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Exploring young learners' prompted and unprompted SRL think-alouds

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ABSTRACT

Background: Think-aloud data have been identified as a valuable source for fine-grained analyzes aimed at understanding learning processes. Yet, they are rarely used to investigate how self-regulated learning (SRL) can be supported in computer-based learning environments (CBLEs). Young learners at lower secondary level have been found to be in a transitional phase of developing metacognitive SRL skills. In this phase, metacognitive prompting may encourage metacognitive SRL in CBLEs. To gain insights into supporting young learners' SRL in CBLEs, the present study used the think-aloud method and process mining to explore prompted and unprompted learners' utterances related to recall learning performance, metacognitive SRL activities, and the sequential structure of these activities.

Methods: In a between-subjects experimental design, secondary students completed a 30-min CBLE learning session while thinking aloud, with either metacognitive prompts ($n = 17$) or no prompts ($n = 16$).

Results: The fine-grained analysis of the think-aloud data showed that learning with metacognitive prompts led to higher domain-general metacognitive SRL activities. Regarding learning performance, no significant differences were found. Process models indicated that prompted learners' process structures resembled traditional SRL models more closely and that they engaged in reflection activities more often at the end of a learning sequence than the control group.

Conclusion: This study revealed fine-grained differences between prompted and unprompted metacognitive SRL activities in young learners. Think-aloud data, combined with process mining, proved to be useful for identifying metacognitive processes. This study, thereby, extends the current debate on the development of metacognitive SRL skills in young learners.

1. Exploring young learners' prompted and unprompted SRL think-alouds

With the continuous advancement of educational technologies across all levels of education, self-regulated learning (SRL) skills have emerged as fundamental for effective learning in computer-based learning environments (CBLEs; Broadbent et al., 2020). SRL skills are referred to as the ability to monitor and adapt one's learning using cognitive, motivational, metacognitive, and affective processes (Panadero, 2017). Metacognitive processes of SRL have shown particular promise in enhancing learning performance among primary and secondary school students in CBLEs (Guo, 2022; Xu et al., 2022; Zheng, 2016). However, young learners often struggle to apply these skills effectively, underscoring the need for support beginning early in their education (Dignath et al., 2008; Torrington et al., 2024).

To investigate how these young learners can be successfully supported in their metacognitive SRL activities within CBLEs, the present study focuses on metacognitive prompting, a promising form of scaffolding to support SRL (Bannert, 2009). It targets learners aged 10 to 12 in lower secondary school who are shown to possess basic SRL skills (van der Stel & Veenman, 2014; Whitebread et al., 2009), yet often do not apply them spontaneously (Flavell, 1977). To capture the nuances of these learners' SRL activities, defined here following Jansen et al. (2019) as self-regulatory behaviors enacted during learning, we employ the think-aloud method, allowing for detailed insights into real-time learning processes (Noushad et al., 2023). While think-aloud protocols have been widely used to explore learning processes, it has been rarely applied to explore SRL among young learners (Van Berk et al., 2024; Vandevelde et al., 2015). Therefore, the present study aims to examine the influence of metacognitive prompting on learning performance, metacognitive SRL activities, and the sequential structure of these activities in CBLEs, addressing a critical gap in process-oriented SRL

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research among young learners.

2. Metacognitive prompting among young learners

When learning is self-regulated, learners adjust their thoughts, feelings, and actions to the attainment of their individual goals (Zimmerman, 2000). This involves cognitive, behavioral, motivational, affective, and metacognitive processes of learning (Panadero, 2017). Within the metacognitive process of SRL, the two components of metacognitive knowledge and metacognitive skills are involved in guiding the process of SRL (Boekaerts, 1999; Veenman et al., 2006). Metacognitive knowledge is described as knowledge about learning strategies and is more task- or domain-specific (Stebner et al., 2022; Wirth et al., 2020). Metacognitive skills are seen as the ability to use metacognitive strategies and to generate feedback on their application, regarded as rather domain-general (Stebner et al., 2022).

Metacognitive skills include planning, monitoring, evaluating, and regulating cognitive processes (Flavell et al., 2002) and can be applied in all three cyclical phases of SRL (Panadero, 2017). In the forethought phase, learners analyze the task, set themselves goals, and strategically plan their learning process. In the performance phase, learners employ strategies to monitor their learning process and to perform the task. In the final phase, the reflection phase, learners evaluate their progress against a pre-defined goal and reflect and adapt their actions for future learning (Panadero, 2017).

Current research shows that metacognitive skills develop gradually over time (van der Stel & Veenman, 2010, 2014; Veenman & Spaans, 2005). Elementary forms of metacognitive skills were found in preschool years (Whitebread et al., 2009), increasing in quantity and quality during secondary school (van der Stel & Veenman, 2014) and becoming more sophisticated over time in more complex learning situations, although these activities might not always be used spontaneously (Bannert & Mengelkamp, 2013). Learners between the ages of 10 and 12 were found to be in a transitional phase in their use of metacognitive activities. At this age, they begin to develop the ability to generalize their application of metacognitive activities from using them in specific domains to using them across domains (Veenman & Spaans, 2005). While learners in this age were found to increasingly use motivational and behavioral SRL strategies, a decline was noted for metacognitive SRL strategies (Alvi & Gillies, 2021). If learners are observed struggling to appropriately apply certain learning strategies, this is referred to as a production deficiency (Flavell, 1977), a common challenge in this age group (Brod, 2020).

