



The impact of different types of self-regulation scaffolds on learning science with hypermedia

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ARTICLE INFO

Handling editor: Nicolae Nistor

Dataset link: [SRL scaffolds \(Original data\)](#)

Keywords:

Scaffolds

Hypermedia

Self-regulated learning

Learning strategies

Achievement

ABSTRACT

Effective use of scaffolds in hypermedia should support students' self-regulated learning while considering their individual differences. Metacognitive and cognitive scaffolds, but not motivational scaffolds, have been extensively researched. There is no clear evidence that using only one type of scaffold is more effective than combining different types. The aim of this study was to determine if the use of different types of scaffolds and their combination in hypermedia predicts learning achievement over and above individual student differences. In the first phase of our quasi-experimental study, 443 ninth graders learned about visual perception in hypermedia. We measured their individual characteristics (grade point average [GPA], intelligence [IQ], learning time, and the number of learning strategies used) and their learning achievement and divided them into six comparable groups. In the second phase, the groups learned about olfactory perception using different scaffolds embedded in hypermedia: 6 cognitive, 6 metacognitive, 6 motivational, all 18 scaffolds together, a selected subset of 6 mixed scaffolds, and no scaffolds. We administered a pre-test and a post-test to assess what students learned, and collected data on students' note-taking, self-reported use of learning strategies, and interest in the topic. Hierarchical regression analysis of data from 288 students revealed that students with a higher GPA, specific prior knowledge and interest in the topic, and those who used more self-regulation strategies learned more. Scaffolds did not significantly contribute to the prediction of learning outcomes. Implications for the research design of studies investigating the effects of learning scaffolds in hypermedia are discussed.

1. Introduction

Individual learning using hypermedia is becoming an increasingly common form of learning for all generations of learners. Its frequency increased especially during the coronavirus disease 2019 (COVID-19) pandemic. Distance learning takes place in an e-environment and usually requires learners to use a variety of digital sources to acquire new knowledge. Learning outcomes can be influenced by the quality of these sources and by a student's characteristics (e.g., prior knowledge and interest) and their self-regulation. The aim of the present study was to investigate how scaffolds embedded in hypermedia to support self-

regulated learning (SRL) contribute to learning outcomes, controlling for the individual characteristics of students.

Hypermedia includes text, graphics, audio, video, and hyperlinks and is therefore non-linear. The use of hypermedia allows for a more dynamic presentation of learning content. Its features such as interactivity and the use of two-dimensional (2D)/three-dimensional (3D) animations and videos can facilitate cognitive processing of learning material, visualisation of context, understanding of content, and construction of knowledge. There is great flexibility and numerous possibilities in the use of teaching methods and in the design of multimedia learning units that can support learning (Mayer, 2014).

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Compared with traditional paper-based learning, individualised learning with digital technology provides a student with less guidance and allows them to move independently through the hypermedia and to learn in a sequence and at a pace of their choosing. This flexibility and interactivity in learning with hypermedia compared with learning with paper requires a higher level of self-regulation skills to acquire quality knowledge (Azevedo, 2005; Devolder et al., 2012) and to achieve more (Broadbent & Poon, 2015). One possible solution to improve self-regulation in e-learning is to provide hypermedia with scaffolds that support the self-regulation of learners.

Most research on SRL scaffolds in science education has been related to problem-based learning (PBL) approaches, where scaffolds support learners to solve complex, ill-structured problems and to develop higher-order thinking skills (Belland, Walker, Kim, et al., 2017). Much less is known about learning with hypermedia where learners acquire basic science concepts. Scaffolds can promote cognitive, metacognitive, or motivational aspects of self-regulation. Most of the research has focused on cognitive and metacognitive scaffolds, and there have been only a few studies on motivational scaffolds (Belland, Walker, Kim, et al., 2017; Daumiller & Dresel, 2019). Therefore, more studies need to be conducted to investigate self-regulation scaffolds in science learning with hypermedia and their effects on student outcomes.

1.1. SRL

Self-regulation is a key process for effective learning. Theories emphasise the importance of cognitive, metacognitive and affective-motivational processes in SRL (Boekaerts, 1997; Efklides, 2011; Efklides & Schwartz, 2024; Pintrich, 2000; Zimmerman, 2008). These processes underlie the use of appropriate self-regulation strategies at different phases of learning – that is, preparatory, performance, and appraisal (Panadero, 2017; Puustinen & Pulkkinen, 2001) – and relate to setting goals, monitoring the learning process, and regulating this process according to the goals and demands of the environment (Pintrich, 2000). Therefore, students can use cognitive, metacognitive, and motivational strategies before, during, and after learning (Zimmerman, 2008) to improve their performance.

Cognitive strategies refer to the processing of learning content and relate to the rehearsing, elaboration, and organisation of information and relationships between them (Weinstein & Mayer, 1986). Self-reports of cognitive strategies can be unreliable (Dent & Koenka, 2016; Veenman, 2011), but the notes students take while learning can provide a more objective indicator of the strategies they used. When taking notes, students either use surface strategies (they simply write down parts of the content) or they use higher-level, deep strategies, such as elaboration or organisation, which enable the reconstruction of the learning material (Marton & Sjö, 1976). Several studies have shown that the association between academic achievement and rehearsal strategies is lower than with elaboration or organisational strategies (Akyol et al., 2010; Dent & Koenka, 2016). Prem and Peklaj (2021) reported a similar finding when they derived the learning strategies that students used based on their note-taking while learning with hypermedia.

Metacognitive strategies refer to planning, self-monitoring, self-control, and self-evaluation (Boekaerts, 1997; Pintrich, 2000; Zimmerman, 2008). They are moderately associated with academic achievement, and the associations are generally stronger than for cognitive strategies (Dent & Koenka, 2016). The strongest associations have been found for planning (Dent & Koenka, 2016), monitoring (Hattie & Donoghue, 2016; Roebers et al., 2014), self-checking (Dent & Koenka, 2016), evaluation, and reflection (Hattie & Donoghue, 2016).

Motivational strategies refer to the regulation of effort during learning. They are an essential component of SRL when students need to persevere in learning despite having to complete difficult or uninteresting tasks. Research on motivational strategies is much scarcer than that on cognitive and metacognitive strategies. Nevertheless, a weak association between effort regulation and achievement has been found

in online learning environments (Broadbent & Poon, 2015; Lehmann et al., 2014).

1.2. Other factors affecting SRL

The use of SRL strategies also depends on the learner's motivation. In a study on SRL in online language courses, Lin et al. (2017) found that higher learner motivation predicts higher use of learning strategies, which leads to higher learning achievement. Students' motivation (computer self-efficacy, goal orientation, and specific interest) directly affects their comprehension of hypertext on daily life topics (Shang, 2016), and students' interest is related to their knowledge gain in learning hypertext on physics (Lehmann et al., 2014) and learning about neuroplasticity (Lee & Hong, 2023). Students' interest in science topics at the beginning of the school semester is related to their grades at the end of the semester (Laine et al., 2020) and persistence with the text and achievement (Ainley et al., 2002). Interest in a topic is an important predictor of student achievement in science, so it is necessary to include it in studies on SRL.

