Supporting Young Learners' Self-Regulated Learning in Computer-Based Learning Environments: The Effects of Adaptive Metacognitive Prompting

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Abstract

Background. Self-regulated learning (SRL) has been identified as fundamental for learning in computer-based learning environments (CBLEs) and lifelong learning. One way to effectively support SRL in CBLEs was shown to be metacognitive prompting, a form of support which aims at activating strategies that are not used spontaneously. Young learners in lower secondary schools were found to possess basic forms of metacognitive SRL skills, however, in CBLEs, they were observed to experience difficulties in using them.

Aim and Method. To gain in-depth insights into the effects of metacognitive prompting in young learners, in the research in the present thesis, two empirical studies were conducted to explore young learners' prompted and unprompted SRL activities and the relation to recall and transfer learning performance. In the first study, prompted (n = 17) and unprompted (n = 16) 6th grade students were compared in their SRL activities by means of the think-aloud method during a 30-minutes learning session in the CBLE. Furthermore, process mining to analyze the sequential structure of the SRL activities and a recall knowledge test to assess learning performance were used. In the second study, 6th grade students received metacognitive prompts (n = 38) or no prompts (n = 34) to investigate their metacognitive SRL activities using self-reports and their online learning behavior during a three weeks learning period using trace data. Also, their recall and transfer learning performance was measured.

Results. The results show that learning with metacognitive prompts, in the first study, lead to higher domain-general metacognitive SRL activities, and in the second study, to higher self-reported metacognitive SRL activities. The prompts did not yield significant differences in learning performance. However, in the second study, prior performance level was identified as a significant moderator influencing the interaction between the prompts and transfer learning performance.

Conclusion. In the present research, adaptive metacognitive prompting was shown to be a promising tool to support young learners in their metacognitive SRL activities in an authentic CBLE. Future research is needed to more precisely understand young learners' needs for adaptive SRL support in CBLEs, focusing particularly on low achieving young learners. The present research highlights the developmental perspective of SRL in metacognitive prompting for young learners and draws conclusions in terms of prompt compliance and prompt design. Future directions within adaptivity in CBLEs and SRL support are discussed.

1. Introduction

„Perhaps our most important quality as humans is our capability to self-regulate. It has provided us with an adaptive edge that enabled our ancestors to survive and even flourish when changing conditions led other species to extinction. Our regulatory skill or lack thereof is the source of our perception of personal agency that lies at the core of our sense of self." - Zimmerman (2000, p.13)

The ability to regulate one's learning process, known as Self-Regulated Learning (SRL; Zimmerman, 2000), has been defined as an essential 21st-century skill that enables productive lifelong learning (European Union, 2019). With the increased use of computer-based learning environments (CBLE) in the educational sector due to technological advances and the Covid-19 pandemic (OECD, 2016), the need for SRL is more pronounced. CBLEs offer more personalized and non-linear ways of learning (Devolder et al., 2012) and thereby require learners to steer their learning, navigating and structuring their learning process by themselves (Winters et al., 2008).

SRL is seen as an extraordinary umbrella which subsumes cognitive, affective, motivational and metacognitive processes, active in different phases of the learning process to attain a certain goal (Azevedo et al., 2012; 2022, Panadero, 2017). It has been shown to positively influence academic performance (Broadbent & Poon, 2015; Xu et al., 2023), taking on an important role from early age on. Basic forms of skills to metacognitively self-regulate can be found in the age of preschool (Whitebread et al., 2009), and were shown to become more sophisticated during primary and secondary school (Perry et al., 2018; van der Stel & Veenman, 2014). However, many learners in secondary school were found to experience difficulties to self-regulate their learning spontaneously (Askell-Williams et al., 2012; Lawson et al., 2019), intensifying the issue for digital learning (Azevedo & Feyzi-Behnagh, 2011).

With the aim to overcome the difficulty of self-regulating one's learning in CBLEs, previous research has identified prompting to be a valuable way to enhance learners' SRL activities (Azevedo et al., 2004; Sonnenberg & Bannert, 2016, 2019) as well as learning performance (Bannert et al., 2015; Guo, 2022; Zheng, 2016). Seen as a kind of scaffolding, prompts can be embedded into CBLEs in form of hints or suggestions to activate SRL strategies that are not applied spontaneously by the learners (Bannert, 2009). While a vast amount of research has been conducted with university students (Guo, 2022), it remains to be investigated how prompts can be designed and integrated into authentic CBLEs for young learners to encourage them to engage in SRL activities in digital learning.

The present research in this thesis, therefore, aims to investigate whether adaptive metacognitive prompting can successfully support young learners in lower secondary school in their metacognitive SRL and learning performance within an authentic CBLE. The following sections first introduce the theoretical underpinnings of this dissertation project, second, present the two empirical studies conducted and third, discuss the overall findings of this research in terms of theoretical, methodological, and practical implications.

2. Self-Regulated Learning

A learner's self-regulation consists of a series of consecutive, cyclical activities whereby learners adjust their thoughts, feelings and actions to the attainment of their individual goals (Zimmerman, 2000). Self-Regulated Learning developed with the advent of constructivist learning theories following the idea that learners should be responsible for their own learning and be active participants (Zimmerman, 2000, Dignath & Büttner, 2008). Over the years, different SRL models have been developed including Zimmerman's (2000) social cognitive Cyclical Phases Model of SRL and Winne and Hadwin's (1998) COPES Model which form the basis of this research. This chapter introduces the theoretical basis of SRL and metacognition and describes the development of metacognitive SRL from childhood to young adulthood. While SRL and metacognition are frequently investigated among university students (Theobald et al., 2021), this research focuses on young learners' metacognitive SRL.

2.1 Theoretical Framework of SRL

A considerable number of other SRL models have been developed over time, defining the process of self-regulation through three cyclical phases: the forethought, performance, and appraisal phase (Panadero, 2017; Puustinen & Pulkkinen, 2001). Within these phases, depending on the underlying SRL model, several processes have been defined to constitute SRL. The Dual Processing Model (Boekaerts, 1996, 2011), the Self-Regulated Learning Model (Pintrich, 2000), the Metacognitive and Affective Model of SRL (Efklides, 2011), and the Socially Shared Regulated Learning Model (Hadwin et al., 2011; Järvelä & Hadwin, 2013) have all received substantial attention in the field of education. When considering models that focus on metacognition in the context of young learners, two stand out as particularly noteworthy.

Firstly, Zimmerman's (2000) Cyclical Phases Model of SRL, which has been found to be a useful framework when providing explanations on SRL in learning environments for younger learners (Moos & Ringdal, 2012; Panadero, 2017). This model's forethought phase is described as paving the way to act, including a series of processes in which learners analyze their tasks and activate self-motivational beliefs. The process of task analysis is specified to contain two micro-level processes: setting goals and strategically planning tasks and appropriate strategies. For Zimmerman (2000), these processes are informed by self-motivational beliefs including self-efficacy and outcome expectations which play a pivotal role in the phase of initiating and sustaining the efforts towards a goal. According to the model, the performance phase includes the processes of self-instruction and self-observation during the performance itself. These processes are described as requiring continuous adaptation when learners' competencies grow or task demands change. Modification or replacement of initial strategies is then needed. The last phase defined in the model, the self-reflection phase, is begun after having engaged in a learning activity, and can be described with two self-reflective processes, self-judgement and self-reactions. Learners reflect on their learning with regard to pre-defined goals and standards, and use these evaluations to adapt their cognitive, metacognitive, affective, and motivational processes of SRL for the next learning cycle (Zimmerman, 2000).

Secondly, Winne and Hadwin's (1998) COPES Model is considered important for this research due to its metacognitive focus. It defines SRL through four stages: task definition, goal setting and planning, enactment, and adaptation. For each stage, the authors defined micro-level processes of SRL. In the task definition stage, learners gain an understanding of the task, possible constraints and resources. In the second stage, learners select or define goals and a study plan to achieve these goals. In the third stage, learners enact the tactics that were developed before. Subsequently, in the fourth stage, learners reflect and thereby change cognitive structures to develop tactics for future study tasks and self-regulatory processes. Five facets have been defined to be present in all four stages: conditions, describing factors that can affect the engagement in tasks; operations, consisting of tactics and strategies; products, namely, internal cognitive conditions created by operations; evaluations, describing the feedback provided internally or externally; and standards, indicating criteria on the basis of which products are being monitored. By modelling self-regulation in four phases and five facets, Winne and Hadwin (1998) describe a cognitive architecture that is used or generated by learners during learning.

2.2 Metacognition in SRL

Metacognitive processes are, according to Azevedo et al. (2012, 2022), one out of four processes of self-regulation. Next to cognitive, affective, and motivational processes, metacognitive processes are involved in all phases of SRL (Panadero, 2017), constituting the central component in SRL to regulate one’s behavior towards a desired state (Winne & Hadwin, 1998).

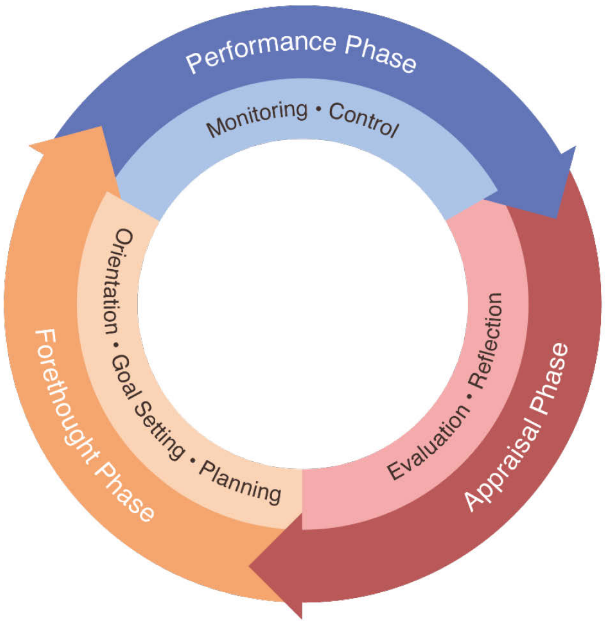
Metacognition is defined as thinking about one's own thoughts for the purpose of regulating one's own cognition (Flavell, 1979). Two components of metacognition, metacognitive knowledge and metacognitive skills, can direct the process of SRL (Veenman et al., 2006; Boekarts, 1999). Metacognitive knowledge refers to declarative knowledge of interactions between persons, tasks, and strategy characteristics (Flavell, 1979). It is described as knowledge about learning strategies that influence information processing, and is considered to be task- or domain-specific (Strebner, 2022; Wirth et al., 2020). Metacognitive skills are seen as the ability to apply metacognitive strategies and to produce feedback during the learning process which is regarded as rather domain-general (Strebner, 2022).

Metacognitive skills comprise the activities of planning, monitoring, evaluating, and regulating cognitive processes (Flavell et al., 2002). In the forethought phase, metacognitive skills can be used for learners to analyze the task, set goals for themselves, and plan their learning process strategically. During the performance phase, learners employ metacognitive skills such as cognitive strategies to monitor their learning process and to perform the task. In the final phase, the reflection phase, learners evaluate their progress in comparison to a pre-defined goal as well as reflect and adapt their actions for future learning situations (Panadero, 2017).

Based on these insights and theories of SRL and metacognition in SRL, the framework *Cyclical Framework of Metacognitive SRL in Young Learners* was created to visualize the theoretical underpinnings of the research in this thesis (Figure 1). The framework includes the three phases of self-regulation following Zimmerman's Cyclical Phases Model of SRL (2000). It furthermore integrates the crucial micro-processes of task analysis, goal setting and planning, as well as adaptation following the COPES model by Winne and Hadwin (1998). The framework created for the research in the present thesis, thus, includes in the forethought phase, the micro-level processes of orientation, goal setting and planning. In the reflection phase, the framework contains the process of evaluating and reflecting on the learning progress and learning outcomes against predefined goals. In the performance phase, learners are described to monitor and control their current execution of the task by realizing strategies to process the content and solve the task (Winne, 2019). As in this phase, cognitive strategies such as reading, elaboration, and organization strategies are usually present to monitor and control (Weinstein & Mayer, 1983, Bannert, 2007), these strategies are not included in the present research of this thesis focusing on metacognitive processes of SRL.

Figure 1.

Cyclical Framework of Metacognitive SRL in Young Learners



2.3 Development of Metacognitive SRL in Young Learners

Research in metacognition and SRL has shown that metacognitive skills develop over time (van der Stel & Veenman, 2010, 2014; Veenman & Beishuizen, 2004; Veenman & Spaans, 2005). Elementary forms of metacognitive skills and self-regulation were detected in preschool years (Whitebread et al., 2009; Montroy et al., 2016), improving in quantity and quality during elementary and secondary school (van der Stel & Veenman, 2014). A growing metacognitive awareness can be found at the end of primary school (Perry et al., 2018), also seen on the neurological level including higher levels of executive functioning, as well as a higher degree of inhibitory control (Diamond, 2016). Learners between the ages of 10 and 12 were found to be in a transition in how they apply metacognitive skills. It was observed that at this age, learners start to acquire the ability to generalize their metacognitive strategies, thus, transferring their application of strategies in a specific domain to other domains (Veenman & Spaans, 2005).

Over time, these skills become more sophisticated and are applied in more complex learning situations, however, they may not always be used spontaneously (Bannert & Mengelkamp, 2013). Secondary school learners were found not to possess the skills of a self-regulated learner (Askell-Williams et al., 2012; Lawson et al., 2019; Vosniadou, 2020), typically tending not to regulate their learning spontaneously, and face difficulties in adequately planning, monitoring, and evaluating their learning (production deficit, Flavell, 1979; Veenman et al., 2005). This absence of skills to self-regulate one's learning seems to remain underdeveloped until entering university, resulting in considerable student attrition in the first years of university learning (Vosniadou, 2020). It is, therefore, necessary to further understand how metacognitive SRL develops with young learners and investigate how it can be fostered to improve learning. These skills to metacognitively self-regulate learning processes are particularly crucial in computer-based learning, which will be elaborated in the next chapter.

3. SRL in Computer-Based Learning Environments

Developments in technology and the Covid-19 pandemic have majorly increased the use of computer-based learning in the educational sector (OECD, 2016). Digital technologies have enabled various ways to construct and validate knowledge, displacing traditional kinds of knowledge acquisition (OECD, 2021), and thereby leading to significant changes in education (van Laer & Elen, 2017). For successful learning in CBLEs, SRL has shown to be a key requirement (Greene et al., 2011). The absence of these competencies, or a lack of support within the CBLE, may precipitate a state of overwhelming stimulation for the learner. To understand the importance of SRL in CBLEs, the following sections introduce the characteristics of learning in CBLEs and provides insights into the elements of cognitive load when learning in these learning environments.

3.1 Learning in CBLEs

Learning in CBLEs is considered as technology-enhanced learning (TEL). TEL refers to the process of learning in which teachers and students employ digital tools to stimulate learning activity with the aim of reaching their teaching and learning goals (Shapiro et al., 1995). It is considered effective if involvement with the presented learning materials is supported (Shapiro et al., 1995). TEL is characterized by the possibility of a highly flexible use, in groups or alone, face-to-face, hybrid or fully online (Harley et al., 2018).