To address production deficiencies and foster the development of advantageous learning behaviors early on, it is critical to provide support during the initial stages of learning (Hattie et al., 1996). Various forms of SRL support have been explored, including both implicit and explicit instruction as well as embedded support within the learning environment itself (Benick et al., 2021; Brown et al., 1981). Among these, metacognitive prompting, a type of scaffolding, has emerged as a valuable type of scaffolding to activate learners' planning, monitoring, and evaluation activities (Bannert, 2009), particularly for students experiencing production deficiencies (Flavell, 1977). Metacognitive prompting explored among university students shows moderately positive effects on learning outcomes, particularly transfer performance (Bannert et al., 2015; Bannert & Mengelkamp, 2013; Sonnenberg & Bannert, 2015). Studies investigating young learners reported positive effects of metacognitive prompting on mathematical problem solving (Jacobse & Harskamp, 2009), science knowledge (Peters & Kitsantas, 2010), and equation solving (Kautzmann & Jaques, 2019), highlighting the potential of metacognitive prompting to enhance young learners' SRL activities, their recall, and transfer learning performance.

Some studies have been unable to find these effects (Engelmann & Bannert, 2021; McCarthy et al., 2018; Pieger & Bannert, 2018; van Alten et al., 2020), suggesting that timing, design, and context of the metacognitive prompts play a crucial role in CBLEs (Guo, 2022; Zheng, 2016). Using adaptive prompts in combination with feedback has shown a significant moderating effect on SRL activities (Guo, 2022). In addition, the integration of scaffolds that support SRL throughout the process of goal setting, planning, and adaptation is most effective in promoting SRL activities, showing the highest positive effects on academic performance (Zheng, 2016). These conclusions on metacognitive prompting are, however, drawn from meta-analyzes that mainly included studies with university students, as investigating SRL support in CBLEs with a focus on younger learners remains rare.

3. Exploring metacognitive prompting using the think-aloud method

To explore whether metacognitive prompting encourages young learners' metacognitive SRL activities, concurrent measures are particularly valuable (Heirweg et al., 2019; Veenman & van Cleef, 2019). Among these, the think-aloud method, where learners are instructed to verbalize their thoughts as they engage with tasks (Ericsson & Simon, 1993), stands out. It allows for direct observation of the individual and dynamic processes of SRL during learning (Veenman & van Cleef, 2019). Nonetheless, measurement reactivity is a salient concern: instructions that demand explanations or reflections while learning (verbalization level 3) can alter cognitive processing and inflate task performance (Ericsson & Simon, 1993; Fox et al., 2011; Zhang et al., 2024). Accordingly, instructions should be restricted to asking learners to report about their thoughts while learning (verbalizations 1 and 2, Ericsson & Simon, 1993), subsequently enabling the analysis of the learners' conscious processes, including metacognitive processes of SRL appearing as part of the learners' spontaneous utterances. Given that retrospective measures, such as self-reports, have been criticized for relying on memory and being susceptible to socially desirable responses (Greene & Azevedo, 2010), the think-aloud method using carefully designed instructions remains a promising approach to investigate metacognitive prompting.

Previous research has used the think-aloud method to explore metacognitive prompting to support SRL, mainly targeting university students. By analyzing students' utterances, Sonnenberg and Bannert (2015) found that university students supported by metacognitive prompts with strategic choices showed more activities in monitoring, orientation, evaluation, and planning, with the lowest frequencies in planning and goal specification. A second study by the authors (2019) using think-aloud protocols allowed investigating the stability of the effects of the same metacognitive prompts on SRL activities on a detailed level over two learning sessions. Lim et al. (2024) aligned think-aloud data with navigational logs and peripheral data. This multichannel data analysis demonstrated that personalized scaffolds that adapted to the university students' learning progress induced descriptively more SRL activities compared to the groups receiving generalized or no scaffolds. As a potential reason for the absence of an influence on learning performance, the authors name compliance with the prompts. Although the think-aloud data would have allowed for analyzing this matter, they did not include it as a criterion.

Various researchers examining SRL activities among young learners of different age groups have favored the think-aloud method: 8–9 years (Desoete, 2008), 10–11 years (Jacobse & Harskamp, 2012; Vandevelde et al., 2015), 11–12 years (Pape & Wang, 2003), 12–13 years (Veenman, 2006; Veenman et al., 2000, 2005), and 12–15 years (Azevedo et al., 2008; Schellings et al., 2013; van der Stel & Veenman, 2010, 2014). Of particular note is the study by Leites et al. (2024), who found that think-aloud measures to assess SRL were a stronger predictor of learning performance among 6th-grade students than questionnaires. However, to our knowledge, only a few studies have employed the think-aloud method to explore the influence of metacognitive support among young learners. Kramarski and Friedman (2014) investigated the effects of solicited, unsolicited, and no prompts, analyzing think-aloud protocols of metacognitive discourses with pairs of 8th graders. Azevedo et al. (2005) compared adaptive, fixed, and no scaffolding conditions and thereby found that verbal protocols are useful to provide evidence for the effectiveness of scaffolding methods on 10th-grade students' learning. These studies focused on younger learners; however, they did not provide detailed insights into learners' use of metacognitive activities in lower secondary education.

The think-aloud method has, furthermore, been the basis for sequential analysis of metacognitive SRL activities, realized through process mining. Process mining, an educational data mining technique, allows to gain insights into the representation of learners' processes and their temporal structures that are not apparent from the mere frequency data of processes alone (Sonnenberg & Bannert, 2015). Although researchers have reported on the risk of think-aloud data representing only a part of SRL activities (Hu & Gao, 2017; Vandevelde et al., 2015), process mining allows examining the influence of prompting from a cyclical perspective on SRL (Lim et al., 2022; Sonnenberg & Bannert, 2015, 2019). Among young students, only a few studies have applied the process mining approach to explore SRL activities (Heirweg et al., 2020; Rogiers et al., 2020a). Heirweg and colleagues (2020) found that upper primary school students adopted a cyclical approach of preparatory, performance, and appraisal activities during their learning process. Additionally, they found that high-achieving students demonstrated a more strategic and adaptive approach than low- and average-achieving students. Rogiers et al. (2020a) found that in the integrated strategy users' process model, metacognitive and cognitive strategies interacted strongly, with planning being the most interwoven metacognitive activity. Neither of these two studies, nor any other study known to date, has applied process mining techniques to investigate the influence of metacognitive prompting in young learners and thereby compare the sequential structure of the prompted and unprompted metacognitive SRL activities.