A student's general and task-specific prior knowledge is also expected to affect their learning with hypermedia and learning achievement. Chen and Wu (2012) found that prior knowledge is a direct predictor of post-test scores in e-learning. Simonsmeier et al. (2022) also reported a large, positive correlations between the pre- and post-tests in their meta-analysis. They reported fewer studies on the correlations between prior knowledge and knowledge gain in learning, and their results on the effects are inconclusive due to the high variability of the correlations (from -0.69 to 0.62).

1.3. Scaffolds for promoting SRL

SRL can be supported by using learning scaffolds, which are defined as 'providing technology-supported assistance to students when they are engaged in a particular learning task' (Sharma & Hannafin, 2007, p. 29). In the e-learning environment, the concept of scaffolds refers to the tools, strategies, and guidance that enable students to achieve higher levels of knowledge and understanding (Devolder et al., 2012; Puntambekar, 2022).

The definitions of scaffolds vary according to function (conceptual, metacognitive, procedural, and strategic), the type of use (e.g., hints, prompts, and questions), and the psychological processes involved (Devolder et al., 2012). In the present study, we used a classification of scaffolds based on the processes involved in SRL, namely cognitive, metacognitive, and motivational. All three types of our scaffolds were in the form of prompts, hints, tasks and questions, and were used in a fixed mode so that students had to use them to continue learning.

Cognitive scaffolds are guidelines that prompt specific cognitive processes (e.g., they suggest writing down the summary of the text read or connecting two concepts). They help a student to better memorise the content in such a way that they can use it later. Metacognitive scaffolds are instructions that lead a student to think about the learning process, and to plan, monitor, and evaluate the learning path (e.g., they encourage a student to set short-term goals or to review progress); thus, they can increase the results of their learning. Motivational scaffolds contribute to more engaged learning, and they promote learning interest, perceived value of the task, self-efficacy, and persistence in learning (e.g., encourage a student to move forward with the subject matter).

Research has shown that different scaffolds embedded in hypermedia influence the corresponding SRL strategies. Cognitive scaffolds affect the use of cognitive strategies, including locating information, goal-directed search, evaluating content to answer questions, summarising, making inferences (Azevedo et al., 2004), improving annotation reading skills (Chen et al., 2014), organisation and elaboration strategies (Berthold et al., 2007), and motivation, such as reducing task difficulty and effort (Moos & Azevedo, 2008a). These scaffolds also influence metacognitive strategies such as planning (Azevedo et al., 2004; Moos &

Azevedo, 2008a), monitoring and help-seeking (Azevedo et al., 2004), and monitoring and self-diagnosis (Berthold et al., 2007).

Metacognitive prompts are associated with an increased use of metacognitive strategies (Bannert et al., 2009), such as orientation, planning, goal setting, evaluation, monitoring (Bannert & Reimann, 2012; Engelmann & Bannert, 2021), metacognitive control, monitoring and regulation (Daumiller & Dresel, 2019; Lehmann et al., 2014), and monitoring and self-diagnosis (Berthold et al., 2007). They also stimulate cognitive strategies, such as organisation (Bannert et al., 2009) and student motivation – for example, greater persistence in learning (Daumiller & Dresel, 2019). Mixed cognitive and metacognitive scaffolds lead to a higher use of cognitive strategies (elaboration and organisation) and metacognitive strategies, including self-monitoring (Berthold et al., 2007; Petko et al., 2014), self-diagnosis (Berthold et al., 2007), and self-regulation (Petko et al., 2014).

Motivational scaffolds affect student motivation by increasing task value and task-related behaviours, such as persistence in learning; these scaffolds also play a role in metacognitive control (Daumiller & Dresel, 2019). The mixture of metacognitive and motivational scaffolds also affects a student's persistence in learning (Daumiller & Dresel, 2019). Motivational prompts (e.g., personal utility) in addition to the cognitive and metacognitive prompts increase a student's interest in topic as well as their critical reflection ability (Schmidt et al., 2012; Wäschle et al., 2015). These studies show that each type of scaffolds promotes all three SRL processes, not just the related one. Therefore, examining a combination of different scaffolds, in addition to examining the impact of a single type of scaffolds, could contribute to understanding their specific effect on learning.

1.4. SRL scaffolds and learning outcomes

Zheng (2016) reported a medium effect size (0.32) regarding achievement in computer-based environments when using prompts and hints. A meta-analysis of computer-assisted scaffolding in PBL in science, technology, engineering, and mathematics (STEM) showed its significant impact on learning outcomes (Belland, Walker, Kim, et al., 2017; Kim et al., 2020), with larger effect sizes for cognitive scaffolds than for metacognitive and motivational ones.

Some researchers have demonstrated a moderating effect of prompting strategies on learning outcomes (Daumiller & Dresel, 2019; Petko et al., 2014). Cognitive prompts have an impact on achievement (Berthold et al., 2007; Davis, 2000; Leopold & Mayer, 2015; Yu & Pan, 2014) and lead to deeper conceptual understanding but not declarative knowledge (Moos & Azevedo, 2008a). Metacognitive prompts influence knowledge transfer but not recall (Bannert et al., 2009). They also lead to greater integration of knowledge into a student's everyday experiences (Davis, 2000) and affect post-test achievement (Lehmann et al., 2014). Mixed cognitive and metacognitive prompts increase knowledge application (Reid et al., 2017), post-test achievement (Petko et al., 2014), and comprehension (Berthold et al., 2007; Wäschle et al., 2015). The combination of cognitive, metacognitive, and motivational prompts increases comprehension (Schmidt et al., 2012). In contrast to these studies, Van den Boom et al. (2004) found no effect of metacognitive prompts, Reid et al. (2017) found no single effect of cognitive or metacognitive scaffolds on student knowledge, and Bannert and Reimann (2012) found no significant effects of combined cognitive and metacognitive scaffolds. Due to the inconsistencies in the published research, the individual contribution of the different types of scaffolds and their combination, as well as the use of SRL strategies on students' knowledge, should be further investigated under controlled experimental conditions. Such studies would provide more detailed information on the most appropriate types and combinations of SRL scaffolds that could be useful for hypermedia developers.

It is important to note that the effectiveness of using certain types of scaffolds also depends on a student's individual characteristics (Wong et al., 2019). Indeed, a student's grade point average (GPA) moderates

the effect of scaffolds on their achievement (Chen & Wu, 2012). Cognitive and motivational scaffolds are more effective for students with a lower level of prior knowledge than for students with a higher level of prior knowledge (Chen, 2014), while for metacognitive prompts, a higher level of prior knowledge predicts metacognitive regulation and achievement (Lehmann et al., 2014; Moser et al., 2017). In STEM, Belland, Walker, Kim, et al. (2017) reported a larger effect size for the use of scaffolds in high-achieving students (0.36) compared with low-achieving students (0.28), although they found the largest effect size in the normative population (0.48). In another meta-analysis (Belland, Walker, & Kim, 2017), the authors reported that the effect of using scaffolds is the same for high- and low-achieving students (effect size = 0.41). Therefore, when evaluating the effectiveness of scaffolds, it is crucial to consider a student's individual characteristics, such as their GPA (a measure of general academic achievement), their learning strategies, their prior knowledge of the topic studied, and their interest in the topic.