A wide range of different learning environments has been developed in the last years, starting with basic offline computers in the late 1970s, over formal and non-formal massive open online courses (MOOCs), predominantly available in higher education, to sophisticated learning environments using simulations, intelligent agents and virtual or augmented reality (Martín-Gutiérrez et al., 2017; Pataranutaporn et al., 2021). To describe applications of technology for classrooms, many different terms are used including intelligent tutoring systems, interactive multimedia learning environments, microworlds, e-learning environments, hypermedia learning environments and more. Due to the absence of precise characterizations and differentiations of the different learning environments, for the present research, the umbrella term computer-based learning environments (CBLEs) is used which refers to a "broad array of uses of technology that are aligned with the theories that support learning" (Lajoie & Naismith, 2012, p.716).

Learning in CBLEs differs from traditional classrooms in a way that more individual, open and ill-structured learning activities are available to learners (Winters et al., 2008). CBLEs traditionally present learning materials in a non-linear format, offering a wide range of different tasks in multiple representation forms that require learners to navigate and structure their learning process thoroughly (Winters et al., 2008; Azevedo et al., 2004). It allows for a more flexible use in terms of location and time (Müller & Mildenberger, 2021), it requires learners, however, to actively engage in their learning processes (Wang et al., 2013). Next to technological literacy and competency, student isolation, technological sufficiency, and technological complexity, self-regulation has been identified as one of five challenges that learners can experience when using technology to effectively achieve their learning goals (Rasheed et al., 2020). As learning in CBLEs becomes more and more integrated in all levels of education, measures to avoid cognitive overload need to be put in place.

3.2 Cognitive Load in CBLEs

Learning is seen as an inherent association with cognitive load in the working memory (Sweller, 2005). In order to learn, information needs to be incorporated into the working memory. This implies that information received from the sensory memory has to be processed and transferred to the working memory and can be subsequently stored in the long-term memory (Atikinson & Shiffrin, 1971). Baddeley (1992) stated, however, that the working memory is limited in its capacity to retain information in terms of amount and period of time. When learning experiences are created that exceed the capacity of the working memory, cognitive overload can be caused (Mayer & Moreno, 2003).

Especially in association with computer-based learning, cognitive overload needs to be considered (Sweller, 2005; Seufert, 2018). Three sources of cognitive load while learning are described by the cognitive load theory by Sweller (1988, 2005). The first source, *intrinsic cognitive load* (ICL) can be caused by the complexity of the learning materials. It is characterized by the number of elements that are interconnected, inducing higher ICL if more elements need simultaneous processing and less prior knowledge is available (Sweller, 2005). The second source, *extraneous cognitive load* (ECL) can result from how the materials are presented (Sweller & Chandler, 1994). ECL ought to be reduced by appropriate instructional design, as learners' cognitive resources should not be spent on the extraction of information from the presented learning materials but rather on the task itself (Brünken, Plass & Leutner, 2003). The third source, *germane cognitive load* (GCL), refers to the cognitive effort required to form schemas in the long-term memory (Sweller, 2005). Although debated in literature, high GCL is considered to indicate efficient learning (Kalyuga, 2011).

Self-regulation itself also requires cognitive resources during the learning process and can thereby be a source of cognitive load (Seufert, 2018). All cyclical phases of SRL can result in ICL when regulatory processes are performed, and ECL can be caused by off-task demands or processes that are not well aligned with learning goals and the learning process. Planning can pose ECL on the learner as it is carried out additional to the task (Seufert, 2018). When considered as an instructional feature within a CBLE, planning can be of high ECL, particularly when the information needed for planning, as for instance learning goals, is challenging to extract or distractive elements are presented in the feature. Also, described by Seufert (2018), strategy use and monitoring, seen as a part of the second phase, and regulation, seen as a part of the third phase in which information gathered in the monitoring phase is used to evaluate and adopt the learning process, can pose ICL and ECL on the learning process.

Providing learners with support to make use of appropriate strategies to handle these cognitive affordances during a learning process has been recommended (Seufert, 2018). With the aim to investigate how learners can be provided with support that facilitates successful learning in CBLEs and that, at the same time, enables metacognitive SRL without further imposing cognitive load, a specific form of support was created in the present research of this thesis. This will be introduced in the following section.

4. SRL Support

In order to equip learners with the skills necessary for lifelong learning, it has been shown to be essential to focus on the initial stages of learning, as these have been identified as crucial for the development of advantageous learning styles and behaviors (Hattie et al., 1996). Recent developments in technology and online learning require even young learners to use CBLEs (OECD, 2016) and thereby to apply skills to self-regulate their learning. Therefore, valuable forms of SRL support in CBLEs are explored and prior research on SRL support for young learners is identified.

4.1 Forms of SRL Support

SRL support in the form of trainings to promote SRL strategies can occur directly through implicit or explicit instruction, or indirectly through the learning environments (Benick et al., 2021). To promote SRL activities through implicit instruction, teachers and educators use SRL strategies in their instructions and thereby, exemplify them without communicating them (Brown et al., 1981). Direct and explicit instruction, furthermore, consists of a clear verbalization and discussion of the SRL strategies (Brown et al., 1981). When providing SRL support indirectly through the learning environment, the classroom is created in a way that encourages learners to apply SRL strategies (De Corte et al., 2004).

Trainings to provide learners with SRL support to engage in SRL activities were introduced and research has demonstrated that higher SRL skills lead to higher learning performance in CBLEs (Broadbent & Poon, 2015; Lee et al., 2019; Xu et al., 2023). Positive effects of SRL support in online learning environments were found in educational performance (Ceron et al., 2021; Lee et al., 2019; Wong et al., 2019; Yen et al., 2018) and mastery goals (Zheng et al., 2020). Furthermore, undesirable learning patterns were found to be attenuated (Lodge et al., 2018) and test anxiety reduced (Putwain & von der Embse, 2020).

Among the numerous studies that have investigated SRL support in CBLEs, research on pedagogical agents as scaffolders of SRL have received and are currently still receiving considerable attention from educational researchers (Dever et al., 2024). Pedagogical agents act as external co-regulators providing hints to involve learners in planning, monitoring and strategic learning processes (Azevedo et al., 2022). A prominent example is the learning environment *MetaTutor* created by Azevedo and his colleagues (2012, 2022). Their line of research shows that pedagogical agents that prompt and give feedback in the form of a tutorial dialogue, successfully enhance the learners' SRL activities and their learning performance (Azevedo et al., 2016). Prompting as a means to support SRL in CBLEs will be further examined in the next sections.

4.2 Prompting as a Means to Support SRL

Prompting as a type of scaffolding can be used to support learners engage in SRL activities of planning, monitoring and evaluating (Bannert, 2009). Aimed at overcoming production deficits, prompts are designed to activate strategies that have been acquired in its basic forms already, yet cannot be applied spontaneously (Flavell, 1977, Bannert, 2009). From a theoretical perspective, it is assumed that prompts can direct a learner's attention to think explicitly about and reflect on certain aspects of the learning process (Rosenshine et al.,1996). By rendering largely undefined cognitive processes conscious, prompts can support learners to organize their learning process in a more structured and self-regulated way (Rosenshine et al., 1996).

Different types of prompts and their effectiveness have been examined from various perspectives including positive effects on recall and transfer knowledge (Bannert et al., 2015; Sonnenberg & Bannert, 2016, 2019), in educational settings (Azevedo et al., 2004;

Bannert, 2007, 2009; Sonnenberg & Bannert, 2016) and workplaces (Siadaty et al., 2016). Other studies found restricted benefits of the implementation of prompts (Engelmann & Bannert, 2021; Pieger & Bannert, 2018), indicating that timing, design and context play a crucial role (Guo, 2022; Zheng, 2016).

While prompting has been widely used as a means to support SRL in CBLEs among university students, the present research of this thesis aims to investigate whether this promising approach to promote SRL is effective for young learners.

4.3 Prompting Young Learners' Metacognitive SRL

Prior literature reviews and meta-analyzes (Guo, 2022; Li et al., 2018; Xu et al., 2023; Zheng, 2016) show that, compared to research in higher education, prompting young learners' metacognitive activities as a means to support their SRL in CBLEs has been investigated scarcely. While Zheng (2016), Li et al. (2018) and Xu et al., (2023) report about SRL support in general, Guo (2022) focused on their meta-analysis between 1999 and 2021 on metacognitive prompting in particular, and reported that out of the 45 peer-reviewed articles included in the analysis, only eight empirical studies focused on K-12 education.

Prompts in research investigating the effects of metacognitive prompting in secondary school students can differ in the targeted activities and learning strategies, described as *content* following Wirth et al.'s (2009) framework. Teong (2003) used explicit metacognitive training in the form of guiding questions for monitoring and evaluating their actions and strategies during word-problem solving in a CBLE for 11 to 12-year-old low achievers. Jacobse and Harskamp (2009) introduced metacognitive hints in form of the so-called "task stairs procedure", including a picture of a staircase which offers metacognitive skills steps such as "I read carefully" or "I make a plan", for orientation and planning for 5th graders in a CBLE. In the work by Peters and Kitsantas (2010), a metacognitive prompting intervention for 8th graders including self-monitoring checklists, graphing and self-evaluation questions, feedback and examples were developed. Kramarski and Friedman (2014) included free accessible and regularly displayed metacognitive prompts for 8th graders based on the so-called IMPROVE model with comprehension, connection, strategy and reflection questions.

Furthermore, Adler et al. (2016) created metacognitive support through explicit environmentally oriented metacognitive guidance for 7th and 8th graders' learning in a CBLE using two main components, the knowledge about cognition and the regulation of cognition. McCarthy and colleagues (2018) integrated two metacognitive prompts for high school students which aimed at enhancing metacognitive reflection of their performance during the practice. Feyzioğlu et al., (2018) developed a technology enhanced metacognitive learning platform for 7th graders which comprised integrated metacognitive prompts. It was developed to foster the SRL activity of planning by activating prior knowledge and determining learning goals, the SRL activity of monitoring by monitoring learning progress and understanding, and the SRL activity of evaluation by reflecting on the learned concepts. Van Alten and colleagues (2020) created four video-embedded SRL prompts for a flipped classroom environment for middle school students, following Zimmerman's (2000) cyclical phases and providing a prompt at the beginning, middle, and end of the knowledge clip.

Interestingly, the three empirical studies on cognitive and metacognitive prompting in CBLEs among young learners by Hsu et al., (2017), van Dijk et al., (2016), and Kautzmann and Jaques (2019) were not included in Guo's (2022) meta-analysis. In all three studies, learners were presented with metacognitive prompts, or, as referred to in the paper by Kautzmann and Jaques (2019), metacognitive instructions. In the second study of this research, these three studies are further described and analyzed in terms of adaptivity of metacognitive prompting, regarding the aspect *condition* in Wirth and colleagues' (2009) framework. In terms of the aspect *method* of the same framework (Wirth et al., 2009), most of the studies described as K-12 studies by Guo (2022) included pre-, while-, and post prompting that supported metacognitive SRL in the form of feedforward support in the phases prior to, during the task and in the form of feedback support after the task.

Prior studies mainly focused on investigating the effects of prompting on SRL activities as well as on learning performance in terms of recall and transfer knowledge. While some of the empirical studies among young learners report positive effects of the prompts on problem-solving post measures (Teong, 2003; Jacobse & Harskamp, 2009; Peters & Kitsantas, 2010; Adler et al., 2016; Feyziougly, et al., 2018; Kautzmann & Jaques, 2019), others report about differential effects concerning the effects of prompting (van Dijk et al., 2016; McCarthy et al., 2018; van Alten et al., 2020). The absence of positive effects on learning outcomes were frequently explained with a lack of compliance with the prompts, showing that average and low ability children rarely used the prompts (van Dijk et al., 2016), or that some learners read the prompts, but do not actually apply the proposed strategies (van Alten et al., 2020). McCarthy and colleagues (2018) reported that learners' self-explanation scores even suggested detrimental effects of the created metacognitive prompts on learning outcomes indicating that an open-ended and ill-defined learning environment could be less suitable for prompting.

As a result of these differential effects of metacognitive prompting, recent research has called for more attention on person-centered rather than variable-centered approaches in SRL research (e.g. Chen et al., 2023; Dörrenbächer & Perels, 2016). It shows that, next to prompt design and content, human factors may influence the effectiveness of SRL support on SRL activities and learning outcomes (Pieger & Bannert, 2018; Wong et al., 2019) and calls for adaptivity in CBLEs to tailor the contents to the learners' needs.

4.4 Adaptivity for Metacognitive Prompting in Young Learners

Research on adaptive SRL support is developing rapidly, and in recent years, there has been a growing trend of publications focusing particularly on adaptive pedagogical agents as a means of adaptively prompting learners to engage in SRL activities (Molenaar, 2022; Khalil et al., 2024). The underlying premise of adaptive learning environments and adaptive support is that by adapting the environment to the learner's needs, learning can be better supported and enhanced (Brusilovskiy, 2012). Adaptation with the aim to accommodate the learners' individual differences can be decomposed in *adaptivity* and *adaptability*, indicating that depending on the source of control for the adaptation, the learner or the system such as a CBLE, can be adaptive, adaptable or both (Mavroudi et al., 2018). The term *adaptivity*, on the one hand, is used for systems in which data or knowledge about the learner serve as a basis for how the systems adapt (Magoulas et al., 2003). The term *adaptability*, on the other hand, is used for systems in which options for learner control and modification are provided (Magoulas et al., 2003).

From a technical perspective, *adaptability* and *adaptivity* can be enabled through Learning Analytics (LA). LA refers to the process of measuring, collecting, analyzing of and reporting on data concerning learners and their contexts, with the aim to both understand and optimize learning as well as the environments (O'Donoghue, 2023). To process all the information on learners' interactions in the adaptive learning environments, in LA, hypotheses are derived from learning theories and subsequently tested by means of data collection methods, following a top-down approach (Vahdat et al., 2015). Educational Data Mining (EDM), another movement in educational research in the field of data collection and analysis, focuses on big data from a more bottom-up point of view, extracting knowledge from the data to gain insights into learning patterns and models. In the field of learning and instruction, learning analytics in particular has proven powerful to identify real-time learning processes as well as to map effective learning processes with learning performance (Heikkinen et al., 2023; Lodge et al., 2018). Subsequently, learning patterns that require intervention can be detected and used as trigger points to initiate support (Heikkinen et al., 2023).

The creation of adaptive and adaptable CBLEs aims, by no means, at taking over control from the self-regulated learner. The learners themselves should remain the agents of their learning process as proposed by the concept of Open Learner Models (OLM, Nussbaumer et al., 2015). This framework bridges contradicting ideas of learner control and adaptation in adaptive learning environments and SRL support. Adaptive learning environments based on OLM collect the learner's information, create a learner model, and instead of guiding the learners through each step of their learning process, they present this information to the learner, giving them choice and control over their next steps. By presenting learners with additional information about their interactions within the learning environment, they can be supported in reflecting on their SRL process in terms of goal setting, planning, self-monitoring and self-evaluation (Nussbaumer et al., 2015).

One of the very few examples that investigated the effects of adaptive SRL support in CBLEs and with young learners, is the work by Molenaar and her colleagues (for an overview see Molenaar, 2022). In their work, three dashboards were created for learners to facilitate their monitoring of the learning progress, to recognize a need for control actions and to apply SRL strategies following the SRL phases. Their first results are promising, showing that adaptivity allows learning environments and SRL support to be adapted to the learners' needs and thereby positively influence transfer of learning (Molenaar et al., 2020). A key idea in their research is not only to provide support when needed, but also to fade support when it is no longer necessary. The work by Azevedo and his team (for an overview see Azevedo et al., 2022) within the hypermedia-based intelligent tutoring system called

MetaTutor has also been central to research on SRL support, SRL activities and SRL measurement. Their work, however, has focused on high school and college students.