In understanding the development of metacognitive SRL skills among young learners, the approach of the think-aloud method combined with process mining is of particular interest for two reasons. Firstly, the influence of metacognitive prompting among learners aged 10–12 years has yet to be explored, and concurrent fine-grained analysis enables valuable insights into prompted and unprompted SRL activities in CBLEs. Secondly, by exploring the sequential structure of SRL activities, SRL can be studied as a cyclical process that unfolds over time.

4. Aim and research questions

SRL skills have been demonstrated to positively influence learning progress and learning outcomes in elementary and secondary school students (Dent & Koenka, 2016). However, in CBLEs, students often require guidance to successfully engage in SRL activities (Broadbent et al., 2020). Therefore, the present study explores whether metacognitive prompting is an adequate tool to successfully support young learners aged 10–12 years in their metacognitive SRL activities in CBLEs. The following research questions (RQ) guided the present study:

RQ1. How does metacognitive prompting support young learners' metacognitive SRL activities?
RQ2. How does metacognitive prompting influence the young learners' sequential structure of metacognitive SRL activities?
RQ3. How does metacognitive prompting encourage young learners' recall learning performance?

These research questions are addressed using concurrent think-aloud protocols and process mining, as both methods offer detailed, process-oriented insights aligned with the questions' emphasis on *how* metacognitive prompting shapes learners' SRL.

5. Method

5.1. Sample and study design

A total of 47 German-speaking 6th graders voluntarily participated in the study. Fourteen observations were removed due to technical errors. Thus, a total of 33 participants (M_{age} = 12.3 years, SD_{age} = .48 years, 54.5 % female, 0 % diverse) with complete think-aloud data were obtained. All participants' legal guardians gave active informed consent prior to data collection. Ethical approval for this study was obtained from the university's Ethics Committee.

Data were collected in an experimental study with a between-subjects design. Students in the experimental condition received metacognitive prompts ($n = 17$), while the students in the control condition did not receive metacognitive prompts ($n = 16$). Due to the size of the sample, stratified randomization was used to allocate students based on their experience in the CBLE, overall grade, English grade, and overall computer experience to the two conditions.

5.2. Computer-based learning environment

This research is embedded in a CBLE for lower secondary grade students called *Brainix*. The presented learning unit trained the basics of English as a first foreign language in the form of text writing, grammar on word families, and vocabulary on picture description and skateboarding. The learning environment is a closed environment in which the students are guided step by step through the exercises with audio files, texts, grammar entries, and illustrations. Each exercise was evaluated by the system. See Pape & Thomas (2025) for further details.

5.3. Metacognitive prompts

In total, three prompts, the *set goal prompt*, the *prioritize prompt*, the *reflect prompt*, and the calendar *goals planner* were created to promote SRL in the CBLE. The prompts are based on Zimmerman's (2000) and Winne and Hadwin's (1998) SRL model. The prompts were created using the Design Thinking approach (Plattner et al., 2009). In the pilot phase, ten 6th graders tested the prompts. Subsequently, improvements were incorporated into the software. In the present study, the prompts were presented at the beginning and the end of the learning unit. The calendar was available throughout the learning session.

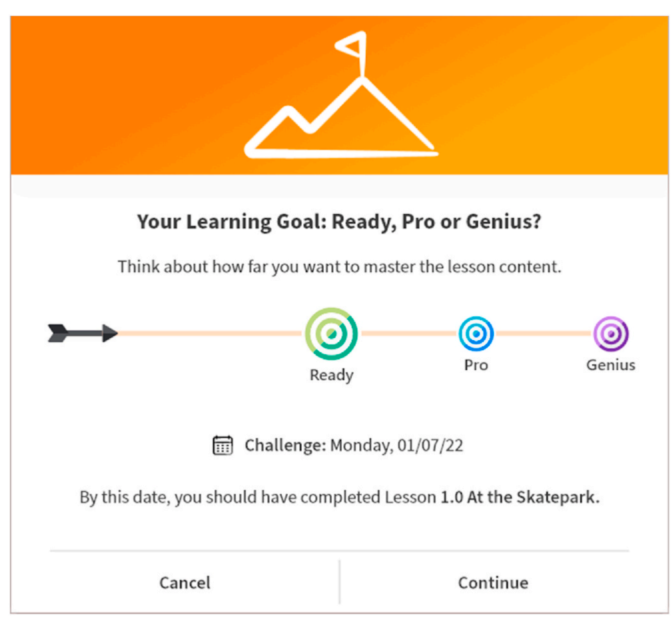

Fig. 1. The set goal prompt in the learning environment.

In the *set goal prompt* (Fig. 1), students are asked to think about the extent to which they want to master the content and thus become *challenge-ready*, the minimum level goal, *pro*, the advanced level goal, or *genius*, the highest-level goal. The *prioritize prompt* (Fig. 2) is designed to give an initial overview of the learning unit and the tasks, and to guide them in personalizing their learning goals. By dragging and dropping, students prioritize three learning contents. The *goals planner* (Fig. 3) contains action plans that are individualized to the students' personal progress, goals, and prioritization using a matching algorithm. These actions show students their upcoming tasks. It, moreover, combines time estimates for each task, calculations of incorrect answers in tasks, and then adapts task recommendations to the students' needs, allowing for adaptive and supported planning. By clicking on the items, students can modify the action plans for their learning week according to their preferences. The *reflect prompt* (Fig. 4) reports on students' individual progress. All prompts are adaptive to the students' progress and include learning goals visualized by a progress bar and goal icons.

5.4. Procedure

Participants were individually invited to an online meeting scheduled for 1.5 h (Fig. 5). Students were introduced to the procedure, the learning environment, and the method. They then went through the 30-min learning unit. At the end, the students took a 10-min recall knowledge test to assess the learners' knowledge of word families, picture description, and vocabulary.

