the 22 analysed studies on chemistry education published between 2010 and 2024 in which the eye-tracking method was used, most students were represented as study participants. The least included student population in the analysed studies were lower and upper secondary school students. Future studies should therefore include samples at the lower levels of chemistry education so that the cognitive processes involved in solving chemical problems with younger students can be investigated. Furthermore, only two studies were conducted with pre-service chemistry teachers, so it could be recommended that future studies be conducted with pre-service chemistry teachers, as it is important to know how these students learn chemical concepts. This is especially important because pre-service chemistry teachers' educators should know how to design courses to develop appropriate mental models of chemistry concepts for the students who will be responsible for teaching these concepts in their future careers.

This study examined papers that were mainly concerned with students' eye movements when using various visualisation methods in chemistry lessons. The studies measured the fixation time, eye movements, pupil dilation, gaze, knowledge retention, knowledge gain, attention, etc. of the participants. In most cases, low-performing and high-performing students were compared with each other based on these measured values. An eye tracker was generally used to collect data to obtain information about eye movements, gaze, fixation times, etc. Knowledge tests in the form of pre- and post-tests and follow-up tests were used to obtain information about the students' learning gains or retention of knowledge. Other instruments such as cognitive load questionnaires, mental ability tests, spatial ability tests etc. were rarely used in the studies examined. Small sample sizes are not uncommon in studies that provide detailed analyses of verbal explanations during problem solving or eye movements due to the complexity of data collection and analysis. The complexity of data collection is also related to the triangulation of instruments used to collect data on students' learning processes and the large number of different types of data collected with the eye tracker. The complexity of data analysis is related to the difficulty of determining which feature of the recorded signals to extract and analyse and how to correlate the eye movement data with other measured variables. It is important to be aware that the conclusions drawn from eye-tracking studies are usually subject to certain limitations due to the small sample sizes and the complexity of the data analysis.

As mentioned above, eye-tracking metrics such as fixation time and pupil dilation can provide clues to cognitive processes and comprehension during chemistry learning. The reviewed papers concluded that teaching with models can improve chemistry learning and lead to better learning outcomes. However, prior knowledge is an important factor in students' ability to learn using this method. Higher performing students can use models with ease and give explanations based on these models. They can also focus on different parts of the diagram, spend less time fixated on certain parts of the models and can distinguish between good and bad representations. In addition, low- and high-achieving students rely on the symbolic level of the presentations. However, fixation time cannot predict the correctness of students' mental models, but it can provide information about how students think. Students' eye movements can also provide information about the cognitive load they are exposed to. A higher number of eye movements can predict higher cognitive load. Therefore, more eye movements are detected in low-achieving students.

The possibilities for studying chemistry learning using eye-tracking methods in the future are enormous. Eye-tracking data can be considered more objective and valid compared to other methods of studying chemistry learning, such as self-reporting. The use of eye-tracking data as additional information about the learning of chemical concepts could potentially lead to many new insights and the development of more effective educational strategies that could be applied in the school environment.

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Povzetek

Glavni poudarek sistematičnega pregleda literature je bil preučiti študije očesnih premikov pri pouku kemije in oceniti uporabnost očesnih premikov pri raziskovanju učenja zapletenih kemijskih pojmov pri učencih, dijakih in študentih. Pregledane študije so večinoma uporabljale majhne vzorce študentov, pri čemer so bili pogosto vključeni študenti dodiplomskega študija, ter so merile spremenljivke, kot so očesni premiki, čas fiksacije, premer zenic itd. Rezultati kažejo, da imajo uspešnejši študenti krajši čas fiksaciji in se bolje učijo s pomočjo modelov, pri čemer je predznanje pomemben dejavnik. Obe skupini študentov se večinoma opirata na simbolno raven predstavitev, pri čemer so uspešnejši študenti boljši pri podajanju razlag. Študije so poročale tudi o težavah, povezanih z zapletenostjo analize podatkov.