Exploring the effects of metacognitive prompts on learning outcomes: An experimental study in higher education

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The use of metacognitive prompting to support self-regulated learning is a well-established area of research in education. Despite receiving considerable attention, the precise mechanism of prompting and its effects on the learning process remain unclear, especially in the context of multimedia learning. This study employed a controlled laboratory experimental design to empirically investigate the effects of metacognitive prompting on learning outcomes, considering both text-based and multimedia learning materials. A population of 110 native Czech undergraduate students in the humanities and social sciences participated in the experiment. Contrary to expectations, metacognitive prompting was not identified as a significant predictor of learning outcomes. Post-hoc analysis indicated that the effects of metacognitive prompting depend on various differences in students and their cognitive processing, which may be further influenced by the nature of the learning material. These findings underscore the importance of considering individual differences when designing and implementing metacognitive prompts in multimedia learning, as well as for follow-up research where they should be closely inspected.

Implications for practice or policy:

- The findings of this study emphasise the importance of individual differences among students in the domain of self-regulated learning, which should be considered when creating meta-cognitive prompts.
- When designing online learning materials, instructional designers should be aware that the effectiveness of metacognitive prompts may vary depending on the type of learning material.
- Educators can focus on providing additional support (beyond metacognitive prompts) to low-achieving students to help them develop their ability to regulate their own learning.

Keywords: self-regulated learning, metacognitive prompts, learning outcomes, multimedia learning, experimental study

Introduction

Over the past 2 decades, self-regulated learning (SRL) has gained significant attention in educational science, leading to remarkable theoretical advancements (Adam et al., 2017; Boekaerts et al., 2000; Zimmerman, 2000; Zimmerman & Schunk, 2011). Several definitions and models of self-regulation and

SRL have been proposed (Panadero, 2017), leading to some theoretical fragmentation and confusion. Most definitions and models consider SRL as a cyclical process consisting of three phases: (a) the preparatory phase, (b) the performance phase (i.e., the phase of actual task performance) and (c) the reflective or appraisal phase. Within each of the three general phases, several specifically focused processes can be further distinguished, such as goal setting, strategic planning, selecting and organising information, time management, monitoring and metacognition, self-evaluation and self-reflection (Azevedo, 2009). In addition to cognitive and metacognitive processes, most SRL models also consider affective and motivational aspects of SRL. These include self-motivational beliefs such as self-efficacy, goal orientation and the subjective value of learning (Panadero, 2017; Wong et al., 2019; Zimmerman & Schunk, 2011).

SRL has drawn research attention due to its positive link to student learning outcomes. Research suggests that students who engage in SRL are able to efficiently manage their own learning and perform better on learning tasks, leading to their academic success (Boekaerts et al., 2000; McInerney et al., 2012). The relationship between SRL and learning outcomes or academic success in general has been a major focus of researchers in this area, and a number of studies provide evidence for the contribution of the cognitive and motivational dimensions of SRL to learning outcomes (de Bruijn-Smolders et al., 2014; Shi et al., 2022; Zimmerman & Schunk, 2011). However, the research has not been entirely conclusive and, for example, the highly cited meta-analysis by Sitzmann and Ely (2011) did not find significant relationships between self-regulatory processes and learning outcomes.

A key explanation for inconclusive results in this research is that students often struggle to employ effective regulatory strategies without support. Thus, researchers have explored scaffolds to aid self-regulation, especially in online learning, where greater autonomy and competence are required to navigate complex multimedia materials (Delen et al., 2014, Wong et al., 2019). Metacognitive prompting is one of the main researched mechanisms to support SRL. Prompts in general can be seen as a temporary support mechanism or scaffold to assist students in using appropriate learning strategies (Bannert, 2009). Metacognitive prompts, in contrast to cognitive prompts, focus on engaging students in higher-level learning strategies such as goal setting, monitoring and reflection. Several studies have provided evidence of the effectiveness of metacognitive prompts in improving student learning outcomes (Azevedo et al., 2011; Devolder et al., 2012; Guo, 2022; Manlove et al., 2009).

Although current research suggests that metacognitive prompts can stimulate the use of higher-order learning strategies and thereby improve learning outcomes, it remains unclear whether and to what extent metacognitive prompts improve student learning outcomes, and how this relationship changes in the context of learning from multimedia learning materials. The aim of this study was therefore to explore the relationship between metacognitive prompting and learning outcomes in the context of multimedia learning. To this end, a controlled laboratory experiment was conducted with a homogeneous population of humanities and social sciences university students to investigate the effects of metacognitive prompting on student learning outcomes and whether these effects vary according to the type of learning material (i.e. text vs. multimedia).

Supporting SRL with metacognitive prompts

In general, prompts can be seen as specific external support tools, usually in the form of hints or questions that act as strategy activators. Prompts do not provide new information, but rather stimulate the use of known cognitive, metacognitive, motivational and resource management strategies during the learning process (Bannert, 2009). The main goal of prompts is to activate strategies or skills that students have acquired but do not use spontaneously (Schumacher & Ifenthaler, 2021; Wirth, 2009). Metacognitive prompts indicate to students when and how to engage in productive processing and encourage them to reflect on their own learning processes, monitor their understanding and regulate their learning activities. Metacognitive prompts are designed to help students become more aware of their own thinking and learning processes and to develop the ability to evaluate and adjust their learning strategies based on the learning situation (Poorman & Mastorovich, 2016; Vaidya, 1999). Metacognitive prompts can take many forms. Some common examples are reflection questions that ask students to think about what they have learned, how they have learned it, and what strategies they have used to learn; self-assessment checklists that provide students with a list of criteria or questions to help them assess their own learning; feedback prompts that provide feedback that encourages students to think about their own learning and how they can improve; goal-setting prompts, which encourage students to set goals for their learning and monitor their progress towards those goals; summarising prompts, which encourage students to summarise what they have learned in their own words, which helps them to consolidate their understanding (Bannert & Mengelkamp, 2013; Colthorpe et al., 2019; Domokos & Huey, 2023; Teng, 2021).