1.5. Aim of the study

Given the abovementioned inconsistencies in the literature, we aimed to investigate the effect of using different SRL scaffolds with hypermedia on learning outcomes. Previous research has shown that the use of SRL scaffolds in e-learning environments has positive effects on learning outcomes (Daumiller & Dresel, 2019; Kim et al., 2020). Most studies on SRL with hypermedia have investigated cognitive scaffolds (Davis, 2000; Leopold & Mayer, 2015; Yu & Pan, 2014) and metacognitive scaffolds (Bannert et al., 2009; Daumiller & Dresel, 2019; Davis, 2000; Lehmann et al., 2014; Van den Boom et al., 2004), while motivational scaffolds have been examined less frequently (Daumiller & Dresel, 2019). Some researchers have also reported on the combination of cognitive and metacognitive scaffolds (Bannert & Reimann, 2012; Nückles et al., 2009; Petko et al., 2014; Reid et al., 2017) or metacognitive and motivational scaffolds (Daumiller & Dresel, 2019). Moreover, the authors of two studies elucidated the effect of a combination of cognitive, metacognitive, and motivational prompts on diary writing in biology lessons (Schmidt et al., 2012; Wäschle et al., 2015). Therefore, we investigated whether the use of different types of scaffolds in hypermedia compared to no scaffolds has an impact on learning outcomes. We designed a quasi-experimental study in which learning outcomes in the no-scaffolds condition were compared with learning outcomes in five experimental conditions: the condition with cognitive scaffolds, with metacognitive scaffolds, with motivational scaffolds, and two conditions with a mixture of these three types of scaffolds.

Most studies related to e-learning have been conducted on PBL, with much less effort dedicated to the acquisition of conceptual knowledge with hypermedia. The goal of scaffolds in PBL is to promote higher-order thinking skills to solve ill-structured problems (Belland, Walker, Kim, et al., 2017). Here, we aimed to determine how the SRL scaffolds embedded in hypermedia affect the acquisition of basic concepts in olfactory perception and the comprehension of the integration of biological and chemical processes. As previous studies have shown that the learning outcome also depends on a student's individual characteristics, such as GPA (Chen & Wu, 2012), task-specific prior knowledge (Chen, 2014; Chen & Wu, 2012; Lehmann et al., 2014; Moser et al., 2017), motivation to learn about the topic (Lee & Hong, 2023; Lin et al., 2017; Shang, 2016), note-taking (Prem & Peklaj, 2021), and strategy use (Broadbent & Poon, 2015; Dent & Koenka, 2016; Greene & Azevedo, 2010; Hattie & Donoghue, 2016) during SRL, we controlled for the effects of these factors. Hence, our aim was to examine the effects of different types of SRL scaffolds (cognitive, metacognitive, motivational) and their combination in hypermedia on students' science achievement, controlling for the effects of their individual characteristics, to assess more precisely the independent contribution of the scaffolds to the learning outcome.

2. Materials and methods

2.1. Design

This quasi-experiment was conducted in a regular school setting in two phases, with the same students individually learning a different science topic during each phase. In both phases, the learning using hypermedia took place in a class.

In the first phase, the students' GPA and ability data (intelligence quotient [IQ] score) were collected, and then the students learned Unit A without any scaffolding. Their scores on the Unit A knowledge test were used together with other learning measures (GPA, IQ, learning time, and the number of learning strategies used) to form six matched groups for the different experimental learning conditions of the second phase. The first phase and its results were only used to assign the students to the six groups so that each group was as similar as possible in terms of the evaluated learning measures. In the second phase, each group was subjected to a different experimental condition. Each group studied a science topic different from the one studied in the first phase (Unit B), with different types of embedded SRL scaffolds. Five experts in educational psychology designed the scaffolds based on the literature. The Unit A and B sessions each lasted 60 min: 10 min for instruction, 20–30 min for learning, and 20 min to complete the knowledge test about the unit topic and the learning strategies checklist.

2.2. Participants

The first phase of the study involved 443 ninth graders (224 girls and 219 boys) from 25 classes in 14 basic schools in Slovenia,² whose parents had signed an informed consent form. In most cases, an entire class participated. The second phase was conducted with a smaller sample due to the sudden outbreak of the COVID-19 pandemic and school closures in spring 2020. Therefore, only 305 students from the total sample (155 girls and 149 boys) from 18 classes in 12 schools were included in the sample of the second phase. The mean age was 14.40 years (standard deviation [SD] = 0.40 years). The students learned chemistry as a school subject for the second year; the average grade in chemistry in the previous year (in the eighth grade) was 3.77 (on a grading scale from 1 to 5; SD = 1.10). Their GPA in all school subjects in the eighth grade was 3.96 (SD = 0.77). According to the students, they had virtually no experience of learning with e-textbooks prior to the study: 62 % of students had no experience, 16 % had used e-textbooks once or twice in their lives, and 20 % had used them more frequently.

2.3. Materials and measures

2.3.1. Learning units

The learning units for both experimental phases were taken from the approved Slovenian digital textbook for ninth-grade chemistry (Jamšek et al., 2014) and slightly redesigned by adding a glossary, scaffolding, and making minor editorial changes. The units were validated as part of the curricula and used in schools in the ninth grade in the elective subject Chemistry in Life. Both units were new to the students. In the first phase, Eyes and Colour Perception (Unit A) was used, and in the second phase, Olfactory Perception and Properties of Scents (Unit B) was used (see examples of both units in Fig. 1).

Unit A included the following topics: (i) light and photons; (ii) the visual process in humans; (iii) the structure of the eye and the role of rods and cones in the retina; (iv) the importance of vitamin A, β -carotene, and retinal in colour perception and their chemical structural formulas; (v) the chemical processes involved in colour perception; and

(vi) the concept of mimicry in animals. The unit consisted of text divided into six chapters that included 20 images and photographs, 5 schemes of chemical structures, and 1 video clip (on the water solubility of β -carotene). The glossary was available (as hypertext) for additional explanations of the five main concepts presented (e.g., photon, retinal, and light).

Unit B covered (i) the olfactory sensitivity of humans compared to dogs; (ii) the process of olfactory perception (from receptors to recognition in the brain); (iii) the chemical composition of essential oils; (iv) the difference between edible and essential oils; (v) the volatility of essential oils; (vi) the sensitivity of odour to small changes in molecular structure (the concept of optical isomers in the case of limonene); and (vii) the introduction of 'the olfactory champion' – the silkworm moth. Unit B was divided into six chapters containing text, 4 figures and 6 photographs, 6 schematics of chemical structures, and 1 video clip (on volatility of essential oils). The glossary was available (as hypertext) for additional explanations of the 21 main concepts presented (e.g., triglycerides, monoterpenes, optical isomers, esters, lipids).

The students worked through each unit step by step, clicking on one chapter at a time. When they were finished with all the chapters, they could review the content of the unit.

2.3.2. Scaffolds

In the 'no scaffolds' condition (control group), only the Unit B topic was presented. In each experimental condition, different types of fixed self-regulation scaffolds were embedded in Unit B. In the 'cognitive' condition, six cognitive scaffolds were embedded, one per chapter. In the 'metacognitive' condition, 6 metacognitive scaffolds were used, and in the 'motivational' condition, 6 motivational scaffolds were presented. In the 'all mixed' condition, all three types of scaffolds (6 cognitive, 6 metacognitive, and 6 motivational, i.e., 18 in total) were presented, three per chapter. In the 'selected mixed' condition, a combination of all three types of scaffolds was embedded, two of each type, one per chapter.