To assess the students' spontaneous and prompted SRL activities, the think-aloud protocol analysis was used (Ericsson & Simon, 1993). Students were instructed to continuously report what was going through their minds. Each session was audio, screen, and video recorded, ensuring concurrent thinking aloud. As the think-aloud method has been criticized for incompletely capturing certain activities (Ericsson & Simon, 1993), participants received a comprehensive training of the think-aloud procedure consisting of (a) an explanation phase, in which they were shown how to think aloud, (b) a demonstration phase, in which they watched a researcher show the method, and (c) a practice phase, in which they practiced in a trial learning unit. If participants fell silent during the learning session, they were asked, "What is going through your mind?" or told to continue thinking aloud. The entire think-aloud procedure was tested in pilot sessions beforehand.

Transcriptions were performed using audio, screen, and video recordings. Following Vandevelde et al. (2015) and Annevirta and Vauras (2006), three learning environment-related, non-verbal actions from screen recordings were incorporated. One, cognitive activities (Bannert, 2007) were marked and not coded. Two, exercises were numbered in the transcription protocol to support task-level coding. Three, feedback given by the system was marked. In total, 8349 activities were coded from the approximately 30-min learning sessions.

All verbalizations were coded using a coding scheme developed from both theory and data. The coding schemes of Bannert (2007) and van der Stel and Veenman (2014) were used as a basis due to their target group and context. In addition, following Chi (2006), a thorough analysis was conducted to identify lower secondary school students' metacognitive SRL activities. This creation process was followed as previous studies had reported that metacognitive activities may be difficult to measure (Bannert & Mengelkamp, 2008; Rogiers et al., 2020b). The resulting coding scheme sensitive to young learners' metacognitive SRL activities was applied to ten think-aloud protocols, then revised and subsequently used for all participants. Two trained coders independently coded 12 % of the total number of participants. A substantial interrater reliability (Cohen's $\kappa = 0.79$) was found. The coding scheme is shown in Table 1.

5.5. Data-analysis

To investigate the first research question, coded think-aloud data were used for frequency calculations. For group comparisons, t-tests for independent variables were conducted for the frequencies of metacognitive SRL activities that were normally distributed, and Mann-Whitney U tests for those activities that did not meet this requirement. For the second research question, process models were created using the Fuzzy Miner Algorithm included in *Disco* (Günther & Rozinat, 2012). The resulting process models display both the kind and order of the performed activities as well as the paths and connections between the performed activities. They show unidirectional paths, bidirectional paths, and loops, indicating that learners engaged in SRL activities consecutively, alternately, or that the same activity was shown successively (Rogiers et al., 2020a). For the current process models, the inclusion value of 33.3 % most frequent paths (Heirweg et al., 2020) and of 100 % most frequent activities was set. Groups are compared based on absolute frequencies, starting and ending activities. To examine the third research question, the difference between the groups on the posttest results was evaluated using a Mann-Whitney U test due to the non-normally distributed data.

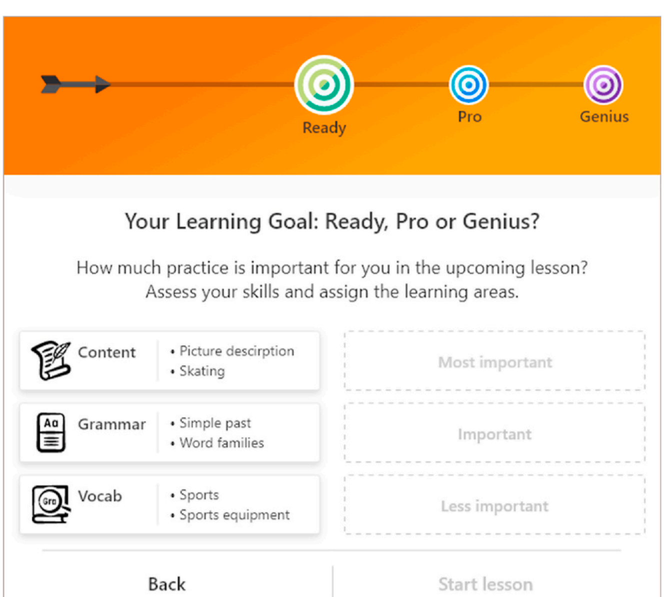

Fig. 2. The prioritize prompt in the learning environment.

6. Results

6.1. Influence on the students' metacognitive SRL activities

To answer the first research question, the frequencies of all coded metacognitive SRL activities were examined. The two groups were compared in their metacognitive SRL activities in terms of overall frequency of activities, frequencies of main categories, frequencies of subcategories, and frequencies of sublevel categories.

Regarding the overall frequency of metacognitive SRL activities, a *t*-test for independent variables showed no statistically significant difference between the control group ($M_{CG} = 263.25$; $SD_{CG} = 94.96$) and the experimental group ($M_{EG} = 243.35$; $SD_{EG} = 64.24$) with regard to metacognitive SRL activities ($t(31) = -.71$, $p = .484$). Concerning the four main categories of *orientation, planning, evaluation,* and *reflection*, descriptive analysis showed that the control group displayed more activities in all categories. No significant differences were revealed between the groups in terms of main categories of the learners' metacognitive SRL activities (*orientation*: $t(31) = -1.006$, $p = .322$; *planning*: $t(31) = -.363$, $p = .719$; *evaluation*: $U = 126.00$, $Z = -.361$, $p = .736$, *reflection*: $U = 171.00$, $Z = 1.262$, $p = .207$). Concerning the nine subcategories of metacognitive SRL activities, no statistically significant differences were detected.