Many studies have shown that metacognitive prompts led to higher learning gains as well as significant improvements in planning, monitoring, and reflection (e.g., Adler et al., 2016; Bannert & Mengelkamp, 2013; Bannert et al., 2015; Castronovo et al., 2022; Devolder et al., 2012; Kollar et al., 2007; Kramarski & Friedman, 2014; Panadero et al., 2012). On the other hand, a considerable number of studies presented conflicting results when reporting no additional benefits of metacognitive support such as prompts (e.g., Berthold et al., 2007; Lehmann et al., 2014; Moser et al., 2017). Metacognitive prompting may not be an effective tool for promoting SRL in all settings and situations, as research on the use of prompting to support student learning has shown mixed results. For example, the findings of Bannert and Reimann (2012) have suggested that the effectiveness of prompts might vary depending on the cognitive abilities of students. Students with lower prior knowledge of the topic might not have the additional cognitive resources to process the metacognitive prompt presented and to subsequently use appropriate SRL strategies to achieve better learning outcomes. Similarly, there has been considerable debate about the specific effects of prompting for different types of students, with certain groups of students thought to benefit less from metacognitive prompts that require deep learning (Colthorpe et al., 2019; Paas et al., 2003; F. Zhao et al., 2023). These studies have discussed the suggestion that low-achieving students may struggle with the cognitive demands of deep learning activities, such as making connections between different pieces of information, which may lead to cognitive overload and hinder their ability to learn effectively.

The effectiveness of metacognitive prompts may be influenced by a number of other factors. Hill and Hannafin (2001) have suggested that the ineffectiveness of metacognitive prompts may be due to student lack of metacognitive skills. In this case, students may not be able to make appropriate choices about what support they need and when or they may not be able to use metacognitive prompts as a productive part of learning. Another reason that has been discussed that can lead to the ineffectiveness of metacognitive prompts is that students often do not use the prompts in the intended way (Bannert, 2009; Guo, 2022). For example, a study by Furberg (2009) showed that instead of following the prompts, students responded by simply copying and pasting responses in order to answer correctly. A meta-analysis by Guo discussed several other potential moderators of the effects of metacognitive prompts, such as the design and delivery of the prompts, the context in which the prompts are presented and the way in which the effects of metacognitive prompts are evaluated.

Metacognitive prompts in multimedia learning

Multimedia learning refers to the use of learning materials that combine different forms of media (such as text, images, audio and video) to present information to students. Examples of complex multimedia learning content may include interactive simulations, animated videos and digital textbooks with embedded video and audio; in the most general sense, the term *multimedia* refers to the presentation of a combination of words and images (Mayer, 2014). Words can be either printed or spoken text in the form of an audio recording. Images can be either static graphics such as diagrams, photo and illustrations or dynamic graphics such as animations and videos. Multimedia learning is understood as the process of building mental representations from words and images (Mayer, 2014).

Research on multimedia learning hypothesises that multimedia learning materials designed in accordance with how the human mind works can lead to more meaningful learning. Based on this hypothesis, the cognitive theory of multimedia learning describes how people learn from multimedia learning materials (Mayer, 2014). This theory has three basic assumptions: dual channel, limited capacity and active processing. First, according to Paivio’s (1990) dual coding theory and Baddeley’s and Logie’s (1999) working memory multiple-component model, the dual channel assumption states that people have separate channels for processing visual and auditory information. Second, according to Baddeley's and Logie's working memory multiple-component model and Sweller's (1994) cognitive load theory, the limited capacity assumption states that the amount of information people can process in each channel at one time is limited. Third, the active processing hypothesis postulates that people are active agents in selecting, organising and integrating incoming information to construct coherent mental representations (Mayer, 2014).

The use of metacognitive prompts in multimedia learning has been shown to improve learning outcomes. They can be particularly effective in helping students to engage with different forms of media and to make connections between them (Mayer, 2014; Moreno & Mayer, 2007; Renkl et al., 2004). For example, students can be asked to think about how an image or video relates to the text they are reading or to evaluate how an interactive element helps them to understand the content (Mayer & DaPra, 2012). Single-media content, such as text-only content, is limited in its ability to engage students and promote deeper understanding (Sweller et al., 2011). Text-based content may be more difficult for some students to process and retain than multimedia content that incorporates visual and auditory elements. However, several studies (Arslan, 2012; Moreno & Mayer, 1999; L. Zhao, 2011) have suggested that multimedia-based learning content may increase extraneous cognitive load due to the additional sensory information, whereas text-based learning content may be more efficient in promoting deep learning because it places less demand on working memory. This means that multimedia learning can lead to cognitive overload. The use of metacognitive prompts can help to compensate for some of these potential disadvantages. By providing students with guidance on how to process and evaluate different forms of media, metacognitive prompts can help them to manage the cognitive demands of multimedia learning more effectively (Hoch et al., 2023; Sweller et al., 2011).

Considering the influence of the aforementioned individual differences of students, a study by F. Zhao et al. (2023) suggested that low-achieving students had more difficulty with integration of information from different sources in a multimedia-based learning environment. Specifically, the study found that low-achieving students tended to give up earlier in multimedia learning compared to high-achieving students. Given this conflicting evidence, further research on metacognitive prompting in different media settings is needed in a laboratory-controlled setting.