These insights inform about adaptivity in SRL support and while this research line has shown to be valuable for learning (Azevedo & Hadwin, 2005; Molenaar, 2022), there is still much more to be explored in the field of development and measurement of SRL support (Guo, 2022; Zheng, 2016). As shown in the previous chapters, there have been some attempts to bridge the gap with research on SRL support for young learners, yet, within the field of adaptive metacognitive prompting for young learners, only few studies (e.g. Kautzman & Jaques, 2019) have been conducted so far. With a focus on authentic CBLEs, the research of the present thesis attempts to close the detected research gap: providing young leaners in lower secondary school with metacognitive prompts which adapt to the learners' current learning progress, and thereby facilitate the learners' engagement in metacognitive SRL activities when learning in an authentic CBLE.

5. The Present Research

5.1 Aim of the Present Research

Despite the necessity of adaptive SRL support in CBLEs for young learners, research has scarcely investigated the effects of adaptive metacognitive prompting in authentic CBLEs on SRL activities and learning performance in learners in lower secondary school. The previous sections introduced the theoretical framework of SRL as well as metacognition, and presented arguments on supporting young learners' SRL by means of metacognitive prompting that adapts to individual learning progress. The main objective of the research in this dissertation is to advance SRL support among young learners, offering solutions with advanced learning technologies for authentic CBLEs. Three research goals were pursued in this dissertation project:

1. The theory-based and user-centered creation of adaptive metacognitive prompts for 6^{th} grade students for an authentic CBLE.
2. The integration of these metacognitive prompts into the CBLE using modern technologies to provide adaptivity.
3. The evaluation of the effects of the adaptive metacognitive prompts.

Two research questions guided the evaluation of the effects of the adaptive metacognitive prompts:

RQ1: Do the adaptive metacognitive prompts influence the young learners' metacognitive SRL activities?

In Study 1, this research question was addressed by examining metacognitive activities of SRL with the help of the think-aloud method and process mining.

In Study 2, this research question was approached by investigating SRL skills and online learning behavior with the help of self-reports and trace data.

RQ2: Do the adaptive metacognitive prompts influence the young learners' learning performance?

In Study 1, this research question guided the analysis of effects on recall knowledge after a 30-minute learning session in the CBLE.

In Study 2, this research question directed the analysis of effects on recall and transfer knowledge after a three weeks learning unit in the CBLE.

An overview of the two studies of the present thesis can be found in Table 1.

Table 1.

Overview of the Studies in the Present Thesis.

Study	Participants	Focus	Methods	Analysis
Study 1	33 lower secondary school students (M_{age} = 12.3 years) Prompted: n = 17 Unprompted: n = 16	Fine-grained analyzes of learners' prompted and unprompted metacognitive SRL activities	**SRL activities:** Think-aloud method enhanced by video and screen recording Process Mining **Learning Performance:** Recall learning performance measure	Qualitative analysis Sequential analysis
Study 2	72 lower secondary school students (M_{age} = 10.4 years) Prompted: n = 38 Unprompted: n =34	Online learning behavior in long-term prompt use and learning session	**SRL activities:** Self-Report Questionnaire Trace Data **Learning Performance:** Recall learning performance measure Transfer learning performance measure	Quantitative Analysis Moderation Analysis

5.2 Project Context

This research project is embedded into a CBLE provided by an EdTech company. The company was not involved in the study design, data collection, analysis, or the publication of the journal articles. This chapter, firstly, introduces the CBLE as well as the test material for this research. It, secondly, presents the development of the metacognitive prompts including their theoretical underpinnings, the design thinking and visualization process and the adaptivity of the prompts.

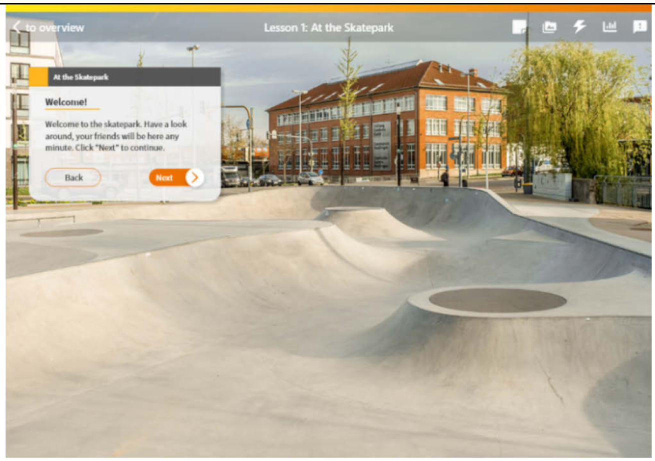
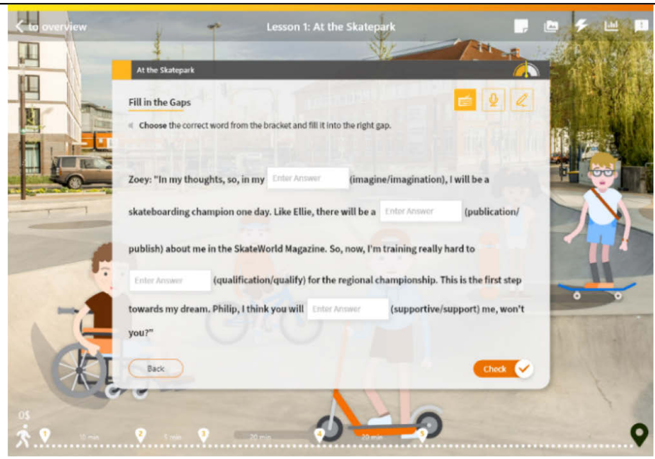
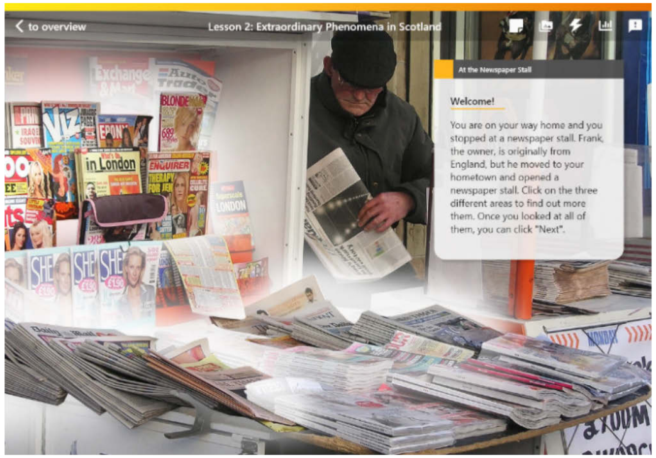
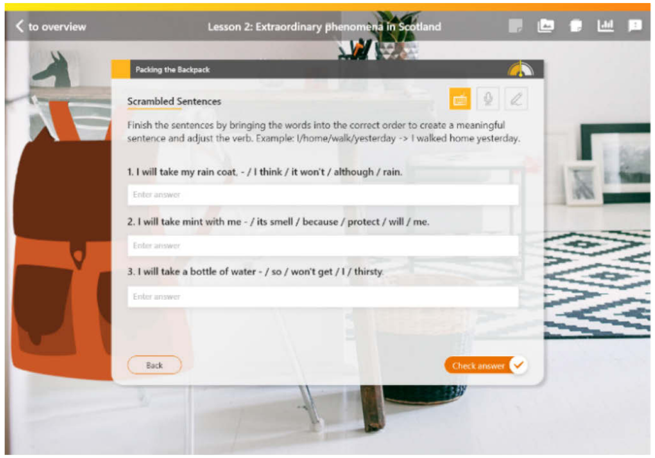
5.2.1 The Authentic CBLE Brainix and Test Material

This research is embedded in the CBLE *Brainix* provided by the German software company Brainix GmbH. *Brainix* was created as a web-based learning environment offering learning materials in the subjects Math and English as a first foreign language for 5th and 6th graders for a whole school year. The learning environment and the materials were, therefore, not created for experimental research, but for authentic classroom learning situations. The learning materials are constructed in the form of narratives that employ everyday scenarios and are integrated into the experiences of fictional characters. Derived from the German curricula, learners are presented with learning content through texts, pictures, audios, videos, as well as dialogues, and subsequently, train in exercises interacting with drag and drop, fill in the gap or open question formats. Each exercise is corrected by the system.

For the two studies conducted in this research, a shorter and a longer test lesson in *Brainix* was created. For the first study, a 30-minute lesson was created on skateboarding, including grammar on word families and vocabulary on picture description. For the second study, a lesson of about 3.5 hours was developed for students to work freely in the learning environment for three weeks. It focused primarily on competences of word families, picture description and conjunctions, embedded into a storyline around a haunted castle in Scotland. Table 2 shows examples of the learning material of both learning units.

Table 2.

Examples of the Learning Material

<table>
<tr><th>Study</th><th>Example 1: Introduction</th><th>Example 2: Exercise</th><th>Digital Access</th></tr>
<tr><td>Study 1</td><td>
</td><td>
</td><td>Link Learning Unit Material:
https://xd.adobe.com/view/6b39bf23-6a24-45ea-9524-a6f89b507f79-3e6a/?fullscreen
Link Recall Test Material:
https://xd.adobe.com/view/32571c00-7e71-4107-b6a9-34172d7083c6-6704/?fullscreen</td></tr>
<tr><td>Study 2</td><td>
</td><td>
</td><td>Link Learning Unit Material:
https://xd.adobe.com/view/220e6c8b-94c5-4af2-bc60-7c6b18b27b92-775d/?fullscreen</td></tr>
</table>

5.2.2 The Development of the Adaptive Metacognitive Prompts

Theoretical Foundation of the Prompts. To foster metacognitive SRL in an authentic CBLE, in total, three prompts and one calendar were created. The contents of the prompts are derived from research in goal setting, planning and reflection and are introduced in the following paragraphs. All prompts and the calendar are displayed in Chapter 5 and Chapter 6 as part of the empirical studies conducted in this research project.

The first and second prompt aim at facilitating goal setting. In the first prompt, the *set goal prompt*, the learners are encouraged to set a goal for the upcoming learning session by choosing between the goals *challenge-ready*, the minimum level goal, *pro*, the advanced level goal, or *genius*, the highest-level goal. In the second prompt, the *prioritize prompt,* learners are asked to prioritize the learning contents according to their learning goal differentiating between three categories. In the test learning unit for English, these categories were *grammar*, *vocabulary* and *content* including examples for each category.

The contents of the two prompts base on empirical findings on goal setting which is seen to play a vital role in the forethought phase in SRL models (Puustinen & Pulkkinen, 2001, Panadero, 2017). Research in goal setting and goal orientation shows that in contexts where the focus lies on skill acquisition, specific and challenging learning goals, instead of goals that urge to do one's best or performance goals, are conducive to learning (Kozlowski & Bell, 2006; Locke & Latham, 1990, Kanfer et al., 1994, Seijts & Latham, 2005). Furthermore, these goals should be set proximally and attainable instead of distal (Seijts & Latham, 2001). It has, therefore, been decided to include learning goals that are to be set for one learning unit. The prioritization of the learning contents displayed in the second prompt are aimed at giving the learners an overview over planned learning contents and support setting a specific learning goal.

Furthermore, a calendar is implemented to encourage planning and time management in the CBLE. It is designed to help learners plan their learning week based on their learning goals for each lesson and subject. Research shows that planning the necessary actions to achieve one's learning goals is a mediator in the goal-performance relationship (Latham & Arshoff, 2015). According to Azevedo et al. (2005), planning is a critical component of SRL and should be included in hypermedia for students to plan their actions derived from an overall learning goal. Based on these findings combined with those by Moeller et al. (2018), the calendar of the present research, called *goals planner,* includes a weekly overview with action plans that adapt to the students' progress, goals and their prioritization.

After having finished a lesson, the third prompt, the *reflection prompt,* is displayed. It shows the learners' individual learning progress with regard to their learning goal, prompting them to reflect on their learning process. The *reflection prompt* is based on findings on research on goal progress feedback. Prior research has shown that progress feedback that displays the learning progress towards a defined process goal can be beneficial in learning situations (Schunk & Rice, 1991). Harkin et al. (2016) report in their meta-analysis that interventions that provided learners with options to monitor goal progress are effective for self-regulation and suggest that monitoring bridges the gap between setting and successfully attaining a goal. The prompt uses visuals of the goals that are also integrated into the other prompts and the *goals planner.*

Design Thinking and Prompt Visualization. After creating a theoretical basis of the adaptive metacognitive prompts, the development was continued following the Design Thinking Approach (Plattner et al., 2009), a user-centered approach that guided the process of prototype development for this project. Analyzing theoretical underpinnings and empirical findings helped identifying the need and goals for the prompts, and thereby allowed the definition of central components, resulting in a first prototype. This included the conception, design and development of instructions, goals icons and prioritize icons, header of the prompts as well as moveable and clickable buttons.

The principle of visualizing learning contents has shaped the development of the prompts. Visualization of learning contents has been found to be an effective way to support reading processes, especially among young learners experiencing increased difficulties at word, sentence and text level (David & Sulaiman, 2021). When learning, visualizations can be constructed by the learners themselves, creating internal or external non-verbal representations of the text, as well as by educators as additional visual information to support the reading process (David & Sulmainen, 2021). The prompts created for the present study included a progress bar and goal icons, visualizing the continuous learning process in combination with the learning goals. Appearing in every prompt, the learners were reminded of the goals in every step in a visual way, supporting them in their monitoring of their progress.

Subsequently, this prototype was tested in a usability test with ten 6th grade students who were asked to evaluate the prompts and the calendar in a prototypical learning unit. Participating individually in an online meeting, they were asked to answer the following question “Please, describe what you can see. What you can see and what is it for?”. Some minor ambiguities in the prototype were found which were subsequently improved. Thereafter, the prompts and the calendar were integrated into the software.

Prompt Adaptivity. To allow the metacognitive prompts to adapt to the learners’ interactions in the learning environment *Brainix,* primarily two measures were included: learning progress and task correctness. The learning progress describes the leaners’ progress within a learning unit in *Brainix*, including completed tasks, individual learning paths and additional training exercises. The task correctness included the overall correctness level of a completed task and the individual competence levels derived from competence categorization and difficulty level of the tasks.

The metacognitive prompts adapted according to the current status of the learner's progress and task completion. This includes which prompt is shown, when the prompt is shown and what is displayed in terms of learning progress on the prompt. Particularly, the *goals planner* used the detailed measurement of learning progress and task correctness to not only display the current learning status, but also to recommend next action steps. These action steps were recommendations of next exercises based on the measured progress and correctness to align learner's learning status with next learning tasks. This included, for instance, when a learner progressed in the learning unit, an additional grammar entry was recommended or an exercise was suggested that allowed to train a current weakness in a certain competence. From the overview in the goals planner, learners were taken directly to the recommended next action step.

In the following two chapters, the empirical studies that investigated the effects of the adaptive metacognitive prompts on metacognitive SRL activities and learning performance are included. As they contain a detailed description of the methods that were used to gain insights into the effects of the prompts, no further elaborations are provided in this theoretical part of the dissertation.