The cognitive scaffolds consisted of the tasks that stimulated elaboration or organisational strategies: (1) marking key words in the text, (2) sorting the words into the correct process sequence of odour perception, (3) writing down the differences between two figures of molecules that the students noticed, (4) sorting the words that define two types of oils, (5) visually inspecting two pictures used as analogies for the isomeric molecules, and (6) constructing three questions about the topic that the teacher might ask.

The metacognitive scaffolds included tasks and prompts for monitoring, regulating, and evaluating learning: (1) assessing the current level of knowledge about the topic at the beginning of learning, (2) directing thoughts back to the content, (3 and 5) assessing the level of understanding a specific process presented in the hypermedia using a visual analogue scale, (4) thinking about whether reading leads to an understanding of the topic, and (6) assessing the understanding of the topic when completing learning.

The motivational scaffolds consisted of prompts and hints to highlight the intrinsic value of the content, persistence, and self-efficacy: (1) a question to get the student interested in the topic (e.g., 'Why do you think the police use dogs to identify drug smugglers?'), (2) a video clip about how to become a perfumer, (3) an encouragement that they are already halfway through the unit, (4) a multiple-response question with feedback provided, (5) encouragement that they are almost at the end (just need to take a look at one more example), and (6) encouragement to do well on the knowledge test that will follow. The actual cognitive, metacognitive, and motivational scaffolds that were used are shown in the Appendix (Table A in the supplementary materials).

The 'all mixed' condition included all 18 of the abovementioned scaffolds embedded in the hypermedia. However, since the higher number of scaffolds in this condition compared to 6 scaffolds in conditions with a single type of scaffolds could affect the learning outcome and therefore confound the results, we decided to add another

² In Slovenia, basic education consists of nine grades and comprises two levels: primary and lower secondary. Therefore, the participants in our study attended the last grade of the lower secondary level.

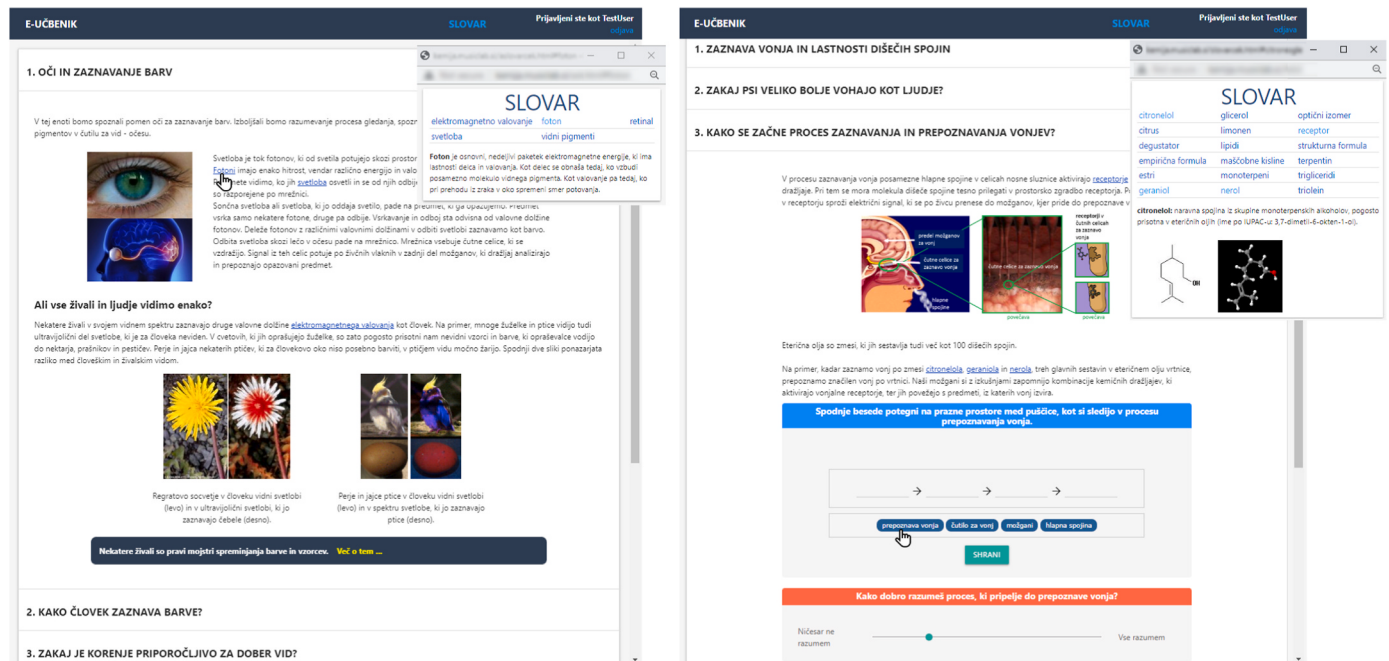


Fig. 1. An example of the learning units used in the experiment. Left picture: Unit A, showing the content of the first chapter about the eyes and colour perception. New concepts are underlined and linked to the glossary (SLOVAR) which is shown open in a new window. The glossary could be accessed at any time from the top menu. The use of hypertext allowed for a flexible display of the content. The content of the chapter was displayed after clicking on the chapter title. Clicking on the yellow link 'Več o tem ...' displayed additional explanations. Right picture: Unit B on olfactory perception was structured similarly to Unit A, but it also included three different types of scaffolds: cognitive (blue band title), metacognitive (orange band title), and motivational (green band title; not shown in this figure). The scaffolds were placed within the text in places where the students might need additional support in regulating their learning. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

condition—the 'selected mixed' condition—in which only six of the mixed scaffolds would be presented. The comparison of the 'selected mixed' and 'all mixed' conditions allowed us to examine whether the number of scaffolds (6 vs. 18) affected the post-test results. The 'selected mixed' condition allowed us to compare the set of six combined selected scaffolds with three sets of six scaffolds of one type.

For the 'selected mixed' condition, the same number of scaffolds as in the 'cognitive', 'metacognitive' and 'motivational' condition was used. A mixture of three types of scaffolds was selected: cognitive scaffolds No. 2 and 4, metacognitive scaffolds No. 2 and 3, and motivational scaffolds No. 1 and 3. These scaffolds were intentionally selected based on the results of a pilot study conducted in a similar setting but with a different sample (Kavčič et al., 2021). In that study, after learning, students were asked to rate the scaffolds based on their perceived usefulness for learning. For each type of scaffolds, we selected one of the highest and one of the lowest rated scaffolds (rather than selecting two scaffolds of each type rated most efficient). With this, we wanted to ensure that the set of selected mixed scaffolds was of comparable efficiency to the sets of scaffolds used in the 'cognitive', 'metacognitive' and 'motivational' condition.

2.3.3. Measures

To control for the individual student differences in variables that may affect learning outcomes, the following data were collected prior to the experiment: GPA, intellectual ability, prior knowledge of the topic covered, and interest in the topic. After learning, the students were asked about the learning strategies they used.

The Sequences Test (Pogačnik, 1994) was used to measure the student's intellectual abilities (fluid intelligence). Each student had to find the correct solution (one of five) for the logical sequence of patterns presented in 44 tasks. The number of correct answers was used as the final score. According to Pogačnik (1994), the results of this test correlate strongly with the Purdue intelligence test ($r = 0.70$) and the

Domino 48D test ($r = 0.79$); the Kuder–Richardson reliability coefficient for the test was 0.86.