Present study

The effect of metacognitive prompts on learning and learning outcomes is complex and may depend on a variety of other factors, including the nature of the learning material, that is, whether it is text-only material or multimedia learning material combining both textual and visual information. The aim of this study was therefore to investigate the effectiveness of metacognitive prompting on learning outcomes, taking into account the type of learning material. We investigated whether students who are exposed to metacognitive prompts while learning from text-only and multimedia-based learning materials perform better on a subsequent knowledge test than those who are not exposed to such prompts. In addition, we explored whether learning from different types of study materials leads to different learning outcomes, and whether the relationship between metacognitive prompts and learning outcomes varies depending on the type of study material used during learning. The research questions of this study can be summarised as follows:

(1) Do metacognitive prompts affect student learning outcomes?
(2) Do student learning outcomes vary depending on the type of learning materials; if so, how?
(3) Is the relationship between metacognitive prompts and student learning outcomes moderated by the type of learning materials?

Methods

Experimental design

In order to address our research questions, a controlled laboratory-based experiment was designed and conducted with experimental and control groups and task randomisation. The experiment used a within-between subjects 2 x 2 factorial design with a knowledge post-test to assess the performance of students dealing with specific learning content. Two balanced groups of participants were between-subjects cases in which the presence of metacognitive prompts while studying learning materials was manipulated as an independent variable (first factor, two levels). At the same time, all participants (within-subjects cases) studied two different types of learning materials (text-only materials and multimedia materials), constituting a second independent variable (second factor, two levels).

Participants were randomly assigned to one of two groups (experimental and control) with regard to the use of metacognitive prompts. Participants in the experimental group studied the learning materials supplemented with metacognitive prompts, that is, pieces of information that promoted metacognitive processing of the content being studied; participants in the control group were presented with no additional learning support. The main reason for randomly assigning students to the experimental and control groups was to prevent a potential transfer of the prompt-based learning strategy to non-prompted tasks. In total, all participants studied eight pages of learning materials, four of which were text-only and four of which consisted of a combination of text and visual information. The order of the materials was randomised to avoid a serial position effect within subject cases. The randomisation of the stimuli was carried out automatically using the SMI Experiment Center software, which was employed for stimulus presentation and data recording. The randomisation principle ensured a unique random presentation of the materials for each participant, effectively mitigating the serial position effect. After studying all the learning materials, participants completed a knowledge test covering topics equally from all learning materials presented. The basic scheme of the experiment is shown in Figure 1.

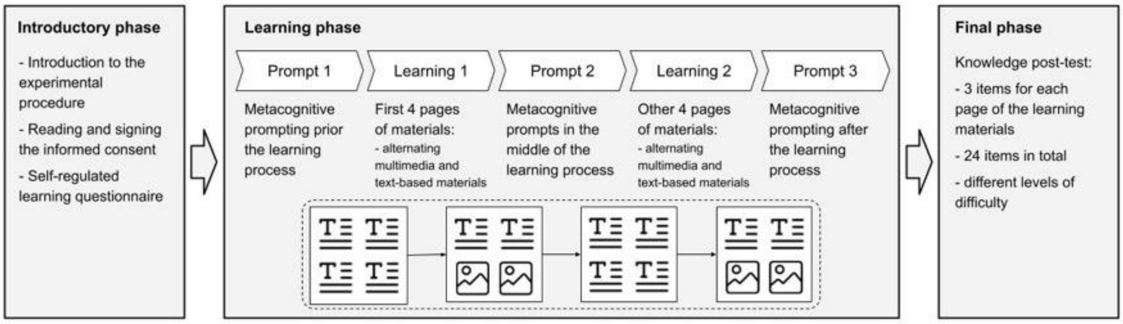

Figure 1. Schematic diagram of the experimental design.

The experimental setting consisted of a standard desktop computer, computer monitor, height-adjustable chair and control device (computer mouse). The session was held in an isolated laboratory setting with constant light and noise conditions. At the time of the data recording, one research assistant was present in the laboratory. Participants were tested one by one, always with a few minutes' break between testing to circulate the air in the laboratory.

Participants

The participants in the experiment were 110 university students of humanities and social sciences. The age of the participants ranged from 19 to 25 years, with a mean age of 20.7 years (*Med* = 21), and 67.3% of the participants were women, which corresponds to the gender distribution of humanities and social sciences students at Masaryk University (Czech Republic).

To ensure the homogeneity of the sample, only full-time bachelor students were approached to participate in the experiment. As the study involved learning materials in the Czech language, only native Czech speakers were recruited. Prior to the experiment, all participants were asked about possible visual or learning impairments and other possible medical limitations, and only neurotypical participants with no serious medical problems and normal or corrected-to-normal vision were invited to participate in the experiment.

Materials

Learning materials

The learning materials used in the experiment were compiled from the field of optics, as the target research sample (i.e., humanities and social science students) was expected to have very little or no knowledge of advanced optometry. The learning materials were designed exclusively for this experiment. The materials consisted of either plain text (four pages of learning materials) or text with associated picture information (four pages of learning materials), which were considered to represent multimedia learning material. All materials consisted of four visually distinct content blocks, as illustrated in Figure 1. In the case of the textual materials, all four content blocks were in the form of plain text. In the case of the multimedia learning materials, the top two blocks were textual and the bottom two blocks were visual. The materials were presented on a desktop computer monitor in the form of a standard PowerPoint-like visual format.

Metacognitive prompts

Participants in the experimental group were presented with metacognitive prompts at three different stages of the learning session. The first prompt was presented before the study of the first set of learning material, the second prompt was presented in the middle of the learning session, between the fourth page and the fifth page of the learning materials, and the third prompt was presented after the study of the last (eighth) page of the learning materials. All three metacognitive prompts were presented in a text-based format.