6. Prompting in Young Learners and the Think-Aloud Method (Publication I)

Hidden Effects of Metacognitive Prompting in Young Students' SRL

Rebecca Pape and Joachim Thomas

The Version of Record of this manuscript is currently under review with *Learning and Instruction.*

Abstract

Background. Prompting has been shown beneficial to facilitate Self-Regulated Learning (SRL) in computer-based learning environments (CBLEs) and thereby improve learning performance. Despite this, there is limited evidence investigating the effects of prompting in young learners in the age of lower secondary school who have been found to be in a transitional phase in their development of metacognitive SRL activities. To gain in-depth insights into the effects of metacognitive prompting in young learners, the present study used the think-aloud method and process mining to explore prompted and unprompted learners' utterances in relation to recall learning performance, metacognitive SRL activities and the sequential structure of these activities.

Methods. In an experimental design, secondary school students received metacognitive prompts (n = 17) or no prompts (n = 16) during a 30-minute learning session in the CBLE.

Results. It was found that learning with metacognitive prompts lead to higher domain-general metacognitive SRL activities. Regarding learning performance, no significant differences were found. Process models indicated high similarities in the sequential structure, with the experimental group's model more closely resembling traditional SRL models.

Conclusion. Using think-aloud data, this study revealed fine-grained differences between prompted and unprompted learners beyond the quantity of SRL activities, thereby extending the current debate on the development of metacognitive skills in young learners.

Keywords: self-regulated learning, metacognition, think-aloud protocol, process mining, domain-generality, secondary education

Hidden Effects of Metacognitive Prompting in Young Students' SRL

With the continuous growth of emerging educational technologies that have become available for all levels of education, skills to self-regulate learning (SRL) have been identified as fundamental to ensure effective digital learning in computer-based learning environments (CBLEs) (Broadbent et al., 2020). Recent studies emphasize the importance of effectively promoting SRL in primary schools (Dignath et al., 2008; Torrington et al., 2024), showing that particularly the use of metacognitive strategies among primary and secondary school students is promising to improve learning performance in CBLEs (Guo, 2022; Xu et al., 2022; Zheng, 2016).

Metacognitive prompting has been found to effectively support metacognitive SRL activities in CBLEs (Guo, 2022; Zheng, 2016). Based on the assumption that learners aged 10 to 12 possess basic SRL skills (van der Stel & Veenman, 2014; Whitebread et al., 2009), but do not apply them spontaneously (Flavell, 1977), this study investigates whether metacognitive prompting can be an effective tool to support lower secondary school students' SRL in CBLEs.

In previous studies, the think aloud method has been found to be a valuable way to gain process-oriented insights into young students' SRL activities (Vandevelde et al., 2015) and has been used as a basis for process mining (Heirweg et al., 2020). However, using the think-aloud method to analyze of the effects of metacognitive prompting on learning performance, metacognitive SRL activities and the sequential structure of these activities among lower secondary school students in CBLEs remains understudied and is therefore the aim of the present study.

1. 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 SRL process, learning is monitored and regulated (Flavell, 1979) and the current state is evaluated against meta-level standards (Nelson & Narens, 1990). Two components of metacognition can be involved to guide the process of SRL (Boekaerts, 1999; Veenman, 2006). First, metacognitive knowledge which is described as knowledge about learning strategies and is considered to be more task- or domain-specific (Stebner et al., 2022; Wirth et al., 2020). Second, metacognitive skills which 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 they 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 skills. It was found that at this age, they begin to develop the ability to generalize their application of metacognitive strategies from using them in specific domains to using them across domains (Veenman & Spaans, 2005).

Metacognitive prompting, as a type of scaffolding to activate students' activities of planning, monitoring information, and evaluating (Bannert, 2009), aims to support students who suffer from a production deficit (Flavell, 1977). Metacognitive prompting explored among university students was found to have a significant, moderately positive effect on learning outcomes, particularly on transfer performance (Bannert & Mengelkamp, 2013; Bannert et al., 2015; Sonnenberg & Bannert, 2015). While research with university students has differentiated between recall and transfer performance, this differentiation has hardly been applied to research with young learners. Studies investigating young learners' SRL reported about positive effects of metacognitive prompting on mathematical problem solving (Jacobse & Harskamp, 2009), science knowledge assessed using short-response items and open-ended questions (Peters & Kitsantas, 2010), and first-degree equations solving (Kautzmann & Jaques, 2019). Azevedo et al. (2005) combined a matching, a labelling task and an essay to assess the adolescents' learning performance, showing significant positive effects on all three tasks. These studies demonstrate that metacognitive prompting holds promise for supporting young learners' SRL activities and thus, their recall and transfer learning performance.

Some studies have been unable to find these effects (K. 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 role (Guo, 2022; Zheng, 2016). Using adaptive prompts, and 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, to adaptation is most effective in promoting SRL activities, showing the highest positive effects on academic performance (Zheng, 2016). Also, domain-general scaffolds have shown to have a higher positive effect on academic performance than domain-specific scaffolds (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 remain rare.

2. Measuring Effects of Metacognitive Prompting

SRL research has emphasized concurrent methods as a measure for SRL, as self-reports have been repeatedly challenged due to their reliance on memory and the risk of socially desired answers (Greene & Azevedo, 2010). Particularly for young learners, concurrent measures, such as the think-aloud method, which allow observing the individual and dynamic processes of SRL during learning, are seen to stand out (Heirweg et al., 2019; Veenman & van Cleef, 2019).

The think-aloud method allows learners to verbalize their thoughts during learning without interpretation or judgement (Ericsson & Simon, 1993) and has been favored by various researchers examining SRL activities in young learners of different age groups: 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 et al., 2000; Veenman et al., 2005; Veenman, 2006), and 12–15 years (Azevedo, et al., 2008; Schellings et al., 2013; van der Stel & Veenman, 2010, 2014). In these studies, the think-aloud method was found to be a valuable tool for gaining more objective and process-oriented insights into students' SRL activities (Vandevelde et al., 2015).

The think-aloud method, however, has been criticized for incompletely capturing certain activities (Ericsson & Simon, 1993). Bannert and Mengelkamp (2008) reported that metacognitive activities are difficult to measure, as did Rogiers and colleagues (2020b), who found low to moderate correlations between task-specific self-reports and think-aloud protocols in secondary students' text learning strategies, but not for metacognitive strategies. This suggests that a coding instrument sensitive to metacognitive strategies is needed (Rogiers et al., 2020b) to successfully capture the effects of metacognitive prompting.

Previous studies have assessed the effects of prompting by means of the think-aloud method. By analyzing students’ utterances, Sonnenberg and Bannert (2015) found that students supported by metacognitive prompting showed more activities in monitoring, orientation, evaluation and planning, with lowest frequencies in planning and goal specification. The authors did not, however, discuss this finding in terms of how to improve the metacognitive prompts. A second study by the authors (2019) using think-aloud protocols allowed investigating the stability of the effects of metacognitive prompting on SRL activities on a detailed level over two learning sessions. It was revealed that the prompted activities were transferred to a subsequent learning task, however, they argue that the amount and timing of the support necessary to achieve stable effects need to be further explored.

Lim et al. (2022) used think-aloud protocols to align the data with navigational logs and peripheral data. This multichannel data analysis demonstrated that personalized scaffolds that adapted to the students’ learning progress induced descriptively more SRL activities compared to the groups receiving generalized or no scaffolds, yet, no effects on learning outcomes were detected. As a potential reason for the absence of effects, the authors name compliance to the prompts. Although the think-aloud data would have allowed to analyze this matter, they did not include it as a criterion. These few studies that used the think-aloud method to analyze effects of prompting were conducted among university students.

To our knowledge, so far, only a few studies have been conducted using the think-aloud method to investigate the effects 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 the 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 insights into learners' use of metacognitive skills in lower secondary education.

The think-aloud method has, furthermore, been the basis for sequential analyzes of metacognitive SRL activities. Although researchers have reported on the risk of think-aloud data representing only a part of SRL activities (Hu & Gao, 2017) and discussed the tip-of-the-iceberg phenomenon (Vandevelde et al., 2015), process mining allows examining the effects of prompting from a cyclical perspective on SRL (Lim et al., 2022; Sonnenberg & Bannert, 2015, 2019).

Only a few studies have applied the process mining approach to young students' 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 effects of metacognitive prompting in young learners.

In understanding the development of metacognitive SRL activities among young learners, the approach of the think-aloud method combined with process mining is of particular interest for two reasons. Firstly, the effects of metacognitive prompting among learners aged 10 to 12 years have yet to be explored and fine-grained analyzes of the think-aloud data enable 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.

3. Aim, Research Questions and Hypotheses

SRL activities can positively influence learning progress and learning outcomes in elementary and secondary school students (Dent & Koenka, 2016). Yet, especially in digital learning environments, students need support to engage in SRL activities (Broadbent et al., 2020). Metacognitive prompting has been found to be an effective way to foster metacognitive SRL strategies in CBLEs among university students (Guo, 2022; Zheng, 2016). In order to gain detailed and process-oriented insights into whether metacognitive prompting successfully supports learners aged 10 to 12 years in their recall learning performance, metacognitive SRL activities and sequential structure of these activities, in the present study, the think-aloud method and process mining were used. Three prompts and a calendar were created and integrated into the authentic CBLE *Brainix*. With the aim to extend previous SRL research in CBLEs by focusing on young learners and their development of metacognitive skills, the following research questions (RQ) guided the present study:

RQ1. What are the effects of metacognitive prompting on recall learning performance?

H_1: Previous findings have repeatedly found positive correlations between SRL and learning performance (Dent & Koenka, 2016). Given the limited research investigating the effects of metacognitive prompting on recall learning performance in young learners, the present study focuses on recall learning performance. It is hypothesized that the prompts positively influence the students' recall learning performance.

RQ2. What are the effects of metacognitive prompting on SRL activities?

H_2: Building on previous findings that reported an increase in the frequency of SRL activities when prompt support was offered (P. Engelmann & Bannert, 2019; Sonnenberg & Bannert, 2015, 2019), it is hypothesized that students supported by prompting will engage in a higher frequency of metacognitive SRL activities than students who were not supported.

RQ3. What are the effects of metacognitive prompting on the sequential structure of SRL activities?

H_3: Following the approach of Lim and colleagues (2022), this research question is raised from an exploratory perspective, so, no hypothesis was formulated. We expect, however, that planning activities will play an integral role in the process models due to the structure of the learning tasks.

4. Method

4.1 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 was obtained. All participants' legal guardians gave active informed consent prior to data collection. Students received a small gift for their participation.

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.

4.2 Computer-Based Learning Environment

This research is embedded in a CBLE for lower secondary grade students called *Brainix*. The presented learning unit trained basics of English as a first foreign language in 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.

4.3 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 a 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 at the end of the learning unit. The calendar was available throughout the learning session.

In the *set goal prompt* (Figure 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* (Figure 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* (Figure 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* (Figure 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.

Figure 1

The set goal prompt in the learning environment

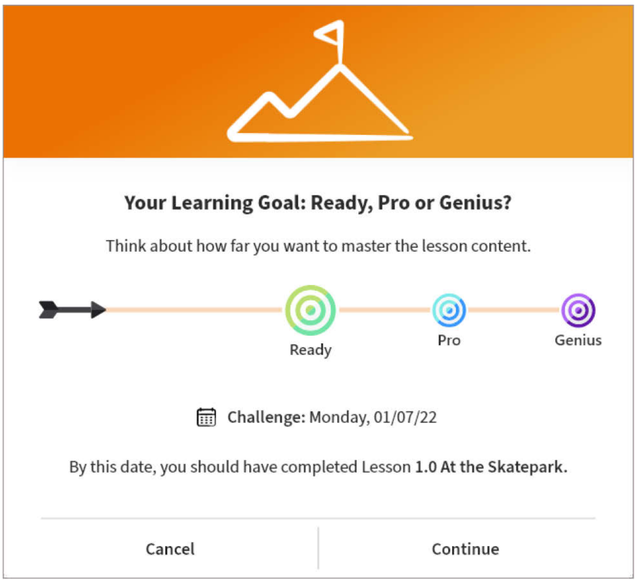


Figure 2

The prioritize prompt in the learning environment

Figure 3

The goals planner in the learning environment

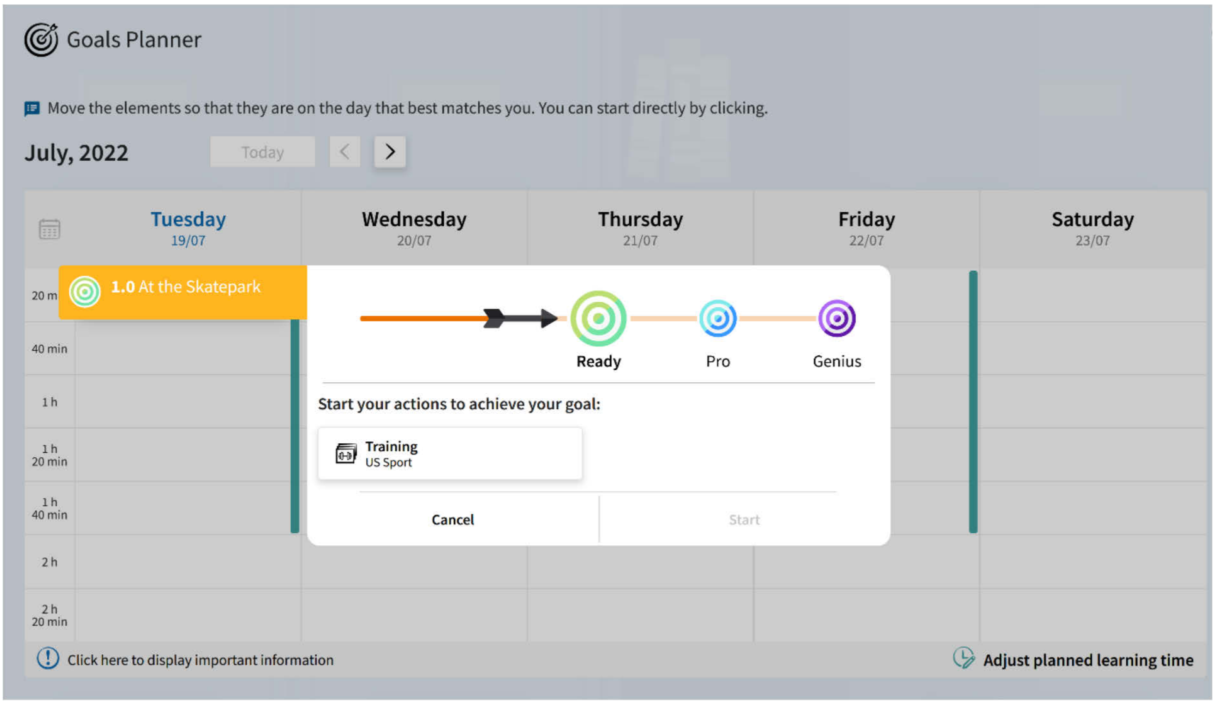
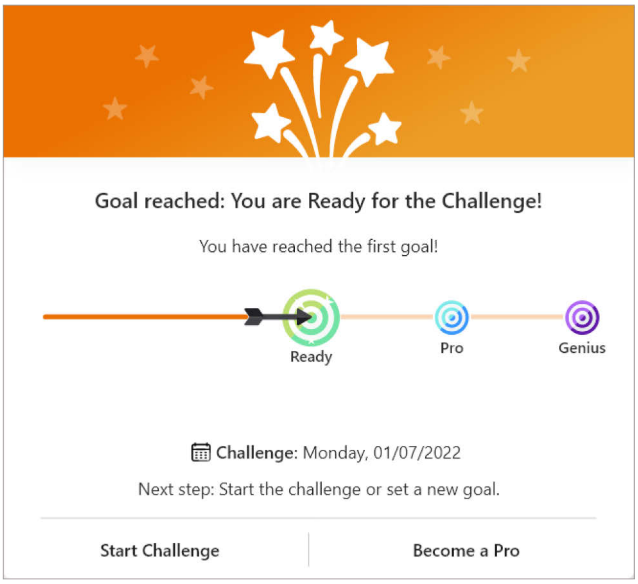