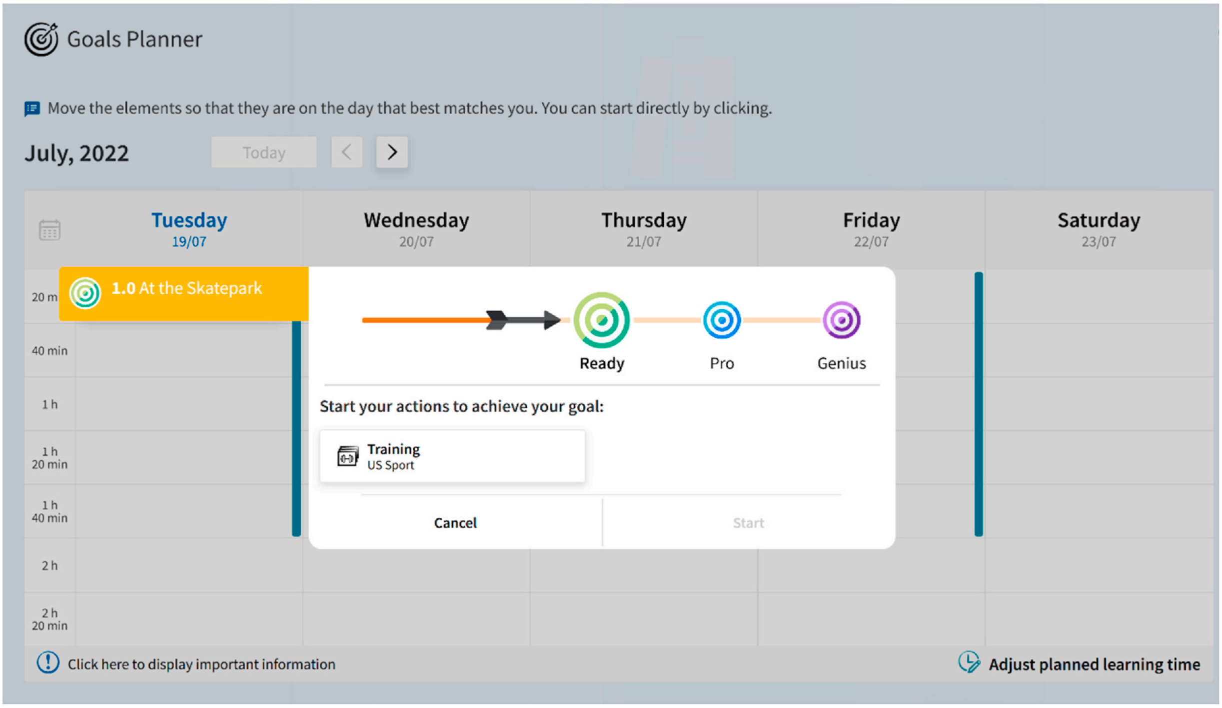

Fig. 3. The goals planner in the learning environment.

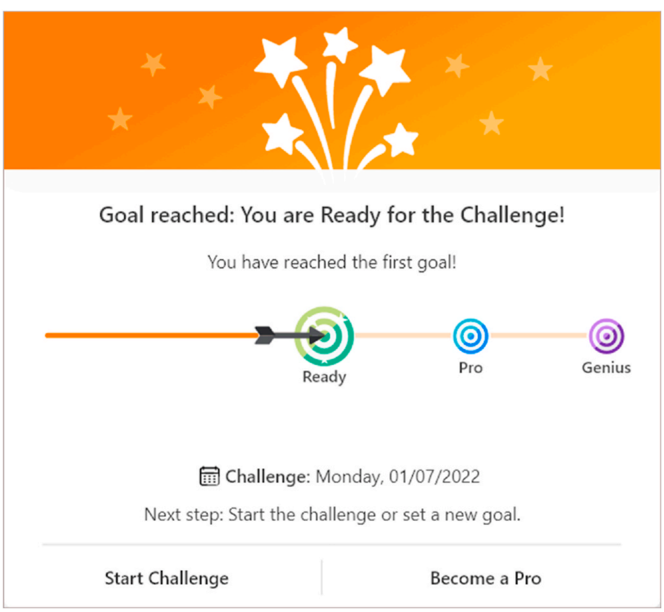

Fig. 4. The reflect prompt in the learning environment.

Concerning the sublevel categories that differentiate between *domain-general* and *task-specific* metacognitive SRL activities, results indicate that students in the experimental group engaged in *domain-general* metacognitive SRL activities more frequently than students who were not prompted (see Table 2). This difference, using a Mann-Whitney *U* test for non-normally distributed variables, was found to be significant in the two subcategories *goal specification* ($U = 23.50$, $Z = -4.28$, $p <$ .001) and *strategic planning* ($U = 47.0$, $Z = -3.58$, $p <$ .001). In the subcategory *evaluating progress*, no difference between the groups was found. Utterances within the sublevel category of *task-specific* did not differ significantly between the groups.

Using the think-aloud method to analyze the influence of metacognitive prompting also allowed to investigate the use of the metacognitive prompts. The *set goal prompt* was responded to appropriately in three out of 17 times ($M_1 = 17.65$ %). The *prioritize prompt* was appropriately responded to in 17 out of 17 times ($M_2 = 100$ %). The *reflect prompt* was appropriately reacted to in five out of 17 times ($M_3 =$ 29.4 %). In ten out of 17 times ($M_4 = 58.82$ %), the calendar was appropriately reacted to. An appropriate response to a prompt was when, one, students actually responded to the prompt by expressing their thoughts, and two, these expressions implied that students understood the prompt correctly.

In sum, metacognitive prompting was not found to be associated with metacognitive SRL activities coded on the level of main categories and subcategories. The fine-grained analysis in the sublevel category, however, revealed that the experimental group showed significantly more *domain-general* metacognitive SRL activities compared to the control group. In total, two prompts were responded to well, and two prompts were responded to in less than 30 % of the cases.