The metacognitive prompting before the actual learning focused on orientation and planning (*Try to remember what you already know about the topic. Think about how you can make sure that you learn everything you need to know from the learning material.*) and included basic instructions on how participants should proceed or what questions they should try to answer when studying each learning material (e.g., *What points have I not yet understood? What concepts were not sufficiently explained?*). The metacognitive prompt in the middle of the learning session focused on monitoring and regulation (*Summarise what you have learned so far. Would it be useful to change your current approach to studying the learning materials?*). The prompt after the learning session focused on evaluation and reflection on the study of the learning materials (*Repeat in your own words the most important things you learned from the materials presented. Could you explain the concepts and principles presented to someone else?*).

Participants in the control group were only given general instructions with no metacognitive prompts. The amount of time participants were shown metacognitive prompts (i.e., experimental group) or general instructions (i.e., control group) was the same for all participants and all prompts or instructions. Similar to the learning materials, the prompts and general instructions took the form of a standard PowerPoint-like visual format.

Knowledge post-test

The knowledge post-test consisted of a total of 24 items. The items were based on the learning content presented in the learning materials. The number of items in the post-test was designed to give equal representation to each page of the learning materials, that is, there were three test items for each page of the learning materials (i.e., 8 x 3 items). The items varied in difficulty (for each page of learning materials there was one easy, one medium and one difficult item) and were piloted before the experiment.

Procedure

Participants were invited to the laboratory experiment via an email that explained the general purpose of the study. On arrival at the laboratory, the participants were introduced to the procedure and given an informed consent form for them to read and sign. Participants were directly informed that they could withdraw from the experiment at any time during the entire experimental session and that they could remove their recorded data from the measurement at any time until the experimental data collection and anonymisation had been completed. Participants then completed a questionnaire covering basic demographics, potential visual impairments, current level of fatigue and a short battery of items measuring selected dimensions of SRL. A total of four dimensions of SRL were measured using four subscales of the Motivated Strategies for Learning Questionnaire developed by Pintrich et al. (1991). These were intrinsic and extrinsic goal orientation, metacognitive self-regulation and critical thinking.

After completing the questionnaire, participants were seated in front of the computer screen. Before starting the experimental application, participants were given precise information about what they were to do in the experiment. The experimental application was then launched and the learning session began. In the learning session, participants were given metacognitive prompts (experimental group) or general instructions (control group) and went through the learning materials where they had to read texts and look at pictures in order to gain new knowledge about the presented topic. Participants then took the knowledge post-test. After completing all tasks, participants were directed away from the computer screen, thanked for their participation and debriefed. Finally, participants were rewarded with a small gift (pen, mug) and allowed to leave.

Ethical considerations

Before the experimental session, the participants were fully informed about the purpose of the experiment and about the fact that they could withdraw from the experiment at any time without any consequences. Participants gave their informed consent by means of a written consent form. The research project of which this study is a part was approved by the Research Ethics Committee of Masaryk University (project identification number: EKV-2020-037). The study was conducted in accordance with the relevant guidelines and regulations and the principles of the Declaration of Helsinki.

Data analysis

To address the research questions, linear mixed effects modelling was used. As the dependent variable consisted of the correctness of each item in the knowledge post-test, with correct answers scoring 1 and incorrect answers scoring 0, generalised linear mixed effects models with logit as the link function were used. Exposure to the metacognitive prompts (prompt vs. non-prompt) and the type of learning material (text-only vs. multimedia) were considered as fixed factors. The models included individual participants as random intercepts. After the confirmation-oriented analysis, which focused on answering the predetermined research questions, we conducted an exploratory-oriented post-hoc analysis, which aimed to provide possible explanations for the results of the confirmatory analysis and to offer hypotheses for follow-up research. All data were processed and analysed using R and RStudio software with the packages lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017) used to estimate linear mixed effects models.

Results

Research questions

To address the first research question, a model was constructed with exposure to metacognitive prompts as the only independent variable and item correctness in the knowledge post-test as the dependent variable representing student learning outcomes. In this model, a non-significant effect of metacognitive prompting on learning outcomes was found ($\beta = 0.114$, standard error [SE] = 0.147, $z = 0.775$, $p = 0.438$). The odds ratio for the prompt condition compared to the no-prompt condition was 1.12 (95% confidence interval [CI]: 0.84 – 1.50), indicating that students exposed to metacognitive prompting were not significantly more likely to answer correctly in the knowledge post-test.

Similar to the first research question, a model with only one independent variable was specified for the second research question. The type of learning materials served as the independent variable and item correctness in the knowledge post-test served as the dependent variable. The specified model showed a significant effect of the type of learning materials on item correctness in the knowledge post-test ($\beta = -0.533$, $SE = 0.096$, $z = -5.527$, $p = < 0.001$). The odds ratio for the multimedia learning materials compared to the text-only materials was 0.59 (95% CI: 0.49 – 0.71), indicating that items based on the topics in the multimedia learning materials were significantly more likely to be answered incorrectly.

The third research question focused on the interaction between the two experimental conditions, that is, whether the effect of metacognitive prompts on student learning outcomes is moderated by the type of learning materials. The resulting model included both experimental factors (i.e., metacognitive prompts and the type of learning materials) as independent variables as well as the interaction between these two factors. An overview of the individual effects within this model is presented in Table 1. The table shows that again only the effect of type of learning material on learning outcomes is statistically significant; the interaction between metacognitive prompts and type of learning material is not statistically significant. We can interpret this to mean that the type of learning material does not seem to moderate the effect of metacognitive prompts on student learning outcomes.

The results for all three questions are presented visually in Figure 2.