Figure 4

The reflect prompt in the learning environment



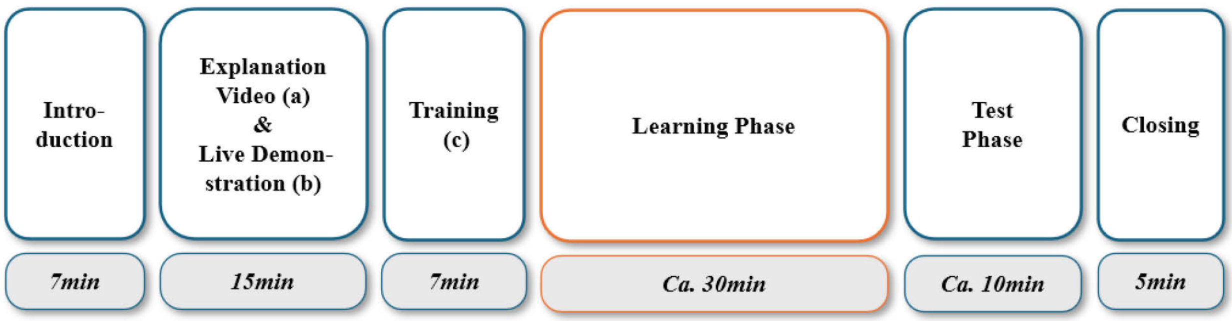
4.4 Procedure

Participants were each invited individually to an online meeting scheduled for 1.5 hours (Figure 5). Students were introduced to the procedure, the learning environment and the method. They then went through the 30-minute learning unit. At the end, the students took a ten-minute recall knowledge test to assess the learners' knowledge on 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 is going through their mind. Each session was audio, screen and video recorded ensuring concurrent thinking aloud. Participants received a 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.

Figure 5

Procedure of the Study



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-minute 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 & 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. The resulting coding scheme was applied to ten think-aloud protocols and then revised. The new coding scheme was used for all participants. Two trained coders independently coded 12% of the total amount of participants. A substantial interrater reliability (Cohen's $\kappa = 0.79$) was found. The coding scheme is shown in Table 1.

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 minutes? Or what if I did another hour now?"*
Evaluation	Evaluating correctness		Evaluation by questioning and commenting on completed steps with regard to correctness.
	Evaluating progress		Evaluation by questioning and commenting on completed steps with regard to 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 minutes, but 20 minutes I think".*
Reflection	Reflecting learning processes		Reflection by drawing conclusions in terms of 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.

4.5 Data-analysis

To examine the first research question, the difference between the groups on the posttest results were evaluated using a Mann-Whitney-U test due to the non-normally distributed data. To investigate the second research question, t-tests for independent variables were conducted for the frequencies of activities that were normally distributed and Mann-Whitney-U tests were conducted for those that did not meet this requirement.

For the third 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 learning 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.

5. Results

5.1 Effects on the students' recall learning performance

To answer the first research question, the effects of metacognitive prompts on the students' recall learning performance were examined. Descriptive analyzes showed that participants in the control group achieved an average score of 55.71% correctness (SD_{CG} = 16.97), 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 hypothesis was not confirmed.

5.2 Effects on the students' metacognitive SRL activities

To answer the second research question, the frequencies of all coded metacognitive SRL activities were calculated. 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 analyzes showed that the control group displayed more activities in all categories. Statistical analyzes revealed no significant differences 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.

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 were found. Utterances within the sublevel category *task-specific* did not differ significantly between the groups.

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.

Using the think-aloud method to analyze the effects 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, the hypothesis was partially supported. Among the metacognitive SRL activities coded in main categories and subcategories, no effects of metacognitive prompting were found. 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, although two prompts were responded to in less than 30% of the cases.

5.3 Effects on the sequential structure of the students' metacognitive SRL activities

To answer the third research question, the process models of the two groups were analyzed in terms of their starting and ending activities, the activity at heart of the model and self-loops. For both groups, *orientation* activities appeared to be the most frequently used activity to begin a task. Following *orientation*, students in both groups frequently continued with *planning* activities. *Planning* emerged as the heart of the process models, serving as a transition step between *orientation* and *evaluation*. Self-loops appeared in both groups mainly in the case of *orientation* and *planning* 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 (Figure 6), while in the experimental group, *reflection* activities were most frequently used as the last activity of a task (Figure 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).

Figure 6

Process Model of the Control Group

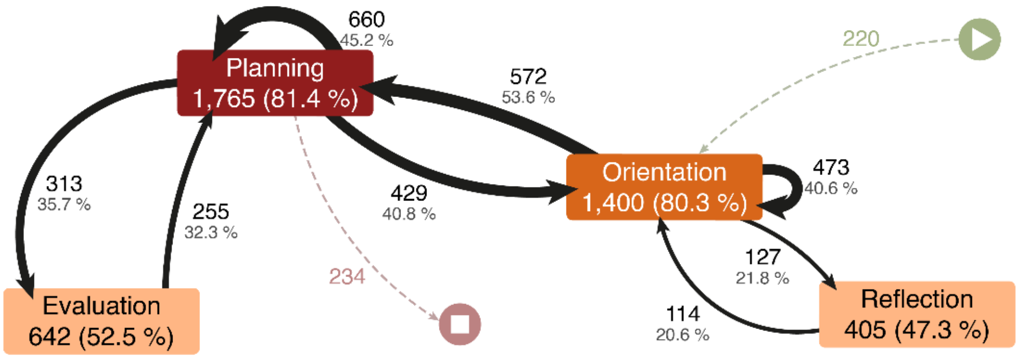
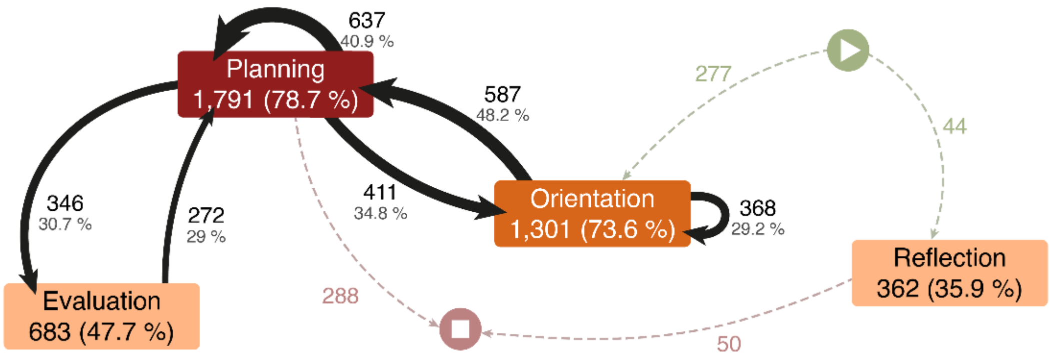


Figure 7

Process Model of the Experimental Group



6. Discussion

The present study analyzed the effects of metacognitive prompting on lower secondary school students' recall learning performance, metacognitive SRL activities, and sequential structure of these activities 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.

6.1 Findings on recall learning performance

Investigating the first research question, no effects of metacognitive prompting on recall learning performance were found. 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 are crucial in influencing the type of learning performance. Future studies with young learners need to enhance generalizability in learning performance measures by improving the classification of measures into recall and transfer learning performance, following K. Engelmann et al. (2021). However, due to the time-consuming nature of think-aloud experiments (Hu & Gao, 2017), it can be challenging to assess transfer performance in young learners and future research should explore ways how to assess this performance using short tests on transfer knowledge.

Furthermore, extraneous cognitive load may have limited the effects of the metacognitive prompting on recall learning performance. Asking young learners to think aloud throughout the learning process can add additional cognitive load (Bannert, 2002), especially when capturing metacognitive SRL processes (Hu & Gao, 2017). This may have been exacerbated by prompting which can be intrusive (Daumiller & Dresel, 2019), overwhelming (Lim et al., 2022), and require time for adaptation (Gašević et al., 2017). Scott (2008) found, however, that the think-aloud method can offer a more complete understanding of young learners' learning than questionnaires. Coding think-aloud protocols not only in terms of frequency of uttered strategies, but also in in terms of quality (van der Stel & Veenman, 2014; Veenman & van Cleef, 2019) may provide further insights into learners' effective use of metacognitive SRL activities, potential limitations due to cognitive load and their effects on recall learning performance.

6.2 Findings on metacognitive SRL activities

Regarding the second research question, analyzes 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 analyzes 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 on domain-general metacognitive SRL activities, yet, they might not be able to effectively apply it 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 supported, strategies that are transferable across domains are facilitated (Braad et al., 2022; Wang, 2015).

The absence of an overall effect of the prompting on the frequency of metacognitive SRL activities 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). K. Engelmann et al. (2021) concluded from their equivocal results that how learners used the prompts impacted whether or not the prompts were beneficial in terms of transfer performance. Using the think-aloud method in the present study allowed to detect inappropriate uses of prompts by the learners' responses. A distinguishing feature, that may have made the difference between the prompts that were responded to appropriately and those that were not, can be the interactive elements in the prompts. These required students to respond to the prompts, whereas without, some did not respond and simply continued. This finding is not in line with Guo's (2022), showing that there was no significant difference in the effect sizes whether a response to the prompts was required or not. This meta-analysis, however, mainly included research with university students. Future research needs to establish the importance of interactive elements in metacognitive prompts for secondary school students.

6.3 Findings of metacognitive prompting on the sequential structure of metacognitive SRL activities

Regarding the third research question, analyzes indicate that the process models of the two groups are highly similar, except for reflection activities. The process models demonstrated *planning* to be a central and well-integrated metacognitive SRL activity between *orientation* and *evaluation* activities. This finding is in line with Rogiers et al. (2020a) who concluded that, compared to limited strategy users who frequently planned, the integrated strategy users showed strongly interwoven planning activities. These results suggest that not frequency but integration and systematic enactment of planning activities are crucial for successful learning.

Furthermore, self-loops are highly present in both groups in the activities of *orientation* and *planning*. Rogiers et al. (2020a) see self-loops and interlinkage of activities as a sign for a cyclical learning process with repeated and recursive SRL activities, finding that limited strategy learners followed a more linear approach, while the other groups frequently switched between multiple strategies. Assuming that metacognition develops gradually and is still applied on a rudimentary level during elementary school (Veenman, 2006), these findings suggest that lower secondary school students may need to improve their engagement in *evaluation* and *reflection* activities in order for self-loops and interlinkages of these strategies to be detected in process models.

Lastly, *reflection* activities differed between the groups in two aspects: their integration into the models and their frequency of being an ending activity. The model of the prompted students showed that the activity *reflection* was most frequently not well-integrated, while the control group's model showed *reflection* to be interlinked with *orientation* activities. K. Engelmann & Bannert (2021) discovered that interlinking between activities is more common among prompted university students. This may suggest that the control group outperformed the prompted students.

In the experimental group's process model, however, *reflection* was used more frequently as an ending activity than as a starting activity, in contrast to the control group, where *reflection* was used more frequently as a starting activity. From an exploratory perspective, this could indicate that the experimental group's learning process is more similar to 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. Process models are seen as valuable for identifying sequential patterns in SRL activities, however, they also tend to simplify them making it challenging to draw precise conclusions. Further research is needed to investigate clear cut-off values for the inclusion of paths and activities to allow for comparisons across studies.

6.4 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 analyzes. However, given the effort involved in collecting and analyzing data with young learners and the reasonably large amount of learners' coded metacognitive SRL activities, the present study provides a foundation for future studies with this age group. With regard to current developments in artificial intelligence (AI) in data analyzes, future studies can apply AI classifiers such as the one put forward by Wang & Li (2023) to automatically code SRL activities from think aloud protocols.

Moreover, the specific context of learning environment, learning materials, and metacognitive prompting, limit 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 generalizability of the sequential findings (Rogiers et al., 2020; Sonnenberg & Bannert, 2019). To move away from exploratory research, confirmatory analyzes testing learning patterns can be used to facilitate a better validity of applied analytical approaches (Sonnenberg & Bannert, 2019).

Future studies investigating young learners, furthermore, need to include means of measuring SRL activities using more than one approach. As recommended by Du et al. (2023), the approach to segment and code learners’ utterances was defined prior to data collection and well explained to the transcribers and coders. Given the young age of the participants, segmentation of the think aloud protocols was challenging due to a high number of incomplete sentences. However, with the help of the video and screen recordings, the learners’ online interactions could be identified and integrated into the transcriptions. Although this was the best endeavor feasible under the circumstances of the authentic CBLE, future research should include a trace-based method as suggest by Fan et al. (2023) that allows for triangulation of different SRL data collection methods.

7. Conclusion

The aim of the present study was 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 analyzes 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 analyzed, explaining to some extent the absence of effects on recall learning performance. Interactive elements in metacognitive prompts which require young learners to respond appropriately seem beneficial. Using the think-aloud method, furthermore, enabled process mining, finding that the sequential structure of the experimental group's metacognitive SRL activities was more similar to traditional SRL models. To further advance research in the development of self-regulation in young learners, using the think-aloud method to investigate the effects of metacognitive prompting can be enhanced by AI classifiers to more effectively code the learners' utterances, confirmatory analyzes for an improved generalizability of process models and trace data to map CBLE interactions with learners' utterances.

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7. Prompting in Young Learners and the Role of Prior Performance

(Publication II)

Adaptive Metacognitive Prompting in Young Learners and the Role of Prior Performance

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Abstract

Metacognitive prompting has been shown to effectively support Self-Regulated Learning (SRL) in computer-based learning environments (CBLEs) and thereby enhance learning performance. Adaptive prompting as a way to successfully tailor prompts to the learners’needs remains understudied, especially among young learners in lower secondary education who were shown to be in a critical phase in their development of metacognitive skills. The present study investigates the effects of adaptive, metacognitive prompting on SRL activities through self-reports and trace data, and on learning performance. In a pre-post experimental design, 72 lower secondary students received prompting (n = 38) or no prompting (n = 34). Results show that metacognitive prompting led to higher self-reported metacognitive SRL activities. It did not result in significant differences in learning performance, however, prior performance level was identified as a significant moderator. Implications for SRL research with focus on low achieving learners are discussed.

Keywords: self-regulated learning, metacognitive prompting, online behavior, adaptivity, secondary education

Adaptive Metacognitive Prompting in Young Learners and the Role of Prior Performance

Learning in computer-based learning environments has attracted increasing interest from policymakers, educators, and researchers following the COVID-19 pandemic and the increasing availability of modern technologies in the educational sector. In these online environments, students are given more autonomy to create their own learning processes, yet, require them to better self-regulate their learning (SRL; Hew et al., 2023). SRL refers to consecutive, cyclical activities in which learners adjust their thoughts, feelings, and actions to attain their individual goals (Zimmerman, 2000). Previous findings in SRL research indicate that learners' SRL activities can be improved through interventions (Ceron et al., 2021; Lee et al., 2019; Wong et al., 2019; Yen et al., 2018).