6.2. Influence on the sequential structure of the students' metacognitive SRL activities

To answer the second research question, the process models of the two groups were analyzed in terms of their starting and ending activities, the activity at the heart of the model, and self-loops. For both groups, *orientation* activities appeared to be the most frequently used activity ($n_{EG} = 277$; $n_{CG} = 270$) to begin a task. Following *orientation*, students in both groups frequently continued with *planning* activities ($n_{EG} = 587$; $n_{CG} = 572$). *Planning* emerged as the heart of the process models, serving as a transition step between *orientation* and *evaluation* (*orientation* → *planning* → *evaluation*). Self-loops appeared in both groups, mainly in the case of *orientation* ($n_{EG} = 368$; $n_{CG} = 473$) and *planning* ($n_{EG} = 637$; $n_{CG} = 669$) activities. The interlinkage between these two activities stands out in both groups, indicating that they were likely to be used in combination.

Differences between the groups could be seen in *reflection* activities. In the control group, *reflection* activities were most likely to follow *orientation* activities ($n_{CG} = 114$; Fig. 6), while in the experimental

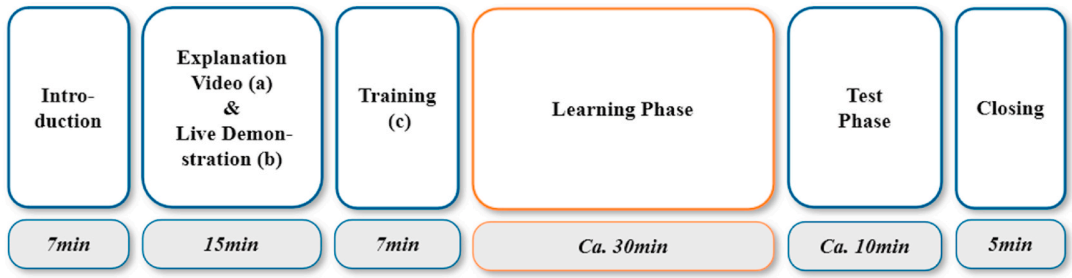

Fig. 5. Procedure of the study.

group, *reflection* activities were most frequently used as the last activity of a task ($n_{EG} = 50$; Fig. 7). An example of a prominent scenario is that students in the experimental group reflected on the learning process at the end of a task by saying "Oh, I really liked that graphic, it helped me understand the vocabulary.", while the control group frequently uttered "Okay, then I will click on 'next' to go on.", coded as a *planning* activity. The absolute frequencies displayed in *Disco* indicated that the control group engaged in *reflection* activities as a starting activity more often than as an ending activity (start frequency = 53, end frequency = 38). The experimental group, on the other hand, engaged in *reflection* activities at the end of a learning sequence more often than at the beginning (start frequency = 44, end frequency = 50).

6.3. *Influence on the students' recall learning performance*

To answer the third research question, the influence of metacognitive prompts on the students' recall learning performance was examined. Descriptive analysis showed that participants in the control group achieved an average score of 55.71 % correctness ($SD_{CG} = 16.97$), and the experimental group achieved 58.32 % correctness ($SD_{EG} = 18.59$). The statistical analysis showed, using a Mann-Whitney *U* test, no significant difference between the groups ($U = 145.50$, $Z = .343$, $p = .736$). Hence, the metacognitive prompts did not significantly support the students' recall learning performance.

7. Discussion

The present study explored how metacognitive prompting supported lower secondary school students' metacognitive SRL activities, the sequential structure of these activities, and recall learning performance in an authentic CBLE. To obtain these results, think-aloud data and process models were used to compare learners receiving metacognitive prompts to learners not receiving prompts.

7.1. *Findings on metacognitive SRL activities*

Regarding the first research question, analysis of the think-aloud data revealed that metacognitive prompting did not significantly increase the frequency of metacognitive SRL activities coded in main categories and subcategories. This result contradicts previous findings among university students (Hsu et al., 2017; Lim et al., 2022; Sonnenberg & Bannert, 2015). The think-aloud method, however, allowed for fine-grained analysis in sublevel categories, showing that learners who received metacognitive prompts were significantly more likely to utter *domain-general* metacognitive SRL activities in the subcategories *goal specification* and *strategic planning* compared to the control group.

This finding contributes to previous research discussing the domain-specificity and domain-generality of metacognitive strategies among young learners (Geurten et al., 2018; Stebner et al., 2022; van der Stel & Veenman, 2010; Wang, 2015). Learners between the ages of 10 and 12 years in their transitional phase of using domain-specific and domain-general metacognitive strategies (Veenman & Spaans, 2005) may possess knowledge of domain-general metacognitive SRL activities, yet they might not be able to effectively apply them in new situations (Bannert, 2009; Flavell, 1977). In the present study, both groups showed similar frequencies of *task-specific* metacognitive SRL activities, indicating that lower secondary school students are capable of performing metacognitive SRL activities. Yet, without prompting, these are performed within the limited scope of the task. With the help of the metacognitive prompts in the present study, students engaged in *domain-general* metacognitive SRL strategies. These results suggest that when prompted, strategies that are transferable across domains are facilitated (Braad et al., 2022; Wang, 2015).

Metacognitive prompting in the present study did not influence the general frequency of metacognitive SRL activities, which may be due to the appropriateness of using the prompts. Past research has shown that compliance with the prompts is not always given (Bannert & Mengelkamp, 2013; Braad et al., 2022; Moser et al., 2017; Pieger & Bannert, 2018). Engelmann et al. (2021) reported that less than half of the university students responded to the prompts appropriately. In the present study, using the think-aloud method allowed for the detection of such inappropriate uses of prompts. As it was shown that prompt effectiveness is largely moderated by prompt design features (Thomann & Deutscher, 2025) and that compliance is increased when students interact with the prompts (Bannert et al., 2015), it may be valuable to include more obligatory interactive elements. Those prompts, in the present study, with interactive elements required students to respond, whereas without, some did not respond and simply continued. Future research examining prompting to support SRL in CBLEs may need to include prompt compliance measurements, including research (e.g., using a co-design process like Amaefule et al., 2025) to establish the importance of interactive elements.