Table 1
Summary of the effects in the third model related to the third research question

	Log odds	SE	Odds ratios	CI	p
Prompting	0.038	0.179	1.04	0.73 – 1.48	0.831
Multimedia	−0.607	0.135	0.55	0.42 – 0.71	**< 0.001**
Prompting × Multimedia	0.152	0.192	1.16	0.80 – 1.70	0.429

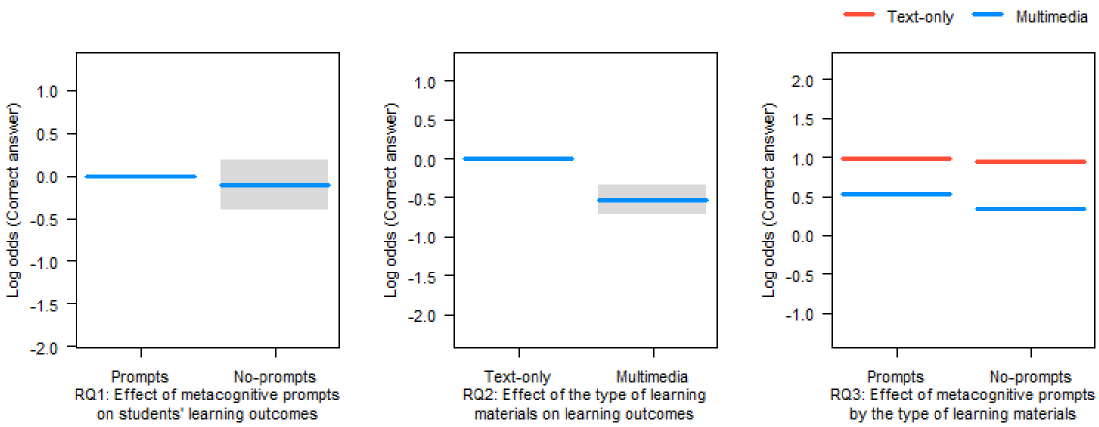

Figure 2. Visual representation of the effects examined in relation to each research question

Post-hoc analysis

The first step in the post-hoc analysis was to examine the differences between the experimental and control groups (i.e., the groups with and without metacognitive prompting) on selected indicators that were available in our data and that were considered to possibly provide some insight into why a statistically significant effect of metacognitive prompting on learning outcomes was not found. Specifically, we focused on gender, age, perceived level of fatigue reported prior to the experiment, four indicators of SRL (intrinsic goal orientation, extrinsic goal orientation, metacognitive self-regulation and critical thinking), time spent studying each learning material, time spent answering each item on the knowledge post-test and scores obtained on the knowledge post-test. The results of this step of the post-hoc analysis are presented in Table 2.

Table 2
Differences between experimental and control groups in selected parameters

	Experimental group (Prompts)		Control group (No-prompts)	
	N	*%*	*N*	*%*
Gender				
females	36	32.7	38	34.5
males	19	17.3	17	15.5
	Mean	*SD*	*Mean*	*SD*
Age	20.8	1.37	20.7	1.11
Fatigue level	4.24	1.61	3.96	1.54
SRL indicators				
intrinsic goal orientation	5.09	0.85	4.94	0.78
extrinsic goal orientation	3.87	1.45	4.16	1.69
metacognitive self-regulation	4.3	0.63	4.35	0.73
critical thinking	4.36	1.15	4.48	0.93
Time spent on learning materials	187.3	82.7	178.4	82.2
Time spent on knowledge test	22.9	16.3	24.7	18.8
Total score in knowledge test	16.5	3.53	16.2	2.66
score on text-only materials	8.22	1.96	8.24	1.88
score on multimedia materials	8.24	1.96	8.00	1.35

Table 2 reveals several potentially important trends in the analyzed data regarding the differences between the experimental and control groups.

Gender and age do not seem to play major roles, although we see partial differences in the representation of men and women between the experimental and control groups. The participant level of fatigue may have played an important role. Table 2 shows that, on average, participants in the experimental group experienced higher levels of fatigue than participants in the control group before the start of the experiment. Higher levels of fatigue may have played a role in the extent to which participants were able to work with and extract relevant information from the learning materials. Increased fatigue may have interfered with the effect of the metacognitive prompts for some participants. Some support for this hypothesis that the higher level of fatigue among participants in the experimental group may have influenced the results of the experiment is provided by the variability in participant scores on the knowledge test, which is considerably higher for participants in the experimental group (SD = 3.53) than the control group (SD = 2.66).

Potentially important information is also revealed by differences in SRL indicators, especially those related to intrinsic and extrinsic goal orientation. The data in the table indicate that participants in the experimental group showed, on average, a higher level of intrinsic goal orientation; participants in the control group showed a higher level of extrinsic goal orientation. Thus, the motivational structure of the participants seemed to differ to some extent between the experimental and control groups, which in turn could influence both the knowledge test scores and the effect of metacognitive prompts on student learning.

There were some differences between the group with metacognitive prompts and the group without metacognitive prompts in the time participants spent studying the assigned learning materials and the time participants spent answering the corresponding questions in the knowledge post-test. We can see that, on average, participants in the experimental group (i.e., with metacognitive prompts) spent more time studying the assigned learning materials. Specifically, participants in the experimental group spent an average of 8.9 seconds more on each learning material, which, with a total of eight learning materials over the course of the experiment, means that they spent an average of 71.2 seconds longer studying the assigned materials than participants without metacognitive prompts. In contrast, participants in the control group (i.e., without metacognitive prompts) spent more time on average answering questions in the knowledge post-test. Specifically, participants in the control group spent an average of 1.8 seconds longer on each item in the knowledge post-test, which means that with a total of 24 test items, participants without metacognitive prompts took an average of 43.2 seconds longer to complete the knowledge post-test than participants with metacognitive prompts.