Various interventions aimed at assisting learners in their SRL have demonstrated positive effects on learning performance and related learning measures. Findings suggest that SRL support can positively influence educational performance (Espinoza & Genna, 2021; Xu et al., 2023), mitigate undesirable learning patterns (Lodge et al., 2018), augment students' mastery goals (J. Zheng et al., 2020), and emphasize its impact on enhancing self-efficacy (Samuel & Warner, 2021). Moreover, Putwain & von der Embse (2020) discovered that these interventions were effective in reducing students' test anxiety. Nevertheless, it remains evident that numerous sub-processes of SRL necessitate distinct types of SRL support, appropriately timed within the educational process, and adapted to the learners' needs (Heikkinen et al., 2023). In particular, SRL support aimed at supporting younger learners in lower secondary school in computer-based learning environments (CBLEs) remains understudied.

The present research, therefore, investigates whether adaptive metacognitive prompting is an adequate tool for younger learners in lower secondary school to support their metacognitive SRL activities as well as their learning performance. The design process of the adaptive metacognitive prompts is presented in detail with the learner-centered approach including the students in lower secondary school. Process measures and product measures that were used to evaluate the influence of the adaptive metacognitive prompts are described in the following.

1. SRL Support and Learner Characteristics

Scaffolding as a way to support SRL has been investigated from various perspectives including its effects on recall and transfer knowledge (Bannert et al., 2015; Sonnenberg & Bannert, 2016, 2019), on group activities and group performance (Molenaar et al., 2011), in educational settings (Azevedo et al., 2004; Bannert, 2007, 2009; Sonnenberg & Bannert, 2016) and in workplaces (Siadaty et al., 2016a, 2016b). However, recent research has called for a focus on person-centered rather than variable-centered approaches in SRL research (e.g. Chen et al., 2023; Dörrenbächer & Perels, 2016), as findings of studies indicate that, next to design variations and the choice of SRL subprocesses, human factors moderate the effects of SRL support on SRL processes and learning performance (Pieger & Bannert, 2018; Wong et al., 2019).

Few studies have investigated how learners' individual differences influence the effectiveness of SRL support. Prior studies reveal that achievement goal orientation (Duffy & Azevedo, 2015), achievement level (Manlove et al., 2007), level of metacognition (Zhang et al., 2015), level of prior knowledge (Yeh et al., 2010), or cognitive ability (Sitzmann et al., 2009) appear to moderate the positive effects of SRL support.

Concerning SRL abilities, Dörrenbächer and Perels (2016b) found that those with moderate and motivated SRL profiles benefited most from the SRL support, while those with low and high SRL profiles did not. Concerning prior knowledge, high levels were found to positively influence both the use of SRL support (Azevedo et al., 2022; Taub et al.,

2014) and thereby impact learning performance (Bannert & Reimann, 2012; Bouchet et al., 2018; Kramarski et al., 2013). Taub and colleagues (2014) found differences between high and low prior knowledge groups in metacognitive SRL strategies, but not in cognitive SRL strategies, suggesting that prior knowledge is particularly relevant to metacognitive SRL. Kramarski and colleagues (2013) examined the effects of generic versus context-specific SRL support approaches and concluded that 7^{th}-grade students with high prior knowledge benefited less from the support than the low prior knowledge group. Concerning ability in terms of academic achievement, van Dijk et al. (2016) found that high-ability children used the prompts when presented, compared to moderate or low-ability children who rarely utilized the prompts. This finding has also been reported by other studies, such as Munshi and colleagues (2023) who found that high and low outcome achievers responded differently to hints and displayed different learning behavior.

These studies implicate that, in contrast to other studies, it is not only the features of the prompts that need to be considered when designing SRL support. Also, the learners' characteristics play a vital role indicating that certain treatments may be beneficial for different individuals (Pieger & Bannert, 2018; Snow, 1991). More rigorous investigations are needed to adapt SRL support to the learners' individual needs, balancing their individual learning prerequisites with the required learning standards.

2. Adaptive SRL Support

Recent research has proposed technological solutions that adapt instructional methods to the learner's level of expertise and create adaptive training (Wong et al., 2019). Positive impacts of incorporating adaptability and individualization into CBLEs have been observed, however, when comparing adaptive scaffolds with no or fixed scaffolds, mixed results have been found regarding their effectiveness (Li et al., 2023; Munshi et al., 2023). A key factor that influences the effectiveness of the adaptive prompts is the in-situ data on the learners' current level of knowledge, recently proposed as the foundation of effective scaffolding (Järvelä et al., 2019).

As learning needs change during the learning process, a valuable method for discovering learning processes as they occur and linking those processes to learning performance has shown to be learning analytics (Heikkinen et al., 2023; Lodge et al., 2018; Winne, 2022). By means of learning analytics models built on the four stages of data generation, tracking, analysis, and action (Heikkinen et al., 2023; Romero & Ventura, 2020), researchers and practitioners can identify learning behaviors that require intervention and define them as trigger points to provide support. However, identifying the right data as triggers for support remains a challenge.

Several studies have tested the use of different triggers to adapt their support to the needs of the students. Examples of using learning progress in a task or a sequence of tasks as a trigger for support can be found in intelligent tutoring systems (ITS) such as *Crystal Islands* (Spires et al., 2011), which implemented a tracking method to measure tasks completed and then add quizzes at certain points. Also, the learning environment *MetaTutor* (Azevedo et al., 2009) which collected data through multiple channels such as log files and eye tracking, triggered a pedagogical agent to prompt the students to engage in different learning strategies (Azevedo et al., 2022). The learning environment *Betty's Brain* incorporated analyzes of ongoing learning behavior to identify students' learning patterns and key transition points which then served as the basis for providing students with strategy scaffolds to help them develop knowledge within the learning environment (Biswas et al., 2016; Munshi et al., 2023) Finally, Molenaar and Roda's (2008) learning environment *AtgentSchool* provided 5^{th}-grade students with adaptive scaffolds based on their activities in the e-learning application, learner characteristics and students' attention focus.

In understanding how adaptive SRL support can effectively enhance learners' SRL and their learning performance in CBLEs, several studies have investigated the optimal timing for scaffolding and how to tailor content to the learners' individual progress and needs. From these findings, it appears promising to combine accurate diagnosis of learners' learning processes with adaptive scaffolds that thereby align individual learning behaviors and learning needs with appropriate SRL support. To create appropriate SRL support for young learners in particular, more research is needed to explore their current and supported SRL activities.

3. Adaptive Metacognitive Prompting in Young Learners

Previous research has shown that metacognitive skills develop gradually over time (van der Stel & Veenman, 2010, 2014; Veenman & Beishuizen, 2004; Veenman & Spaans, 2005). The development of self-regulation was shown to begin in early childhood (Whitebread et al., 2007), with elementary forms of metacognitive skills found in preschool years (Whitebread et al., 2009). As a result of maturational and age-related changes such as a higher level of executive functioning (Diamond, 2016) and a shift from an emotional and external orientation to a more cognitive and internal orientation in their thinking (Montroy et al., 2016), these skills become more sophisticated during primary school. Primary school students are, furthermore, shown to have a growing (metacognitive) awareness regarding their thinking and controlling processes (Perry et al., 2018).

Throughout secondary school, these skills increase in quantity and quality (van der Stel & Veenman, 2014). Secondary school learners, however, frequently do not spontaneously regulate their learning, struggle to adequately plan, monitor, and evaluate their learning (production deficit, Flavell, 1979; Veenman et al., 2005), and thus, lack the skills of a self-regulated learner (Askell-Williams et al., 2012; Lawson et al., 2019; Vosniadou, 2020). However, the ability to self-regulate should not be seen as an "all-or-nothing phenomenon"

(Schunk & Ertmer, 2000, p.632), but rather as an ability that can be learned depending on the developmental stage of the learner (Bronson, 2000). In the age of ten to twelve years old, in particular, metacognitive skills were found to be in a critical phase of development. Learners were found to start to apply metacognitive skills across domains, thus, developing the ability to generalize strategies that are used in specific domains to other domains (Veenman & Spaans, 2005).

Due to recent developments in technology and online learning, even young learners learn in CBLEs, and requires them to apply SRL skills also in these new learning environments (Broadbent & Poon, 2015). To address this challenge, prompting has been found to effectively support metacognitive SRL activities in CBLEs (Guo, 2022; L. Zheng, 2016). These prompts, as a type of scaffolding, can support learners in all cyclical phases of SRL (Bannert, 2009). In the forethought phase, learners can be prompted to analyze the task, set themselves goals, and strategically plan their learning process. In the performance phase, prompts can be aimed at supporting learners to employ strategies to monitor their learning process and to perform the task. In the final phase, the reflection phase, prompts can help learners evaluate their progress against a predefined goal and reflect on and adapt their actions for future learning (Panadero, 2017; Puustinen & Pulkkinen, 2001; Sonnenberg & Bannert, 2015).

Many studies analyzing the effects of adaptive metacognitive prompting in CBLEs have, however, mainly focused on university students (for an overview see Lim et al., 2022). Three of the very few studies that have explored the effects of prompting with young learners are presented here and the need for adaptivity is identified for each.

Hsu and colleagues (2017) developed cognitive and metacognitive prompts for 9th-grade students in a web-based learning environment and found that successful students engaged in metacognitive activities including monitoring and evaluating during the inquiry tasks while prompted at a significantly more frequent rate than the less successful students. Also, their engagement in metacognitive activities was found to be in distinct sequences. The prompts were, however, neither adaptive in terms of timing, nor was the content adapted to the students' needs. They concluded that crucial learning patterns of successful students were identified which can serve as a basis to design necessary support for less successful students. They called for scaffolds that are more dynamically responsive to individual learning patterns and needs.

Van Dijk et al. (2016) conducted a study with 5th and 6th graders, investigating the effects of prompts on children's inquiry process and their learning outcomes. Their results showed that high-ability students demonstrated a more effective learning process than students with average and low ability. Also, they made use of the prompts more often than average and low-ability students who were found to use the prompts in a limited way. The authors conclude that, for young learners to effectively use the prompts, domain-specific prior knowledge may be a factor influencing the ability to better understand the content of the prompts. The language and the number of prompts were piloted prior to the study, however, no adaptability was included. Their findings hint at the necessity of creating adaptive scaffolds that are sensitive to varying levels of prior knowledge among young learners.

Kautzmann and Jaques (2019) examined the impact of an animated pedagogical agent giving metacognitive instructions to 8th-grade students on metacognitive knowledge monitoring ability and learning performance. The animated pedagogical agent was highly adaptive using students' information to vary both the training content and the frequency of intervention. Information on the students' knowledge monitoring ability, domain knowledge, and problem-solving history was tracked during every step of the task, and calculated and the probability of the students' knowledge was inferred. Reflective actions provided by the agent were prompts, feedback on inappropriate metacognitive actions, and self-explanation on metacognitive actions. The results showed positive evidence that by means of an animated pedagogical agent, learning performance and metacognitive knowledge monitoring ability were improved. This approach of adaptive metacognitive instruction including checks of whether students did what they were asked to resulted not only in higher metacognitive knowledge monitoring ability indexes but also in higher task performance. This emphasizes that by using interventions with nuanced, data-driven scaffolding strategies that adapt to students' ongoing metacognitive learning processes, learning can be influenced positively.

In summary, these studies collectively suggest an important research gap in the field of SRL: the need for developing sophisticated, adaptive SRL support for young learners who are in the phase of developing metacognitive SRL skills. From the research presented, we find that SRL support for young learners be created age-appropriate and should dynamically respond to individual learner characteristics as well as their ongoing learning performance, including learning progress. This involves advanced data analytics to create personalized learning experiences, enabling scaffolds to evolve in real time based on learners' changing needs and behaviors. This direction of research holds promise for enhancing the effectiveness of SRL support, especially for young learner between ten to twelve years old who are in need of support in CBLEs in their phase of developing metacognitive SRL skills.

4. Aim, Research Questions and Hypotheses

Engaging in SRL activities can have a positive impact on learning progress and learning outcomes (Schunk & Greene, 2017). However, especially in CBLEs, students require support to successfully perform SRL activities (Broadbent & Poon, 2015). Metacognitive prompting has been found to be an effective way to promote metacognitive SRL strategies in CBLEs (Guo, 2022; L. Zheng, 2016) and has shown to be particularly beneficial when the prompts are adapted to the learner's individual needs (Kautzmann & Jaques, 2019; Lim et al., 2022). To address the identified research gap in SRL, the present study investigates whether adaptive metacognitive prompting successfully supports learners in lower secondary school in their SRL activities and their learning performance. Therefore, we propose an innovative approach involving 1) the development of adaptive metacognitive prompts, and 2) their integration into the highly adaptive and authentic learning environment *Brainix*. With the objective of extending previous SRL research in CBLEs by focusing on young learners and their development of metacognitive skills, the following research questions (RQs) guided the present study:

RQ1. Do adaptive metacognitive prompts influence students' (1a) self-reported metacognitive SRL activities and (1b) their online learning behavior?

RQ2. Do adaptive metacognitive prompts influence students' learning performance in terms of (2a) recall knowledge and (2b) transfer knowledge?

5. Method

5.1 Sample, Study Design and Procedure

A total of 106 German-speaking 6th-grade students voluntarily participated in the study. Due to illness and technical difficulties, complete data sets of a total of 72 participants (M_{age} = 10.36 years, SD_{age} = .51 years, 37.5% female) served for the analysis. A between-subject design with pre- and post-measurement was chosen for this research. All participants' legal guardians gave active informed consent prior to data collection. Students received a small gift for their participation in the study.

Students were invited to participate voluntarily in this research through their schools, including an invitation letter to their parents explaining the aims of the research and the procedure. While parents were informed about the aim to investigate the effects of an SRL intervention in a CBLE, learners were not explicitly informed on that matter, yet, were told that this research is about improving the presented CBLE.

Data were collected in an experimental study with a between-subjects design including pre- and post-measurements. Students in the experimental condition received metacognitive prompts (n = 38), while the students in the control condition did not receive any metacognitive prompts (n = 34). In order to start the intervention with near-equal prerequisites, stratified randomization was used to allocate students to the two conditions.

In total, students were invited to participate in a three-week learning phase, in which they would work independently in the CBLE, from at home as well as at school. Learning sessions were chosen freely in their duration and date by the students themselves. They used their own device or borrowed one from their school when working independently at school. Anonymized accounts were handed out prior to the data collection to each student.