The knowledge tests for both units were constructed *ad hoc* by a smaller group of the authors of this study, who are experts in chemistry and educational psychology. The questions measured the recognition of concepts and comprehension of processes. The test for Unit A consisted of eight multiple-choice questions with five possible answers (the last one was always 'I do not know') and five open-ended questions (e.g. 'Explain the importance of β -carotene for human health'). The Unit B knowledge test consisted of ten multiple-choice questions with five possible answers (the last one was always 'I do not know') and six open-ended questions (e.g. 'What are essential oils?'). The answers to the multiple-choice questions were scored as correct (1) or incorrect (0). The answers to the open questions were scored on a 3-point scale: no answer or an incorrect answer (0), a partially correct answer (1), and a correct answer (2). The sum of all points collected for the different questions was calculated for each student. One third of the open-ended questions were scored independently by two researchers using the same scoring criteria. The inter-rater agreement was 0.96 for the Unit A knowledge test and 0.95 for the Unit B knowledge test. The remainder of the open-ended questions were scored independently. In our sample, the standardised Cronbach's alpha was 0.61 for the pre-test data and 0.76 for the post-test data.

To measure interest in the topic of olfactory perception (the topic of Unit B), we asked each student to rate the item 'I would like to know something about the odour perception' on a 7-point discrete visual analogue scale (from 1 [not at all] to 7 [very much]).

The Learning Strategies Checklist was developed based on the self-regulation models of Pintrich (2000) and Zimmerman (2000). Five experts in educational psychology were involved in the development of the checklist. They compiled a list of 33 cognitive, metacognitive, and motivational strategies relating to the phases before, during, and after learning. Then, they independently categorised the items into seven

categories. Disagreements about the categorisation were resolved through discussion until a consensus was reached. In this way, content validity was achieved. The seven categories of strategies were: (i) surface cognitive (1 item, 'I quietly repeated the learning content during learning'), (ii) deep cognitive (organisation and elaboration; 9 items, e.g., 'While learning, I thought about how I could apply the learning content in life'), (iii) metacognitive (MC) – planning (4 items, e.g., 'I thought about what I wanted to know about this topic before I started learning'), (iv) MC – monitoring (5 items, e.g., 'I monitored whether I was paying attention to the topic while learning'), (v) MC – regulation (8 items, e.g., 'I looked up new and unfamiliar words in the glossary'), (vi) MC – evaluation (3 items, e.g., 'After learning, I asked myself if I knew the content well'), and (vii) motivational strategies (3 items, e.g., 'I encouraged myself while learning to continue to the end.'). The total number of strategies used by the students in learning Unit B was analysed.

We recorded whether each student took notes on a paper during learning or not. We considered notetaking as an indirect measure of cognitive strategy use.

The students also self-reported their final grades in the previous school year (i.e., in the eighth grade) for all school subjects. Grades could range from 1 (unsatisfactory) to 5 (excellent) and were averaged to obtain the GPA.

2.4. Procedure

In the first phase of the study, we followed a sample of students ($N = 443$) during their learning of Unit A. This phase started in September 2019. First, the Sequences Test and the pre-test on Unit A topic knowledge were administered in one school hour. The students' grades were also recorded. Approximately 1 month later, the students were asked to learn Unit A individually using a computer in a school computer room. Immediately after the learning in an e-environment, the same knowledge test was administered again, together with the Learning Strategies Checklist. This took another 1 h.

We then attempted to create six groups of students as equal as possible in terms of GPA, fluid intelligence (based on the Sequences Test scores), the time spent learning Unit A, the total knowledge test score for Unit A, and the number of deep-level learning strategies used in Unit A learning. Descriptive statistics for these measures in the final sample are presented in Table S1 in supplementary materials. With the results of the k-means cluster analysis of 411 students who had complete data on the examined variables, five clusters of students were defined according to their scores on these six variables, and random proportional sampling from the five clusters was used to form six equivalent groups of students (with each group containing all five clusters of students). Students who were not used in the cluster analysis due to missing data on one of the variables ($n = 32$) were assigned randomly to one of the six groups.

The second phase of the study began three months after the first phase (in early February 2020). However, our efforts to form six matched groups were hindered by the sudden outbreak of the COVID-19 pandemic and the closure of schools; consequently, not all students from the first phase participated in the second phase of the study. Specifically, only 305 students participated in learning Unit B and in the measurements for that unit in the school before the closures. An a priori power analysis showed that for the analysis of covariance with group as a factor with six levels and five covariates in the model, an alpha error rate of 0.05, a power of 0.80, and a medium effect size (Cohen's $f = 0.25$), the total sample size required would be 270 participants, i.e. 45 per group, so we considered our final sample to be large enough.

Approximately 1 month prior to learning Unit B, a knowledge pre-test on the topic of the unit was administered. Interest in the topic of olfactory perception (the topic of Unit B) was assessed immediately

before the students began to read the lesson. We recorded whether students took notes during learning Unit B. Immediately after learning, the Unit B knowledge post-test equal to the pre-test was applied, together with the Learning Strategies Checklist. Some students did not complete some of the measurements.

2.5. Statistical analysis

The statistical analysis was carried out using the R software (R Core Team, 2024) and the packages *psych* (Revelle, 2024), *car* (Fox & Weisberg, 2019), *MASS* (Venables & Ripley, 2002), *gvlma* (Peña & Slate, 2022), and *emmeans* (Lenth, 2025). After calculating the descriptive statistics and conducting correlation analyses, a hierarchical linear regression was performed on the 292 students who had complete data on all variables. The post-test score was used as the outcome variable. In step 1, the student variables (the Unit B pre-test score, the average school grade, assessment of interest in the topic, the number of learning strategies used, and the use of notes—yes/no) were simultaneously entered into the model as predictors. In step 2, the experimental group was also entered into the model to assess the independent contribution of the different types of SRL scaffolds after controlling for students' learning characteristics. The no scaffolds group served as the reference group in the hierarchical regression analysis, and five dummy variables were created to indicate the other five groups.

Regression diagnostics revealed four influential points (with large Cook's distances), which were excluded from further analysis. Descriptive statistics were calculated and a hierarchical regression was performed with the remaining 288 students. In the final sample of students with complete data on all variables examined in the second phase, there were 44 students in the no scaffolds group, 50 in the cognitive scaffolds group, 51 in the metacognitive scaffolds group, 48 in the motivational scaffolds group, 48 in the selected mixed scaffolds group, and 47 in the mixed scaffolds group. All statistical hypotheses were tested at the 5 % significance level.

3. Results

Table 1 shows the descriptive statistics for the measured variables and their correlations. The GPA of the students in our sample was quite high (slightly below 4 on a scale of 1–5), but comparable to the national average (consistent with other studies in Slovenian school at the lower secondary level, e.g., Pečjak & Košir, 2003; Zupanc, 2010; Zorc, 2019). The students' interest in the topic was medium (3.85 on a scale of 1–7). From the pre-test to the post-test measurement, the students' knowledge improved by about 7 points on the knowledge test. The students reported using about 40 % of the 33 listed strategies to learn the lesson. More than two thirds of the students took notes while learning.