Our attention was also drawn to the relatively significant difference in the score (and its variability) on multimedia materials within the group without metacognitive stimuli compared to the experimental group, and the score on text-only materials. We proceeded to a more detailed visual analysis of the structure of participant scores on the knowledge post-test in relation to the types of learning materials. A density plot showing the distribution of knowledge test scores for each of the conditions (Figure 3) showed a notable trend with a clear bimodal distribution of knowledge test scores in the experimental group when studying the multimedia learning materials. Given the identified bimodal distribution, we can hypothesise that the metacognitive prompts induced different cognitive processing in the participants studying multimedia learning materials, dividing them into those who performed better and those whose performance declined based on exposure to the metacognitive prompts. Indeed, the follow-up exploratory analysis on the subgroups of "high achievers" and "low achievers" (divided on the basis of the observed bimodal distribution) confirmed that the effect of metacognitive prompts on learning outcomes is statistically significant focusing separately on the group of "high achievers" (significant positive effect) and the group of "low achievers" (significant negative effect).

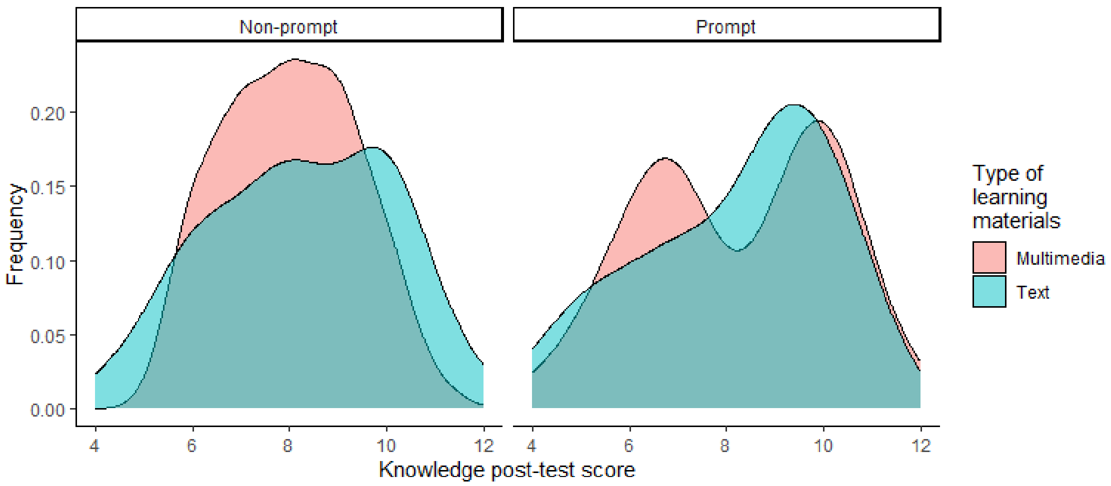

Figure 3. Density plot of the distribution of knowledge test scores for each combination of experimental conditions

The final step of the post-hoc analysis was to explore in more detail the time spent on the learning materials and its relationship to the effect of metacognitive prompts on learning outcomes. There were differences between the experimental and control groups in the amount of time spent studying the materials. In the next step, we were interested in whether and to what extent the time spent studying the learning materials affected student learning outcomes and whether the effect of metacognitive prompts on student learning outcomes was moderated by the time spent studying the learning materials. Therefore, in the manner of an exploratory analysis, we estimated a model with metacognitive prompts and time spent on learning materials as independent variables, as well as the interaction between these two parameters. The results presented in Table 3 confirm that the time spent on learning materials does indeed have a significant effect on learning outcomes. In addition, as shown in the supplementary interaction plot (Figure 4), the relationship between time spent studying the assigned learning materials and performance on the knowledge post-test appears to be stronger for participants in the experimental group.

Table 3
Summary of the effects of metacognitive prompts and the time spent on the learning materials on learning outcomes

	Log odds	SE	Odds ratios	CI	p
Prompting	−0.221	0.296	0.802	0.45–1.43	0.457
Time spent on learning materials	0.177	0.063	1.194	1.06–1.35	**0.005**
Prompting × Time spent on learning materials	0.097	0.088	1.102	0.93–1.31	0.272

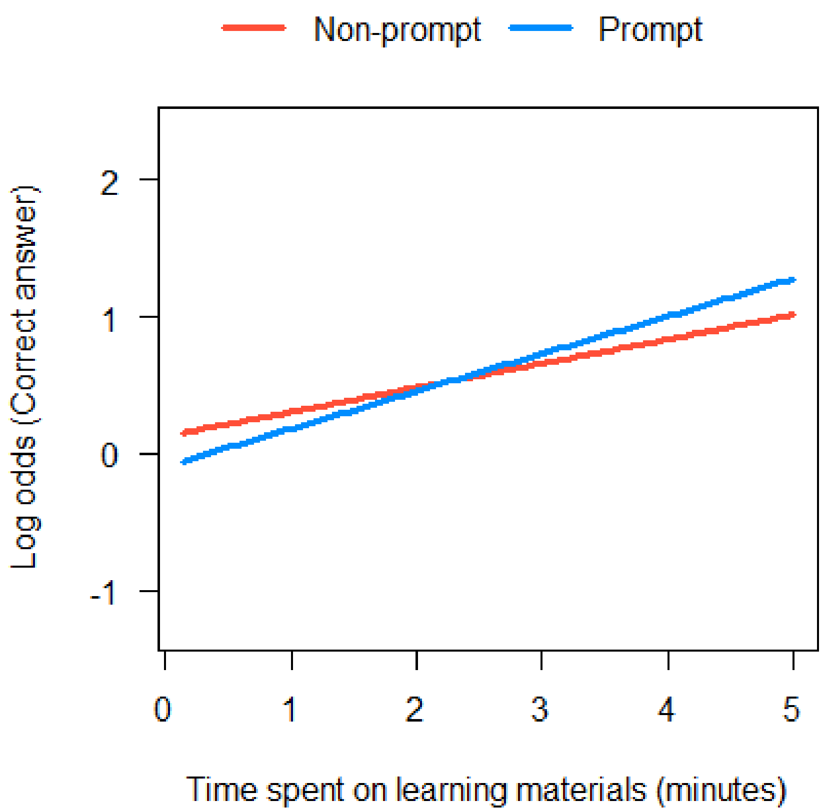

Figure 4. Visual representation of the interaction effect between metacognitive prompts and the time spent on the learning materials on learning outcomes