7.2. *Findings of metacognitive prompting on the sequential structure of metacognitive SRL activities*

Regarding the second research question, analysis indicate that the process models of the two groups are highly similar, except for *reflection* activities. The process models point to *planning* as a central metacognitive SRL activity, well-integrated between *orientation* and *evaluation* activities. This structure reinforces the view that productive metacognitive SRL is not only reflected in how often learners plan, but how systematically and integratively they enact *planning* within the sequence of the activities (Rogiers et al., 2020a). Furthermore, the prominence of self-loops in *orientation* and *planning* activities is consistent with the view of successful SRL as a cyclical learning process with repeated and recursive SRL activities, in which learners revisit multiple strategies (Rogiers et al., 2020a). Given that metacognition develops gradually and is still applied on a rudimentary level during elementary school (Veenman, 2006), these sequential structures suggest that lower secondary school students may not yet be leveraging *evaluation* and *reflection* activities to their full potential.

Reflection activities were shown to differ in the process models between the prompted and unprompted groups. In the prompted group,

Table 1
Main categories and subcategories of metacognitive SRL activities.

Main categories	Subcategories	Sublevel Categories	Description
Orientation	Activating prior knowledge		Orientation by recalling content and words, or expressing that they have not yet learned certain content.
	Searching and collecting information		Orientation by gaining an overview and searching for information to complete the task.
Planning	Goal specification		Planning by specifying goals based on the task instructions, expected outcomes, or personal preferences.
		Task-specific	Example: *"So, I should choose the right word from the options to complete the sentence, I think.", "Ah, I think I can insert different things here."*
		Domain-general	Example: *"You have to complete lesson 1.*0 *At the Skatepark by then at the latest.", "Grammar is important for me.", "I actually want to be a Pro. So, not really good, but not quite a beginner either."*
	Strategic planning		Planning by strategically describing the next steps of actions towards a solution or after a solution is achieved.
		Task-specific	Example: *"I think I will press "Next" now and then see what happens.", "So. I will read now the speech bubble again I think."*
		Domain-general	Example: *"On Fridays, I actually don't really have time.", "Should I do another 40 min? Or what if I did another hour now?"*
Evaluation	Evaluating correctness		Evaluation by questioning and commenting on completed steps regarding correctness.
	Evaluating progress		Evaluation by questioning and commenting on completed steps regarding progress.
		Task-specific	Example: *"So, okay, I think, I have now understood it.", "I think I didn't put it in the right form.", "Done".*
		Domain-general	Example: *"I have earned 48 coins.", "It says now that I have almost reached my goal, challenge ready.", "It didn't take me 1h and 40 min, but 20 min, I think".*
Reflection	Reflecting learning processes		Reflection by drawing conclusions in terms of the learning process.
	Reflecting content		Reflection by drawing conclusions in terms of learning content.
	Reflecting future learning		Reflection by drawing conclusions in terms of future learning.
Others			Not codable utterances.

Note. The category *Others* was excluded from analyzes. Sublevel categories were included following inductive coding. Examples are translated from German.

reflection tended to sit at the periphery of the model, whereas in the control group, it was interlinked with *orientation*. Prior research with university students reports stronger interlinking, particularly with *evaluation* activities, when prompted (Engelmann & Bannert, 2021). This may suggest that, for younger learners in the present study, the metacognitive prompts yielded surface-level and poorly integrated *reflection* activities, potentially leaving the control group at an advantage in this matter. However, the activity's position on the sequential structure is crucial. The prompted group used *reflection* activities more as an ending activity than a starting one, in contrast to the control group, where *reflection* was used more frequently as a starting activity. The prompted group's use of metacognitive SRL activities, thereby, is aligned with SRL models such as Zimmerman's (2000), which postulates reflection as the last phase in the recursive SRL process and Winne and Hadwin's (1998) phase of metacognitively adapting learning activities. While process models are valuable to identify sequential patterns in SRL activities, they tend to simplify causal interpretations of the interlinkages. Further research is needed to investigate clear cut-off values for the inclusion of paths and activities to allow for precise conclusions and comparisons across studies. Comparisons between high- and low-achievers with high sample sizes offer a promising avenue for future research and may help establish empirically grounded cut-off values and interpretations.

7.3. Findings on recall learning performance

Investigating the third research question, the results showed no significant differences between the prompted and unprompted learners in terms of recall learning performance. Azevedo et al. (2005), who found effects of adaptive scaffolding on recall performance, included support not only for metacognitive activities, but also for cognitive strategies. Kramarski et al. (2013), however, who tested the effects of IMPROVE and WWWH questions considered more in the metacognitive field, found positive effects of SRL support on transfer tasks, but not on routine tasks. The findings in the present study may thus suggest that the kind of strategies offered by the prompts is crucial in influencing the type of learning performance.

Despite the absence of between-group differences in recall performance, it would be premature to conclude that the metacognitive prompts were ineffective. Rather, consistent with calls for constructive scepticism about short, one-off interventions (Moreau, 2022), it is plausible that the briefness of the manipulation was insufficient to yield measurable short-term gains in learning outcomes, particularly given that SRL skills typically consolidate over longer periods of practice (Wong et al., 2021). Moreover, prior research indicates that the benefits of metacognitive interventions may emerge after a delay (Eberhart et al., 2025) or primarily in transfer rather than in recall learning measures (Engelmann et al., 2021). Consistent with this interpretation, our process-tracing results from the think-aloud protocols and the process mining indicate that SRL support can improve SRL and SRL-related factors (e.g., self-efficacy in Eberhart et al., 2025), thus enhancing mechanisms that may precede and scaffold later learning gains. Taken together, these considerations underscore the value of analyzing process alongside product data when evaluating the influence of metacognitive prompting, especially under brief exposure.