Correlations among the measures collected during learning (see Table 1, variables 4–6) were weak and positive ($r = 0.17$ – 0.29). Students with a greater interest in the topic were more likely to take notes and reported using more SRL strategies. All three variables showed a weak to moderate correlation with the post-test scores ($r = 0.23$ – 0.36). Finally, the students' GPA showed a moderate positive correlation with prior knowledge ($r = 0.31$) and a strong positive correlation with the post-test score ($r = 0.70$).

The six experimental groups presented in Table 2 did not differ statistically significantly in the pre-test knowledge score ($F_{(5, 282)} = 0.67$, $p = .65$, $\omega^2 < 0.01$), GPA ($F_{(5, 282)} = 0.47$, $p = .80$, $\omega^2 < 0.01$), interest in the topic ($F_{(5, 282)} = 1.20$, $p = .31$, $\omega^2 < 0.01$), or use of notes ($\chi^2_{(5)} = 9.06$, $p = .11$, Cramer's $V = 0.18$). The only significant differences among the groups were in the number of strategies used ($F_{(5, 282)} = 2.52$, $p = .03$, $\omega^2 = 0.03$). The motivational scaffolds group used the lowest number of learning strategies, and the metacognitive scaffolds group

Table 1Description of the studied variables in the second phase of the study and the correlations among them ($N = 288$).

Variable	<i>M</i>	<i>SD</i>	Skew	Kurt	2	3	4	5	6
1 Post-test score	10.49	4.13	−0.02	−0.62	0.39	0.70	0.31	0.36	0.23
2 Pre-test score	3.73	2.32	1.11	1.89		0.31	0.20	0.09	0.05
3 Grade point average	3.96	0.78	−0.45	−0.54			0.24	0.23	0.19
4 Topic interest	3.85	1.38	−0.19	−0.01				0.29	0.17
5 Number of strategies used	12.88	6.31	0.27	−0.29					0.24
6 Use of notes	69 %	–	–	–					

Note. Kurt = kurtosis; *M* = mean; *SD* = standard deviation; Skew = skewness. Pearson correlation coefficients >0.12 were statistically significant at the 5 % significance level.

Table 2

The means (and standard deviations in parentheses) of the studied variables in the six groups of students receiving different types of scaffolds.

Variable	None ($n = 44$)	Cognitive ($n = 50$)	Metacognitive ($n = 51$)	Motivational ($n = 48$)	Selected mixed ($n = 48$)	All mixed ($n = 47$)
Post-test score	10.36 (4.09)	10.80 (4.24)	10.27 (3.79)	10.17 (3.81)	10.62 (4.33)	10.68 (4.65)
Pre-test score	4.02 (2.63)	3.80 (2.12)	3.53 (2.51)	3.42 (1.90)	3.56 (2.29)	4.09 (2.47)
Grade point average	4.11 (0.82)	3.98 (0.78)	3.89 (0.74)	3.95 (0.71)	3.90 (1.43)	3.97 (0.78)
Topic interest	4.18 (1.30)	3.80 (1.11)	4.06 (1.67)	3.62 (1.38)	3.69 (1.43)	3.74 (1.31)
Number of strategies used	13.57 (6.86)	12.46 (5.82)	14.84 (6.25)	10.75 (5.98)	13.48 (6.55)	12.13 (5.91)
Use of notes	64 %	68 %	75 %	77 %	75 %	53 %

reported using the highest number of strategies.

Table 3 shows the results of the hierarchical regression analysis. Together, the predictors explained 57 % of post-test score variance, $F_{(10, 277)} = 38.77$, $p < .001$. Among the student variables entered in the regression model in Step 1, the GPA showed the highest independent contribution to the post-test score. Students with better grades, a higher level of prior knowledge, and who reported a higher initial interest in the topic demonstrated better knowledge of the Unit B learning content. Students who performed better on the post-tests also reported using more learning strategies.

All groups that received scaffolds scored slightly higher on post-test than the reference group that did not receive scaffolds (estimated marginal means were 9.60 for the no scaffolds group, 10.71 for the cognitive scaffolds group, 10.17 for the metacognitive scaffolds group, 10.52 for the motivational scaffolds group, 10.66 for the all mixed scaffolds group and 10.74 for the selected mixed scaffolds group). The beta coefficients in Table 3 show small effect sizes for the different types of scaffolds and their combinations. However, the prediction model did not improve statistically significantly in step 2 when the experimental group was included in the model. The group factor explained less than 1 % of the variance in learning outcomes. No pairwise comparison of different

experimental groups with the reference group reached statistical significance after using the Bonferroni correction for multiple comparisons ($p < .01$).

4. Discussion

Learning with hypermedia is becoming a common method of acquiring knowledge at all levels of education, including lower secondary school. Its effectiveness depends on the individual characteristics of the students as well as the characteristics of the hypermedia. One of the most important competencies of students regarding their learning success with hypermedia is their ability to self-regulate their learning. Self-regulation can be supported by the SRL scaffolds included in the learning material. In the present quasi-experimental study, we investigated the effects of different types of SRL scaffolds on the achievement of ninth graders learning about olfactory perception with hypermedia, controlling for their individual characteristics.

Our hierarchical regression model – which in step 1 included variables describing individual learning differences among the students (GPA, prior knowledge of the topic, interest in the topic, note-taking, and use of SRL strategies) – explained 57 % of the variance. In step 2, SRL scaffolds were entered in the model which additionally explained only 1 % of the variance in the post-test scores and this increase in variance explained was not statistically significant. According to Cohen's (1988) definition of effect size, the set of variables included in the model showed strong predictive power for the knowledge acquired while learning with hypermedia. All individual learning characteristics had a statistically significant effect on the post-test score, except for note-taking. These results suggest that students with more general and specific prior knowledge, with greater interest in the topic, and those who use more SRL strategies learn more from science hypermedia.

The strongest predictor of post-test score was the GPA: a 1-point change contributed to a post-test score that was approximately 3 points higher ($\beta = 0.58$), representing a strong effect. There was a small-to-moderate effect for specific prior knowledge of the learning content, as a 1-point increase in the pre-test score led to a 0.30-point increase in the post-test score ($\beta = 0.17$). The positive relationship we found between prior knowledge and learning achievement is well supported by other studies in e-environments – for example, learning physics with hypermedia (Lehmann et al., 2014) and online language courses (Lin et al., 2017). These studies also showed better learning outcomes when students are more motivated, whereas in our study, the students' initial interest in the topic made only a small contribution ($\beta = 0.10$). The

Table 3

The results of the hierarchical regression analysis for predicting the post-test scores (fixed-effects parameter estimates).