It can be hypothesised that the effect of metacognitive prompts on learning outcomes depends on the amount of time students have to study the learning materials. In our experiment, the study of the assigned learning material was time-limited to a maximum of 5 minutes, after which the participant was automatically redirected to the next learning material. In a considerable number of cases (see Figure 5), the participant's study of one learning material was forcibly interrupted by an automatic transition to another learning material. This forced disruption of the learning process may have interfered with the process of applying appropriate SRL strategies induced by metacognitive prompts, possibly resulting in a non-significant effect of metacognitive prompts on learning outcomes.

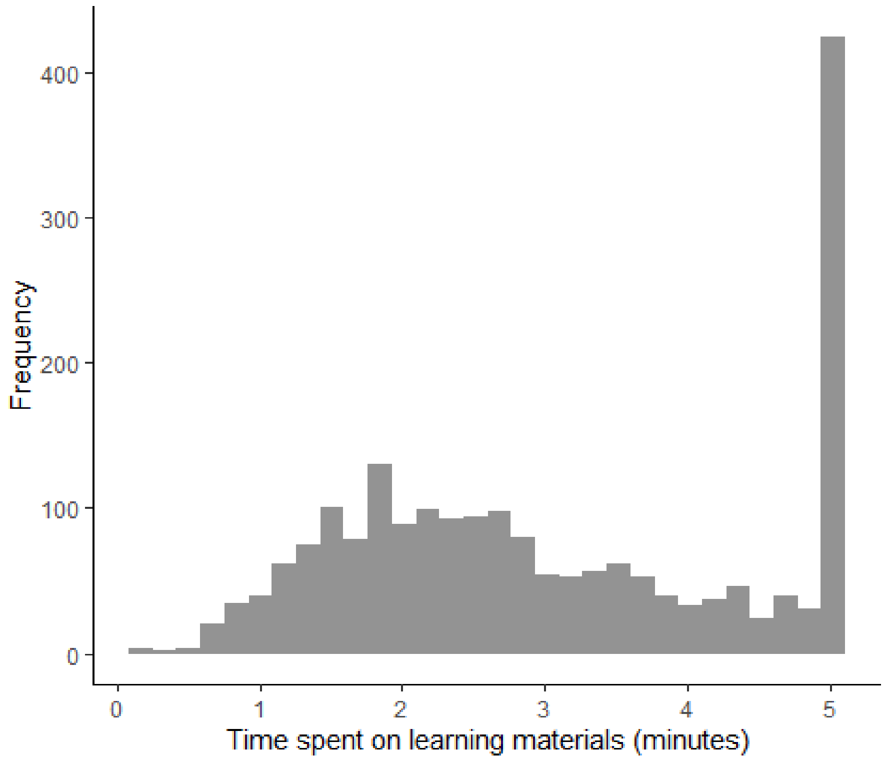

Figure 5. Histogram of the distribution of the time spent on the learning materials

Discussion

The purpose of this study was to investigate the effect of metacognitive prompts on learning outcomes when learning from text-based and multimedia-based learning materials. Specifically, this study aimed to find (a) whether metacognitive prompts affect student learning outcomes, (b) whether student learning outcomes vary depending on the type of learning material and (c) whether the relationship between metacognitive prompts and student learning outcomes is moderated by the type of learning material. To achieve this objective, a controlled laboratory experiment was conducted and generalised linear mixed effects modelling was used to analyze the collected data. An exploratory post-hoc analysis was then conducted to gain further insight into the data and provide possible explanations for the results of the main analysis.

Findings on the predetermined research questions

The results of the main analysis, which was designed to answer three pre-defined research questions, showed a statistically insignificant effect of metacognitive prompts on learning outcomes, contrary to our expectations based on previous research (Azevedo et al., 2011; Devolder et al., 2012; Guo, 2022; Manlove et al., 2009). Faced with this surprising finding, we conducted a post-hoc analysis, the primary aim of which was to offer possible explanations for this non-significant relationship. The results of the post-hoc analysis are presented in the next section.

The analysis dealing with the second research question revealed a significant effect for the type of learning material, showing that questions based on the text-only materials were significantly more likely to be answered correctly than questions based on the multimedia learning materials. This finding contradicts the general expectations of several researchers in the field of educational science (Mayer, 2014; Moreno & Mayer, 2007; Renkl et al., 2004), who promoted multimedia content as potentially increasing learning gains. Rather, our findings support previous claims (Arslan, 2012; Moreno & Mayer, 1999; L. Zhao, 2011), which suggested that multimedia content is more demanding in terms of cognitive load than plain text content.

Finally, with regard to the third research question, the effect of the interaction between metacognitive prompts and type of learning material was found to be statistically insignificant, which means that in our sample the type of learning material did not moderate the effect of metacognitive prompts on student learning outcomes. Despite the statistically insignificant results, there was a partial trend in the analyzed data in which the effect of metacognitive prompts on student learning outcomes was higher in the context of multimedia learning materials than text-based learning materials (Mayer, 2014; Moreno & Mayer, 2007; Renkl et al., 2004).

Findings based on the post-hoc analysis

Given the surprising results of the main analysis, we conducted an exploratory post-hoc analysis to further explore the trends in the data and to suggest possible explanations for the insignificant effect found in the main analysis. On the basis of a post-hoc analysis, we offer the following possible explanations, which should be investigated and possibly verified by further research.