7.4. Limitations and future research

The present study has some clear limitations that should be addressed in future research. One limitation is the number of participants. Due to technical issues, only data from 33 participants could be used for analysis. However, given the effort involved in collecting and analyzing data with young learners and the reasonably large number of learners' coded metacognitive SRL activities, the present study provides a foundation for future studies with this age group. Regarding current developments in artificial intelligence (AI) in data analysis, future

Table 2
Results of domain-general and task-specific metacognitive SRL activities.

SRL activities	Reference	EG: With Prompts (n = 17)		CG: Without Prompts (n = 16)				
		M	*SD*	*M*	*SD*	*t/U*	*df/Z*	*p*
Planning								
Goal specification	Domain-general	2.83	2.43	0.19	0.40	23.5	−4.28	<.001
	Task-specific	47.56	15.77	47.38	20.16	122.0	−.51	.631
Strategic planning	Domain-general	2.33	2.66	0.13	0.34	47.0	−3.58	<.001
	Task-specific[a]	54.17	24.37	62.63	31.82	1.010	31	.320
Evaluation								
Evaluating progress	Domain-general	1.94	1.70	1.19	1.28	108.0	−1.04	.326
	Task-specific	14.50	7.70	12.94	5.94	118.0	−.65	.533

Note. [a]*Task-specific strategic planning* normally distributed, *t*-test for independent variables reported.

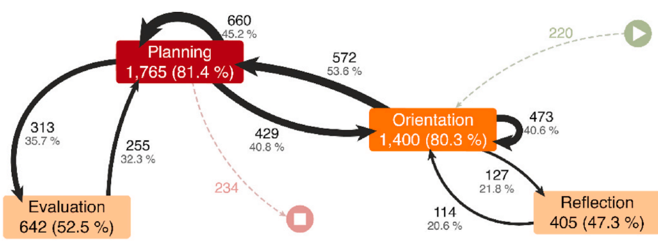

Fig. 6. Process model of the control group's unprompted metacognitive SRL activities.

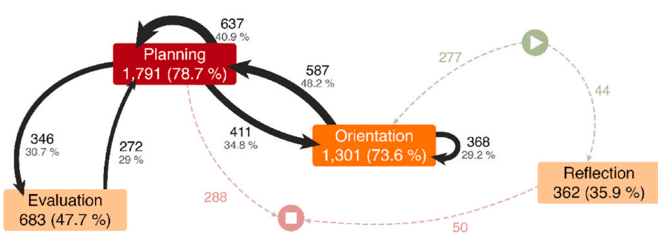

Fig. 7. Process model of the experimental group's prompted metacognitive SRL activities.

studies can apply AI classifiers such as the one put forward by Wang and Lin (2023) and Zhang et al. (2024) to automatically code SRL activities from think-aloud protocols. This may eventually allow think-aloud data to be leveraged for personalized real-time prompting (Azevedo et al., 2022).

Moreover, the specific context of the learning environment, learning materials, and metacognitive prompting limits the generalizability of the present findings. Firstly, although findings regarding *task-specific* and *domain-general* metacognitive SRL activities are consistent with previous research investigating the development of metacognitive strategies (Geurten et al., 2018; van der Stel & Veenman, 2014), future studies should examine whether these inductively identified sublevel categories can be found in other learning contexts. Secondly, the present process models only descriptively compare the groups, requiring the development of standards to enhance the generalizability of the sequential findings (Rogiers et al., 2020a; Sonnenberg & Bannert, 2019). To move away from exploratory research, confirmatory analysis testing learning patterns can be used to facilitate a better validity of applied analytical approaches (Sonnenberg & Bannert, 2019).

Future research investigating young learners' prompted and unprompted SRL activities may benefit from using think-aloud data alongside other data collection approaches. Given the young age of the participants and associated challenges to code incomplete sentences, the think-aloud data were complemented by video and screen recordings that captured the learners' interactions in the CBLE. In future research, it may be valuable to combine think-aloud data with trace-based methods as suggested by Fan et al. (2023) and van Berk et al. (2024) to reduce transcription effort.

At the same time, concurrent think-aloud procedures measuring metacognitive activities have been demonstrated to be susceptible to reactivity effects. Although the extent of such reactivity requires further empirical analysis (Yang & Luo, 2025), prior research indicates that think-alouds can alter metacognitive monitoring and regulation (Double & Birney, 2019), thereby possibly functioning as a form of SRL support for learners. Another line of research work shows, however, that verbalizing thoughts during task engagement may also impose additional extraneous cognitive load, particularly for young learners in CBLEs (Bannert, 2002; Hu & Gao, 2017). Incorporating a silent control condition to control processes to possibly mediate learning performance, as demonstrated by Fox et al. (2011), can strengthen the interpretability of the results.

8. Conclusion

The present study aimed to investigate whether metacognitive prompts, including goal setting, strategic planning, and progress evaluation, would promote SRL and learning performance in young learners in an authentic CBLE. The findings in the present study showed that it is not only the quantity of SRL activities that is important. The think-aloud data allowed fine-grained analysis demonstrating that metacognitive prompting induced higher domain-general metacognitive SRL activities in goal setting and strategic planning in young learners. Furthermore, the appropriateness of the use of the metacognitive prompts was evaluated, which provided insights to some extent into why there might have been no influence on recall learning performance. Interactive elements in metacognitive prompts that require young learners to respond appropriately seem beneficial. Using think-aloud data, furthermore, enabled process mining, finding that the sequential structure of the prompted learners' metacognitive SRL activities was more like traditional SRL models, and reflection activities differed from those of the unprompted learners. To further advance research on the development of self-regulation in young learners, using the think-aloud method is valuable to investigate metacognitive prompting and can be enhanced by AI classifiers to the learners' utterances, confirmatory analyzes for an improved generalizability of process models, and trace data to map CBLE interactions with learners' utterances.

CRediT authorship contribution statement

Rebecca Pape: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Joachim Thomas:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declarations of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.learninstruc.2025.102294.

Data availability

Data will be made available on request.

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