Predictor	<i>b</i>	<i>SE_b</i>	<i>t</i>	<i>p</i>	β
Step 1, $F_{(5, 282)} = 76.05$, $p < .001$, $R^2 = 0.574$, adjusted $R^2 = 0.567$					
Intercept	10.40	0.17	59.80	<0.001	0.00
Pre-test score	0.30	0.07	4.12	<0.001	0.17
Grade point average	3.05	0.23	13.54	<0.001	0.58
Topic interest	0.25	0.12	2.02	0.044	0.08
Number of strategies used	0.12	0.03	4.19	<0.001	0.18
Use of notes	0.45	0.36	1.25	0.212	0.11
Step 2, $\Delta F_{(5, 277)} = 1.21$, $p = .304$, $\Delta R^2 = 0.009$					
Intercept	10.40	0.17	59.76	<0.001	0.00
Pre-test score	0.30	0.07	4.09	<0.001	0.17
Grade point average	3.06	0.23	13.55	<0.001	0.58
Topic interest	0.28	0.13	2.27	0.024	0.10
Number of strategies used	0.12	0.03	4.26	<0.001	0.18
Use of notes	0.41	0.37	1.11	0.269	0.05
Cognitive scaffolds	1.12	0.56	1.98	0.048	0.27
Metacognitive scaffolds	0.57	0.56	1.02	0.311	0.14
Motivational scaffolds	0.92	0.58	1.59	0.113	0.22
Selected mixed scaffolds	1.15	0.57	2.01	0.046	0.26
All mixed scaffolds	1.06	0.57	1.86	0.065	0.28

reason for this result could be that our measure of topic interest contained only a single item, which could have reduced the observed effect of interest due to lower variability and/or discrete scores. The small effect size for the reported use of SRL strategies on the post-test score ($\beta = 0.18$) is consistent with the findings from other studies on the effectiveness of self-regulated learning: researchers have reported a positive relationship between cognitive, metacognitive (Dent & Koenka, 2016), and motivational (Broadbent & Poon, 2015; Lehmann et al., 2014) strategies and achievement.

Our findings regarding the effects of the interest in the topic and the use of SRL strategies on the learning outcomes are consistent with the theoretical models of SRL that emphasise the importance of the interplay of cognitive, metacognitive, and affective-motivational processes for learning achievement (Boekaerts, 1997; Efklides, 2011; Pintrich, 2000; Zimmerman, 2008), as well as with SRL research in e-environments. For example, Ainley et al. (2002) showed that specific interest in a science topic promotes persistence in learning with hypermedia and leads to better learning outcomes. Moreover, Lin et al. (2017) showed that on average, more motivated students in online language courses use more SRL strategies and achieve better learning outcomes.

Note-taking was the only individual predictor in our regression model that did not have a statistically significant impact on the post-test score, even though there was a positive correlation between the two variables. We propose two possible reasons for this lack of a significant prediction. First, the intercorrelations between the individual student variables could reduce the predictive power of note-taking in the regression model. Second, note-taking is a cognitive strategy, whereas our measure of learning strategy use included a broader range of cognitive, metacognitive, and motivational strategies. Dent and Koenka (2016), for example, found a slightly higher correlation of achievement with metacognitive strategies than with cognitive strategies.

Based on the correlations between the examined variables, students with a higher GPA were on average more motivated to learn a science topic, took more notes, reported more self-regulation strategies, and performed better on the post-test. We obtained comparable results for Unit A: high-performing students took more and longer notes and used more deep elaboration and organisational learning strategies (Prem & Peklaj, 2021). Students' prior knowledge correlated positively with interest in the topic and the post-test score, but not with note-taking and the reported use of strategies. It seems that interest in a topic without a well-developed note-taking habit is not a guarantee that the notes will be used for learning. Nonetheless, prior knowledge presented a moderate correlation with the post-test score, a finding that is consistent with previous studies (Bernacki et al., 2012; Greene et al., 2010) and suggests that students with a higher level of prior knowledge can more easily integrate the new information into their existing knowledge and do not need as many strategies as students with a lower level of prior knowledge. Moos and Azevedo (2008b) also found that students with a higher level of prior knowledge learn differently than students with a lower level of prior knowledge. The latter use more learning strategies such as note-taking or summarising to build a coherent knowledge structure.

In this study, we were particularly interested in the effects of the different types of SRL scaffolds embedded in the hypermedia and their combinations on learning outcomes. After controlling for the effects of the individual learning characteristics described above, the regression analysis showed statistically insignificant additional contributions of the different types of scaffolds. This result of our study means that one-time learning without any scaffold can be as effective as learning with different types of scaffolds embedded in hypermedia.

Nevertheless, in all experimental conditions, small effects of the scaffolds on learning outcomes were suggested by the values of beta coefficients. The students who learned using hypermedia with scaffolds scored about half to one point higher on the post-test than the students who learned using hypermedia without scaffolds. The effects of all types of scaffolds (beta coefficients) were relatively large compared to the students' individual characteristics, except for GPA. However, none of

these effects reached statistical significance.

Other studies (Davis, 2000; Leopold & Mayer, 2015; Yu & Pan, 2014) found an impact of cognitive scaffolds on student achievement. One explanation for the lack of statistically significant effects in our study could be the limited learning time. Students in our study learned only once, compared to Yu and Pan's (2014) study, in which students learned six times or in a one-week project (Davis, 2000). The second explanation could be related to the different number of cognitive scaffolds. In our study, we used six cognitive scaffolds (prompts for extracting keywords, finding the differences between essential and edible oils, organising the correct sequence of the olfactory process, etc.), while other studies used only one scaffold, e.g., Leopold and Mayer's (2015) visualisation of relationships between concepts in the text and Yu and Pan's (2014) question generation.

We also expected a stronger effect of the combination the scaffolds supporting all three SRL processes, but we did not find it at a statistically significant level. The authors of previous studies that investigated the combination of mixed cognitive and metacognitive scaffolds (Petko et al., 2014; Reid et al., 2017) have reported positive effects on achievement. Daumiller and Dresel (2019) investigated the combination of metacognitive and motivational scaffolds and reported no effects on achievement. On the other hand, the studies on learning with writing diaries that used a combination of cognitive, metacognitive, and motivational scaffolds showed an effect on outcomes (Schmidt et al., 2012; Wäschle et al., 2015). In our study, we examined the effects of combining three types of scaffolds to learning scientific concepts with hypermedia. We evaluated two options for combining cognitive, metacognitive, and motivational scaffolds: the all mixed scaffolds group used all 18 scaffolds and the selected mixed scaffolds group used 6 selected scaffolds. In the regression model, the effects in both groups were similar and were in the range of the effect of cognitive scaffolds. The effects of the two experimental conditions with combined scaffolds and the condition with cognitive scaffolds could have reached statistical significance if the Covid-19 epidemic had not led to the loss of almost a third of the participants in the sample.

In our study, the exclusive use of metacognitive or motivational scaffolds contributed slightly less to the students' knowledge (the post-test score) compared to the other three conditions with scaffolds, although the contribution was not statistically significant. The research results on the effect of metacognitive scaffolds on achievement when learning with hypermedia are contradictory: both positive (Daumiller & Dresel, 2019; Lehmann et al., 2014) and no effects (Bannert et al., 2009; Reid et al., 2017; Van den Boom et al., 2004) have been reported. The lack of a convincing effect on test scores in our study may be due to the construction of the metacognitive scaffolds. Specifically, they did not capture the entire metacognitive process: they were mostly directed to evaluation, included only one monitoring and regulation scaffold, and did not include planning and adaptation. Zheng (2016) found that supporting the whole metacognitive process has the greatest impact on achievement.

In contrast to Daumiller and Dresel (2019), who found an effect of motivational regulation prompts on the achievement of university students, motivational scaffolds had no effect on the post-test scores in our study. Our results might be different due to our different design of the prompts. Daumiller and Dresel used prompts focused on utility, performance, and intrinsic value. Our SRL scaffolds focused mainly on intrinsic and performance values. It seems that promoting the personal utility value of the learning content plays a critical role in increasing achievement, as found in the studies promoting learning with diary writing in secondary school students (Schmidt et al., 2012; Wäschle et al., 2015).