An exploratory post-hoc analysis of differences between the experimental group and the control group revealed variations in terms of participant levels of fatigue and their levels of intrinsic and extrinsic goal orientation, which can be considered as an affective-motivational dimension of SRL. These differences could influence both the learning process and the process of engaging with metacognitive prompts. Therefore, we propose that student fatigue while completing the learning activity and student motivation to complete the learning task may serve as possible moderators of the effect of metacognitive prompts on learning outcomes (Papadopoulos et al., 2009; Pieger & Bannert, 2018; Schmidt & Ford, 2003; Sonnenberg & Bannert, 2016).

In addition, our post-hoc analysis indicated that the amount of time participants spent studying the assigned materials had a significant effect on student scores in the knowledge post-test. Furthermore, there appears to be an important relationship between metacognitive prompts and the amount of time students spend studying the assigned material. However, the design of our experiment, which gave participants a limited time to study the assigned learning materials, may have interfered with the process of applying appropriate self-regulation strategies induced by metacognitive prompts, thus causing the effect of metacognitive prompts on learning outcomes to show up as statistically insignificant. In any case, the results of our post-hoc analysis suggested that the time taken by students to complete the task is an important factor that should be given more attention in future research (Engelmann et al., 2021).

Finally, the post-hoc analysis revealed a bimodal distribution of student knowledge test scores in the experimental group when using multimedia learning materials. This could be a result of the metacognitive prompts inducing different cognitive processing in participants, dividing them into those who scored higher when prompted and those who scored lower when prompted. Several previous studies (Colthorpe et al., 2019; F. Zhao et al., 2023) that have investigated the influence of individual ability on learning gains in prompt-based learning have had similar results. Further analysis of the identified subgroups of high and low achievers supports the hypothesis that metacognitive prompting can have significant but opposing effects for each of these groups of students. For high achievers, metacognitive prompts seem to increase the likelihood of answering the knowledge test questions correctly; for low achievers, the prompts seem to decrease the likelihood of answering correctly.

This observation speaks for the activation of distinct cognitive mechanisms based on the use of metacognitive prompts, especially in the context of multimedia learning materials. Learning and elaboration of more challenging learning materials is likely to be effective only for some students, as suggested by Colthorpe et al. (2019), especially with multimedia content (Paas et al., 2003). These studies proposed that low-achieving students may struggle with the cognitive demands of deep learning activities, such as making connections between different pieces of information; this struggle may lead to cognitive overload and hinder their ability to learn effectively. Based on the evidence from the present study, we hypothesise that the prompts associated with the multimedia learning materials divided the participants into two subgroups, the first being facilitated to perform better by the prompts and the second being hindered. We consider this a crucial observation, as the data suggest that prompt-based activation could work as a binary criterion.

Limitations and further research

The study has several limitations that should be considered when interpreting the results and designing follow-up research. First, because the study focused on exploring the expected effects of selected factors within the experimental design, relying on the principle of randomisation, we did not control the research sample for a number of participant characteristics and measures, such as academic achievement, cognitive ability or general intelligence. In retrospect, it appears that some of these indicators (e.g., participant cognitive ability) may have played an important role in the observed effects that we could not account for in the analyses conducted (e.g., in the form of an additional control variable). Future research should be more focused on individual differences among students in various aspects and under various conditions. Regarding this, controlling for participants IQ scores and academic achievement would be recommended. The second limitation is related to the first and concerns the motivation to complete a successful learning session, which could vary considerably depending on the research sample and the tasks given, and which was not controlled for in individual cases. Third, the knowledge post-test only captured immediate learning gains, which may have been partially enhanced by the mechanical drill rather than deeper understanding (i.e., recall of concrete text blocks). To better capture long-term learning effects, especially for the metacognitive prompts, a post-post-test would be helpful. For future studies, learning gains should be tested, for example, after a period of rest. Fourth, as the study was conducted as a controlled laboratory-based experiment, the duration of the participants' learning process was inherently constrained. Consequently, participants had limited opportunities to engage deeply in metacognitive processes. This temporal limitation may have been insufficient for the effects of the prompts to manifest and meaningfully influence the participants' learning process, thereby impacting their performance.

Conclusion

The purpose of this experimental study was to investigate the effect of metacognitive prompts on learning outcomes when learning from text-only and multimedia-based materials. Furthermore, the study investigated whether the effect of metacognitive prompts on student learning outcomes differs based on the type of learning materials. The results of our study do not confirm that metacognitive prompts are an effective way to support self-regulation leading to better learning outcomes. However, these findings may be due to a number of factors explored in detail in a post-hoc analysis, the results of which may guide further research in this area.

With regard to the results of both the main analysis and the post-hoc analysis, we suggest that the effect of metacognitive prompts on learning outcomes depends on various individual differences in students and their cognitive processing, which could also be influenced by the type of learning material. Therefore, educators, instructional designers and researchers should consider individual differences in learning and cognitive processing when designing and implementing metacognitive prompts in the context of multimedia learning, as their effectiveness may vary depending on the type of learning material. Further research is needed to explore the underlying mechanisms of the observed effects and to identify effective strategies to improve learning outcomes, especially for potential low achievers as suggested in this study. Regarding this, educators should seek ways to provide additional support beyond metacognitive prompts, particularly for low-achieving students, to help them develop and enhance their SRL skills.

Author contributions

Libor Juhaňák: Funding Acquisition, Project Administration, Conceptualisation, Methodology, Data curation, Formal analysis, Visualisation, Writing – original draft preparation, Writing – review & editing. **Vojtěch Juřík**: Conceptualisation, Methodology, Formal analysis, Writing – original draft preparation, Writing – review & editing. **Nicol Dostálová**: Conceptualisation, Methodology, Data curation. **Zuzana Juříková**: Conceptualisation, Methodology, Writing – review & editing.

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