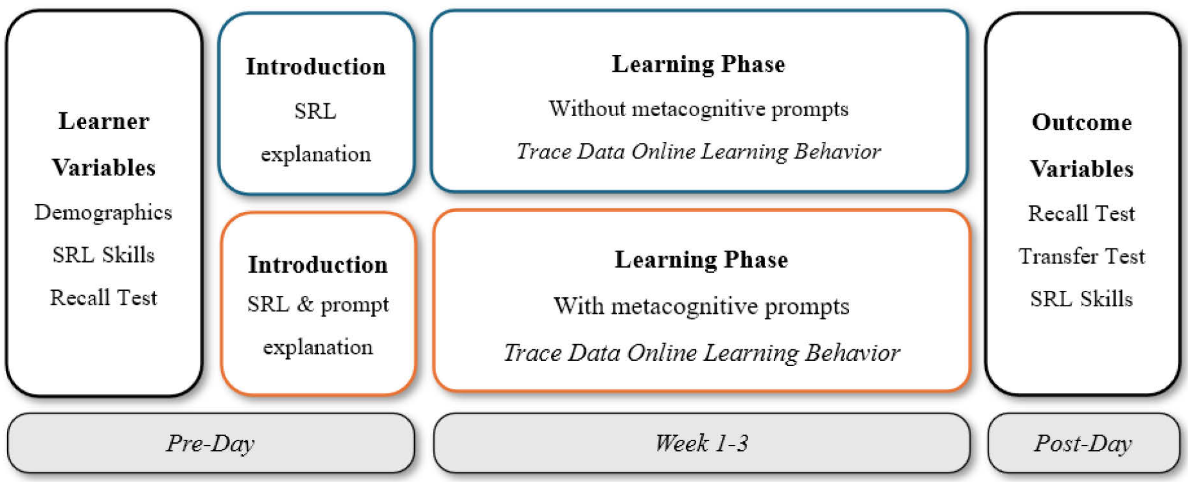
Prior to and past this three-week learning phase, in which the learners studied in the CBLE, students were invited to participate in two data collection days (see Figure 1). The timeline of this study was decided based on the recommendation by Zheng (2016), who analyzed the duration of treatment as one of four key methodological features and recommended SRL interventions to take place for two to four weeks.

On the first data collection day, the students completed a test assessing prior knowledge and a test measuring their SRL skills. Specific performance levels of the subject English were collected from all students. The ratings follow the German grading system from 1 to 6, recoded for better interpretation. The participants, moreover, received an introduction to the study procedure and were shown, following Dignath & Veenman (2021), an explanation video on SRL. The experimental group received, in addition to the SRL explanation video, an explanation of the use of the metacognitive prompts in the CBLE. After studying independently for three weeks in CBLE, students were invited to a second data collection day, the post-day, on which their performance was assessed using two tests, a recall, and a transfer test.

The structure for this research procedure was derived from previous research identifying that for SRL to be appropriately measured process and product measures are necessary (Azevedo et al., 2010; Fan et al., 2022; Molenaar et al., 2023). The measurements are thus a combination of process-oriented trace data learning behavior measures (Du et al., 2023), product-oriented SRL questionnaire (Pintrich, 1991), and learning performance measures (Bannert et al., 2015).

Figure 1.

Design and Study Procedure



5.2 Computer-Based Learning Environment and Adaptive Metacognitive Prompts

This research is embedded in a CBLE for lower secondary students called *Brainix*. It is an enclosed environment in which students are guided step-by-step through exercises with audio files, texts, grammar entries, and illustrations. Each exercise is evaluated by the system. During the study, the students worked in a learning unit estimated for 3.5 hours of study time. The learning unit trained fundamentals of text writing, grammar, and vocabulary of English as a first foreign language integrated into the learning scenario of an adventure to a haunted castle.

In total, three prompts and a calendar were created to adaptively promote SRL in the CBLE. They are based on Zimmerman's (2000) and Winne and Hadwin's (1998) model of SRL and were created using a Learner-Centered Design approach (Tsvyatkova & Storni, 2019) and the Design Thinking approach (Plattner et al., 2009). The Learner-Centered Design ensured that the design was guided by educational and learning psychological theory and adapts to learners' needs, while Design Thinking emphasizes iterative prototyping and user feedback. Learners were inherently involved in the design process to ensure the usability and effectiveness of the adaptive metacognitive prompts. With this approach, it was our goal to follow the idea of co-design and collaboration between researchers and children (Grammenos & Antona, 2018).

The initial development process was inspired by a structured four-phase user-centered Design Thinking approach. In the research phase, a literature review on goal setting, planning, and reflection in SRL support and interviews with educators informed the initial prompt design. During design exploration, early prototypes were developed based on the theoretical frameworks and the empirical findings. In the prototype building and visualization phase, visual elements such as icons, progress bars, and drag-and-drop features were integrated to support comprehension and engagement (David & Sulaiman, 2021). Finally, in the phase of prototype evaluation, a usability test with 6th-grade students (N = 10) was conducted. Students participated in a remote session where they described what they saw in the prototype, its purpose, and whether there were some unclear aspects of the prototype. In total, the usability test with the learners took about 30 minutes. Minor ambiguities were identified and resolved before integration into the CBLE.

Following this phase of prototype building, prototype evaluation, and prompt integration into the CBLE, a quasi-experimental research was conducted (the authors of the present paper, in review), measuring the effects on students' SRL activities during one learning session using the think-aloud method. The think-aloud method was used to assess in-depth how lower secondary school learners ($N = 33$) engaged in prompted and unprompted utterances of metacognitive SRL activities. Based on the results of the coded utterances, more interactive elements were implemented into the prompts, using more and clickable goal icons, less text, and required interaction formats. In the present study, the prompts were presented at the beginning and at the end of the learning unit which the students worked on over three weeks. The calendar was available throughout the whole learning period.

Two aspects, furthermore, seemed important from the conducted research and prior research to focus on. First, following, Geurten et al. (2018), Braad et al. (2022), and the authors of the present study (in review), the prompts should be designed to foster domain-general metacognitive strategies, mainly independent of specific subjects. They aim to enhance students' overall learning rather than focusing solely on task-specific guidance. The focus was, therefore, transferred to more domain-general SRL strategies. Second, following Koszalka et al. (2019) and the authors of the present study (in review), the prompts are designed for interaction, requiring responses from students. These responses are analyzed and stored, enabling the system to personalize learning experiences based on the data collected and the progress of each individual. The prompts, therefore, in this research consist of a structured response format, which required the learners to answer and would not allow them to simply continue without a prompt reaction.

From these iterations, the three prompts, the *set goal prompt*, the *prioritize prompt*, the *reflect prompt*, and the calendar *goals planner* presented in the current research are derived. All prompts were presented to the learners in German, as all of them were beginners in the

English language. For clarity in this paper, they were translated into English. In the *set goal prompt* (Figure 2), 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. To continue, they need to choose one of the goal icons by clicking on it. Once a goal was chosen, the learners continued to the next screen. The *prioritize prompt* (Figure 3), is designed to give an initial overview of the upcoming learning unit and tasks and to guide them in personalizing their learning goals. By dragging and dropping, students prioritize three learning contents and thereby, decide for their individual preferences on the learning content.

The *goals planner* (Figure 4) contains action plans with learning tasks recommended as the next learning action. Action plans are adapted to each student's individual progress, goals, and prioritization, enabled through an algorithm that calculates the learning progress of individual learners, models their learning, and then makes exercise recommendations that are appropriate to their level of knowledge. Each completion of a task generates a booking to the learners' knowledge data bank which includes task correctness and level of difficulty of the task ordered by content. The knowledge database contains, for instance, a content booking in the grammar category on the grammar topic 'simple past' or 'comparison of adjectives' for English language learning. The difficulty level of the task is categorized according to an adapted version of the taxonomy by Bloom et al. (1956) by assigning each task to a certain level in the taxonomy. From the estimates of the total time needed to achieve a task, learning tasks are preselected and proposed to the learners in the form of calendar entries planned in 20-minute increments. Through categorization and time calculation, the system continuously tracks the learner's learning progress on a task-by-task basis, identifying strengths and weaknesses and recommending appropriate tasks to train topics that had been completed with low task correctness. The *goals planner* as well as the learning environment *Brainix* thereby continually adapts to the learner's progress and needs, allowing for adaptive and supported planning and learning. By clicking on the items, students can modify the action plans for their learning week according to their preferences. They were given the overview of the tasks and subsequently, encouraged through the prompts to plan their week timewise and content-wise. Content was presented and recommended based on the identified learning issues through the knowledge database.

The reflect prompt (Figure 5) reports on students' individual progress and offers them a choice of next steps to continue their learning paths. All prompts are adaptive to the student's progress and include learning goals visualized by a progress bar and goal icons. They were presented to the students in German language.

Figure 2

The Set Goal Prompt in the Learning Environment

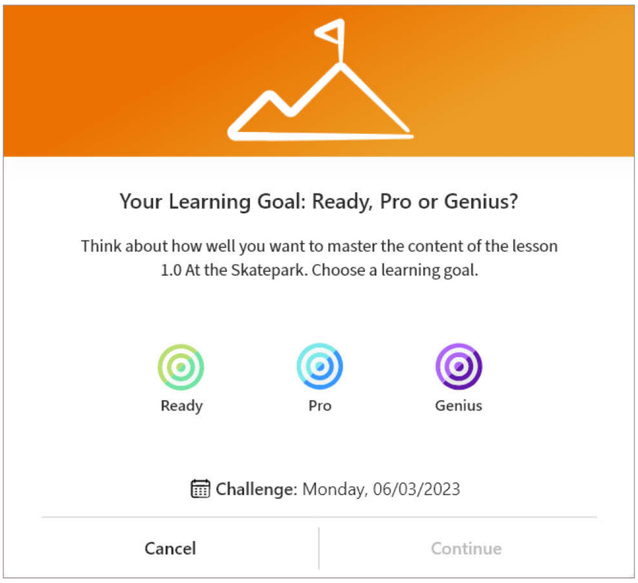


Figure 3

The Prioritize Prompt in the Learning Environment

Figure 4

The Goals Planner in the Learning Environment

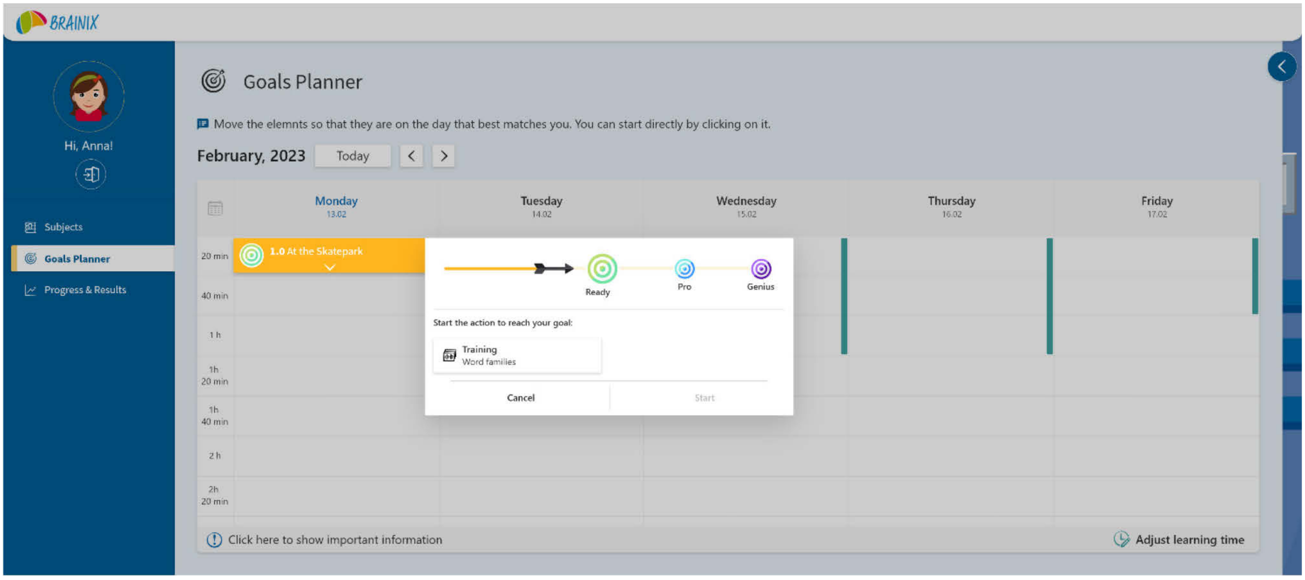
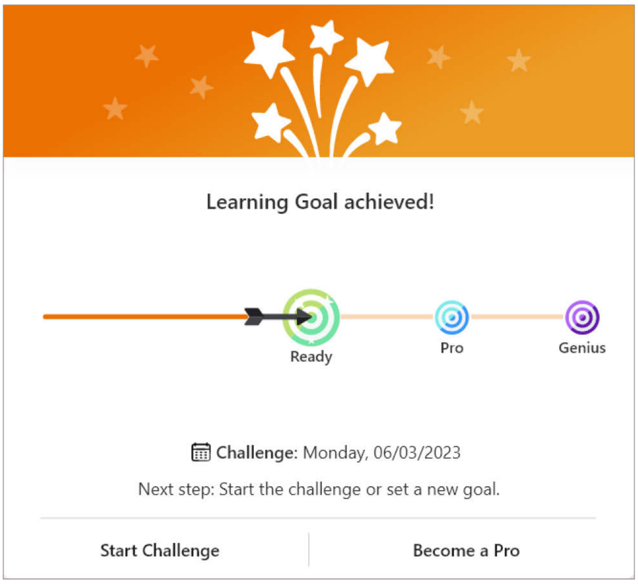


Figure 5

The Reflect Prompt in the Learning Environment



5.3 Measurements

5.3.1 SRL questionnaire

To examine the first research question on the influence of metacognitive prompting on the learners' SRL (RQ1a), two contextualized scales of the MSLQ (Pintrich, 1991) were administered in a pre-post design. The two scales Metacognitive Self-regulation (MSR; 12 items) and Time and Resource Management (TSE; 8 items) were selected due to the absence of suitable alternatives of questionnaires concerning metacognition and time management for lower secondary school students (Koivuniemi et al., 2021). The items in these two scales were translated from English to German and were subsequently adapted for the present research in the context of learning. In the pretest, the items referred to the context of learning in everyday school life (e.g. translated from German MSR1_11: When I study for class, I set myself goals to manage my activities in each learning phase). The answers are used as an indicator of the students' SRL skills prior to the study. In the posttest, items were adjusted to the context of learning in the CBLE (e.g. MSR1_11: When I study in *Brainix*, I set myself goals to manage my activities in each learning phase). This context differentiation is a result of teachers' reports that students rarely learn in CBLEs in everyday school life and therefore cannot evaluate their SRL skills in a digital context prior to the study. For the posttest, however, the items had to be specific to the CBLE context as analog school lessons were taking place simultaneously with the study. The items did not require any further modifications, as the short items were age-appropriate. As shown in Table 1, the contextualized scales of the MSLQ in the pre-and post-test were reliable, and additionally, the reliability values were similar to those when originally validated (Pintrich, 1991).

Table 1

Reliability of Scales on Metacognitive Self-regulation and Time Management of the MSLQ

Scale	Pretest			Posttest		
	N	Items	*α*	*N*	Items	*α*
MSR	105	12	.663	95	12	.736
TSE	105	8	.638	95	8	.685

5.3.2 SRL log data

To investigate the second part of the first research question (RQ1b), the software *LogRocket* (2022) was used to collect event-based trace data logging students' online SRL learning behavior in the CBLE. Following Du et al. (2023), the extracted data were combined with empirical findings to classify SRL processes and subprocesses. In total, four indicators of the students' learning behavior were assessed, and collected during the three weeks of learning in the CBLE. This includes login duration, login frequency, learning progress, and learning regularity. Previously, these indicators of learning behavior have been identified as indicators for SRL activities (Kim et al., 2018; Rodrigues et al., 2019; van Halem et al., 2020; Wong et al., 2021 Jansen et al., 2020).