In summary, our main objective was to investigate the effects of different types of scaffolds on students' achievement when learning with hypermedia, considering individual learning characteristics. Students with a higher level of prior knowledge (general and specific), a higher level of motivation to learn the topic, and who use more learning

strategies perform better. The results suggest that one-time learning with science hypermedia was not more effective when the hypermedia consist of cognitive, metacognitive, and motivational scaffolds or their combination. Their contribution beyond individual characteristics was very small, did not reach statistical significance, and explained only a very small amount of the variance in learning outcomes. The predominant effect of student characteristics suggests that future studies should investigate the effects of learning with hypermedia embedded scaffolds over a much longer time interval and under highly controlled conditions.

4.1. Limitations and future directions

Our study was conducted in a whole-class school setting to ensure the ecological validity of the learning experiment. Students with different learning dispositions, prior knowledge, and topic interest learned the new content of applied science, which is an optional part of the ninth-grade curriculum in Slovenia, in a classroom setting. This setting is similar to the usual classroom teaching, where the teacher explains the new topic, whereas the students in our study learned individually using hypermedia. These circumstances brought some shortcomings, such as lack of motivation in some students, which could also be a consequence of the fact that the knowledge of the learned topic was not part of the regular curriculum and therefore not assessed or graded in any way. These may have affected their diligence in learning and, consequently, the results of the study.

The school environment also posed an unforeseen obstacle to complete data collection when the COVID-19 pandemic broke out in March 2020 and the general lockdown moved school lessons online until the end of the school year. As a result, we were unable to collect the data for the second phase of the study (Unit B) for approximately a third of the students who participated in the first phase. Thus, there were fewer students in the experimental groups to which they had previously been assigned. We were unable to continue the experiment in the next school year because the participating ninth graders had finished their basic schooling and had transferred to different high schools. The smaller number of students in the sample could have led to greater instability of the estimates in the regression model and reduced the impact of the individual variables included in the regression. With a larger sample, we could also conduct a path analysis to estimate the effects of scaffolds on outcomes, using individual student characteristics as moderators in the model and SRL strategies as mediators. In future studies, a delayed post-test could also provide information on the stability of the effects over time. Longitudinal or within-subjects experimental designs with successive iterations of learning with the scaffolds could also show the effects of their use more clearly.

Another possible improvement relates to the measurement of the SRL strategies used. The Learning Strategies Checklist should be more balanced in terms of the number of different types of cognitive, metacognitive and motivational strategies. We suggest adding more cognitive and motivational strategies to the checklist in future studies. This could allow the investigation of direct relationships between the type of scaffolding in hypermedia and the specific type of learning strategies used in learning. The use of SRL strategies was measured based on student self-reports, which is an indirect measurement and may not be valid and reliable enough (Dent & Koenka, 2016; Veenman, 2011), especially when used with children. The use of online measures of learning strategies (e.g., the thinking aloud method or log file data) would improve future studies on this topic. Learning effects could also be improved by teaching students to use different SRL strategies prior to individual e-learning, as already shown in the study by Bannert and Reimann (2012).

In our study, we used a fixed mode of scaffold provision, where students had to use the scaffolds to progress through the hypermedia. A non-embedded form of scaffold presentation, which allows more initiative in use (Narciss et al., 2007), could contribute to better

generalisability of the results to everyday individual learning with hypermedia. Nevertheless, in such an experiment, the actual use of scaffolds should be controlled with the on-line measures of the SRL strategies (e.g., log file data).

One of the limitations relates to the design of the motivational scaffolds. Some of them may promote other than motivational SRL processes, e.g. metacognitive learning strategies (Daumiller & Dresel, 2019; Schmidt et al., 2012; Wäschle et al., 2015). Therefore, scaffolds designed to promote only one specific SRL process – cognitive, metacognitive or motivational – may have conceptual overlap, which limits the interpretation of comparisons between groups of students who have learned with different types of scaffolds. Group comparisons may also be limited by the interaction of SRL processes during learning. Future studies should focus more on the unambiguous design of motivational scaffolds.

Finally, due to a relatively small sample, we only included experimental conditions as a factor and the individual learning characteristics as covariates in our regression model and did not consider the interactions between the experimental group and the covariates. Several previous studies have shown that the effects of scaffolds may differ for students with different prior knowledge or achievement levels (Belland, Walker, Kim, et al., 2017; Belland, Walker, & Kim, 2017; Chen, 2014; Lehmann et al., 2014; Moser et al., 2017). The uniform control of individual learning characteristics in all experimental groups could have masked or reduced the observable differences between the groups, which would lead to an underestimation of the effect of the scaffolding interventions. Future studies with larger samples should consider the possibility that the effects of specific scaffolds may vary among students with different individual learning characteristics and examine the interactions between the type of scaffolds and student characteristics.

5. Conclusion

We conducted a quasi-experimental study in a school setting with entire classes of ninth graders. This contributed to the ecological validity of the results, which may have application in future planning of distance or hybrid education in the post-COVID-19 era, where individualised learning using hypermedia is becoming more widespread. The results may be useful in the creation of hypermedia for curricular subjects with embedded SRL scaffolds that enable individualised learning by eliciting the proper use of strategies, thus stimulating SRL processes during learning and the acquisition of quality knowledge for lower secondary school students. Our results show that students' individual characteristics have a stronger impact on learning outcomes than the use of different types of scaffolds in hypermedia. Although our study did not reveal a statistically significant effect of the different types of scaffolds and their combinations over and above individual characteristics, we believe that further studies that adequately address the limitations we identified could provide more valid insights into the effectiveness of the different types of scaffolds and their combinations in learning.

CRedit authorship contribution statement

Alenka Gril: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Anja Podlessek:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Luka Komidar:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Alenka Kavcic:** Writing – review & editing, Project administration, Investigation, Data curation. **Katja Depolli Steiner:** Validation, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Sonja Pečjak:** Methodology, Investigation, Conceptualization. **Tina Pirc:** Methodology, Conceptualization. **Melita Puklek Levpušček:** Methodology, Investigation, Conceptualization. **Bojana Boh Podgornik:** Project administration,

Methodology, Conceptualization. **Aleš Hladnik:** Methodology, Conceptualization. **Ciril Bohak:** Software, Investigation. **Matevž Pesek:** Software, Investigation, Data curation. **Žiga Lesar:** Software, Investigation. **Matija Marolt:** Supervision, Resources, Conceptualization. **Cirila Peklaj:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Consent

All participants gave their written informed consent for inclusion in the study (by the participants' legal guardians/parents and the students themselves) before participating in the study.

Ethics approval

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Faculty of Arts, University of Ljubljana (approval date: October 16, 2018).

Funding

This research was conducted as part of the basic research project Effectiveness of different types of scaffolds in self-regulated e-learning [grant number J5-9437], and the research programmes Psychological and neuroscientific aspects of cognition [No. P5-0110] and Applied developmental psychology [No. P5-0062], funded by the Slovenian Research and Innovation Agency [Javna agencija za znanstvenoraziskovalno in inovacijsko dejavnost Republike Slovenije] from the state budget.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank all participating schools, students and teachers in Slovenia for their contribution to this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.chb.2025.108670>.

Data availability

Data and R code for the statistical analysis of the second phase of the experiment are available at the hyperlink below.

[SRL scaffolds \(Original data\)](#) (OSF)

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