5.3.3 Learning Performance Tests

To investigate the second research question on the influence of metacognitive prompting on learning performance (RQ2), two tests were developed with the help of teachers. A recall test, in which knowledge was tested using fill-in-the-gaps and multiple-choice exercises, and a transfer test, in which the students were asked to write a long text in the form of an e-mail on the contents of the lesson. Previous research has shown that scaffolding of SRL was less likely to influence recall performance and more likely to impact transfer performance (Bannert, 2007; Lim et al., 2021; Müller & Seufert, 2018; Sonnenberg & Bannert, 2015). Therefore, both performance tests were administered. The recall test was given to the students as a pre-and post-test in order to determine both prior knowledge and learning gain. In total, both tests showed highly significant correlations with the learners' English grades and with each other, indicating a good validity of both knowledge tests.

5.4 Data-analysis

For the questionnaire, the recall and transfer tests, descriptives were calculated. Students were included, if all scales, both recall tests (pre and post) and the transfer test, had been filled out. For the transfer test, an evaluation scheme was developed by researchers and teachers. To assess the interrater reliability, a research assistant independently evaluated fifteen tests, representing 21% of the total amount of participants. A very high intercoder reliability (Cohen's $\kappa = 0.99$) was determined.

Concerning the learners' online learning behavior, login time and login duration were calculated. Learning progress in the lesson was determined at the end of the study. From these values, login frequency and learning regularity were calculated. As these online learning behavior measures correlate with the time management scale of the MSLQ, the variables of online learning behavior can be viewed as valid. If a student logged in several times a day, it was calculated as different logins. Learning regularity was calculated as the standard deviation of the average learning interval, adapted from Jo et al. (2015). Scores obtained with this method correlated highly with other measures of learning behavior and the Time Management Scale. The average learning interval can be expressed as shown:

$$\overline{\Delta t_i} = \frac{\sum_{i=1}^{n-1} \Delta t_i}{n}$$

The value Δt_i stands for the time interval between two learning phases, i.e. the duration of a learning break (in days), including also the days from the start of the data collection period to the first login and from the last login to the end of the data collection period. The value n represents the number of learning breaks between the first and last login. The standard deviation of the learning interval was calculated as follows:

$$S_t = \sqrt{\frac{\sum_{i=1}^{n-1} (t_i - \overline{\Delta t_i})^2}{n-1}}$$

For inferential analyzes, the data were checked for normality and outliers. Separate t-tests for independent and dependent variables were calculated. As the questionnaire items differed in their context, either the context of everyday school life or the context of the CBLE, no repeated measures ANOVA was conducted for self-reported SRL skills. An ANOVA for repeated measures was performed for learning gain. To further analyze interaction effects, moderator analyzes were conducted by means of the PROCESS macro by Hayes (2018) which applies ordinary least squares regression, providing unstandardized coefficients for all effects. Bootstrapping with 5000 iterations samples together with heteroscedasticity consistent standard errors (HC3; Davidson & MacKinnon, 1993) was employed to calculate confidence intervals and inferential statistics. The assumption of normal distribution can, therefore, be neglected. Effects were considered significant if the confidence interval did not include zero. As assessed by visual inspection of the scatterplots after LOESS smoothing, the relationship between all variables included in the moderation analysis was approximately linear.

6. Results

Firstly, descriptive and inferential analyzes of the questionnaire, online learning behavior and learning performance between the treatment groups are presented. Secondly, factors that may influence the use of the prompts and thereby, the learning outcomes, are analyzed.

6.1 Group differences in learner characteristics

Descriptive and inferential analyzes for learner characteristics are shown in Table 2. Independent sample t-tests revealed no significant differences between the groups for learner characteristics assessed in the pretest MSLQ scales, the prior knowledge measured in the pretest recall test, and the students' performance level, the average of learners' current English grades, prior to the study. Additionally, the students' experience in computer use and *Brainix* use was collected to detect differences prior to the intervention, however, no significant differences were found.

Table 2.

Descriptive and Inferential Statistics of Independent Variables

	EG (n = 38)		CG (n = 34)		Two-tailed p value	Cohen's d
	M	*SD*	*M*	*SD*		
Learner Variables						
Prior performance level	4.16	.89	4.18	.87	.929	-.021
Computer Experience	3.55	.86	3.47	.79	.676	.099
Brainix Experience	.34	.48	.35	.49	.925	-.022
Self-regulation						
MSR_1	49.92	8.97	48.79	9.96	.615	.119
TSE_1	43.71	7.27	41.26	8.04	.180	.320
Learning Performance						
Prior Recall Knowledge	10.18	2.10	10.21	2.94	.971	-.009

6.2 Effects on self-regulated learning and learning outcomes

To investigate the first research question, the effects of the metacognitive prompts on the students' SRL skills and their online behavior were examined. In total, as descriptive analyzes of the log data show, students worked on average a total of 4h 3min (*SD* = 1h 56min) in the learning environment and logged in 6.3 times on average (*SD* = 3.2). When they logged in, the learners worked in the environment for 00:45:13 (*SD* = 00:13:19) on average per day. Overall, students had 4.14 (*SD* = 2.43) pause intervals on average in the data collection period, in which they did not log into the learning environment, representing a learning regularity of 4.64 days (*SD* = 3.04). This indicates that every four to five days, the students worked in the learning environment.

Investigating group effects on students' online learning behavior, a mixed ANOVA including the condition and all online learning behavior measures was conducted. While both groups show a high value in lesson progress, the control group (M_{CG} = 97.91; SD_{CG} = 10.00) outperformed the experimental group (M_{EG} = 86.26; SD_{EG} = 21.89) significantly ($t(70) = -.85$, $p < .001$). For login frequency, duration, and learning regularity no significant group differences were found.

Examining students' self-reported SRL skills, independent sample t-tests revealed significant group differences in the Metacognitive Self-regulation Scale ($t(70) = 2.14$, $p < .05$). No group differences were found in the Time Management Scale ($t(70) = 1.1$, $p = .278$). Descriptive analyses show that scale means for the context of everyday school life (M_{MSR1} = 49.39, SD_{MSR1} = 9.4; M_{TSE2} = 42.56, SD_{TSE2} = 7.69) are higher than for the context of CBLEs (M_{MSR2} = 46.54, SD_{MSR2} = 10.69; M_{TSE2} = 40.28, SD_{TSE1} = 7.43).

To investigate the second research question, the effect of metacognitive prompting on learning outcomes, learning gain was determined. An ANOVA for repeated measures found a significant difference between pre-test scores (M_{preRC} = 11.56, SD_{preRC} = .31) and post-test scores (M_{postRC} = 89.23, SD_{postRC} = 1.51) concerning recall knowledge, $F(1, 70) = 2587.72$, $p < .001$. This suggests that the lesson in the CBLE *Brainix* successfully yielded pre-to-post learning gains. To investigate group differences, a mixed ANOVA revealed no main effects of the condition on learning outcomes. Descriptives show that the control group performed better both in the recall knowledge and the transfer knowledge test than the experimental group, resulting in a negative effect size for both recall knowledge (Cohen's $d = -.26$) and transfer knowledge (Cohen's $d = -.21$), indicating small negative effects of the metacognitive prompts. In Table 3, we present all descriptive and inferential statistics for all dependent variables.

Table 3.

Descriptives and Inferential Statistics of Dependent Variables

	EG (n = 38)		CG (n = 34)		One-tailed p-value	Cohen's d
	M	*SD*	*M*	*SD*		
Self-regulation						
MSR2	49.03	10.85	43.76	9.95	.018	.504
TSE2	41.18	7.66	39.26	7.13	.138	.259
Navigation behavior						
Login Duration	3:46:22	1:47:17	4:20:39	2:04:05	.106	-.297
Login Frequency	6.13	3.06	6.44	3.48	.345	-.095
Learning Regularity	4.37	2.76	4.95	3.35	.212	-.190
Progress in Lesson	86.26	21.89	97.91	10.00	.003	-.672
Learning outcomes						
Post-Test Recall	12.47	3.22	13.38	3.72	.135	-.262
Transfer	6.37	3.85	7.12	3.14	.186	-.212

6.3 Aptitude-treatment-effects on learning outcomes

The non-observance of significant main effects of metacognitive prompting could be explained by aptitude-treatment effects (Cronbach & Snow, 1977). It might be the case, that only a subsample benefited from the metacognitive prompting while it might have been hindering for other participants. To determine whether the interaction between treatment and learner characteristics significantly influences recall or transfer knowledge, moderation analyzes were performed. The results of these analyzes are reported in Table 4. Key interactions are detailed below.

For recall knowledge, a significant overall model was found for the interaction of treatment and performance level, $F(3, 68) = 3.58$, $p = .018$, predicting 16.81% of the variance. The moderation analysis, however, showed that performance level did not significantly moderate the effect between treatment and recall knowledge, $\Delta R^2 = 0.5\%$, $F(1, 68) = .354$, $p = .554$, 95% CI[-.932; 2.587]. For prior knowledge, a significant overall model was found for the interaction with treatment, and in terms of recall knowledge, $F(3, 68) = 10.416$, $p < .001$, predicting 25.24% of the variance. Moderation analysis, however, showed that prior knowledge did not significantly moderate the effect between treatment and recall knowledge, $\Delta R^2 = 0.5\%$, $F(1, 68) = .632$, $p = .429$, 95% CI[-.263; .805]. Analyzes did not show that SRL skills moderated the effect between treatment and recall knowledge significantly, $\Delta R^2 = 0.5\%$, $F(1, 68) = .256$, $p = .614$, 95% CI[-.163; .096].

For transfer knowledge, a significant overall model was found for the interaction of treatment and performance level, $F(3, 68) = 6.43$, $p < .001$, predicting 21.22% of the variance. The moderation analysis showed, furthermore, that the performance level did significantly moderate the effect between treatment and transfer knowledge, $\Delta R^2 = 5.97\%$, $F(1, 68) = 6.014$, $p = .017$, 95% CI[-3.569; -.459]. For prior knowledge, a significant overall model was found for the interaction with treatment, and in terms of transfer knowledge, $F(3, 68) = 4.443$, $p = .006$, predicting 8.81% of the variance. Moderation analysis, however, showed that prior knowledge did not significantly moderate the effect between treatment and recall knowledge, $\Delta R^2 = 2.77\%$, $F(1, 68) = 2.079$, $p = .156$, 95% CI[-.241; 1.054]. For SRL skills, no significant overall model, nor a significant moderator effect was found.

Table 4.

Results of Moderation Analyzes: Overall Models and Moderator Effects

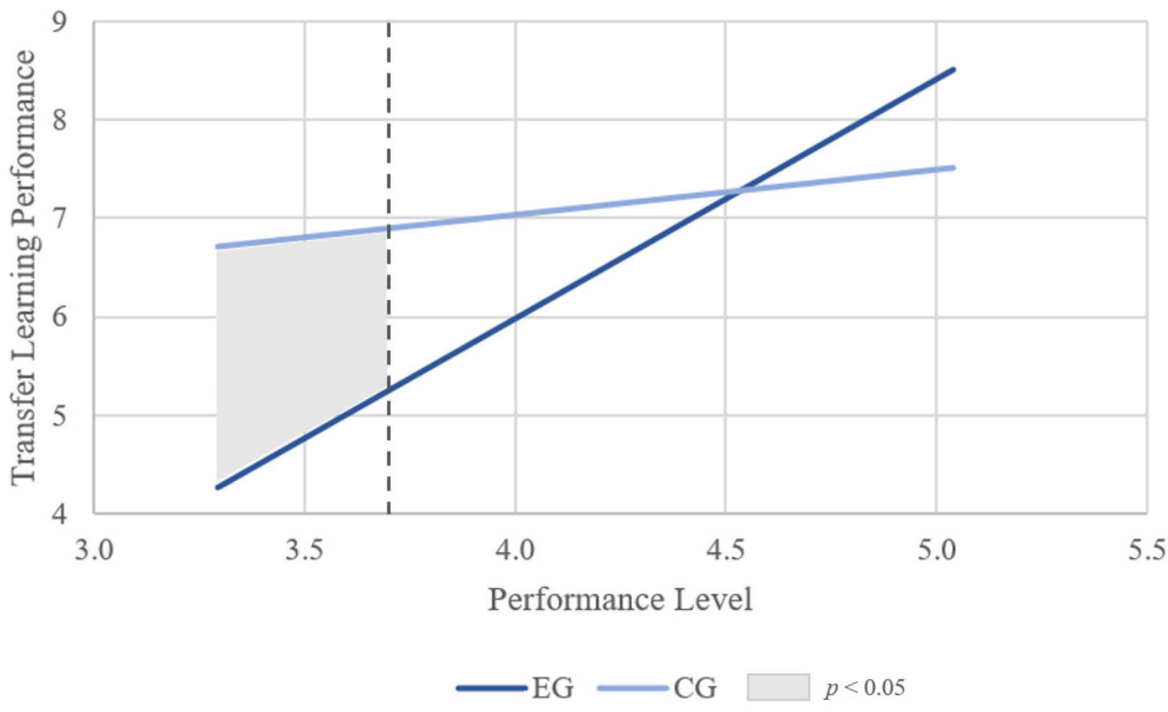
	Regression analysis			Moderation analysis			
	R^2	*F*	*p*	R^2	*F*	*p*	*95% CI*
Recall							
Treatment & performance level	16.81	3.58	.018	0.5	.35	.554	-.932; 2.587
Treatment & prior knowledge	25.24	10.42	<.001	0.5	.63	.429	-.263; .805
Treatment & SRL skills	2.37	.55	.654	0.5	.26	.614	-.163; .096
Transfer							
Treatment & performance level	21.22	6.43	<.001	5.97	6.01	.017	-3.569; -.459
Treatment & prior knowledge	8.81	4.44	.006	2.77	2.08	.156	-.241; 1.054
Treatment & SRL skills	1.91	.51	.679	0.7	.43	.514	-.163; .085

Note. R^2 in percentage.

By means of the Hayes Process macro (2018), the Johnson-Neyman significance region was detected for the moderator value below 23.61% and above 76.39% respectively. To visualize this interaction effect, an adapted Johnson-Neyman-Plot (Johnson & Neyman, 1936) was computed indicating a significant conditional effect of treatment on transfer knowledge, if the moderator performance level was outside the interval [3.64; 7.89], $p < .05$ (see Figure 6). These findings from the Johnson-Neyman significance region in combination with adapted Johnson-Neyman-Plot indicate that those with low performance levels in particular were significantly limited in terms of their transfer knowledge performance by the metacognitive prompting in the CBLE *Brainix*.

Figure 6.

Adapted Johnson-Neyman-Plot of Interaction Effect



7. Discussion

The aim of the study was to investigate the effects of adaptive metacognitive prompts on young learners' SRL and learning performance over a period of three weeks. To obtain these results, a pre-post measurement and between-subject design study assessed SRL through self-reports and online log data, as well as learning performance by means of a recall and a transfer knowledge test.

7.1 Implications of findings on self-regulated learning

Regarding the first research question, analyzes of the self-reports reveal that metacognitive prompting significantly increased the learners' metacognitive SRL in the context of digital learning. These findings, analyzed by means of the scale Metacognitive Self-regulation of the MSLQ, are in line with our expectations and previous findings (Delen et al., 2014; Guo, 2023; Lai & Hwang, 2016). All metacognitive prompts including the goals planner were adaptive to the students' goals and progress including interactive progress bars and adapting goal icons. These findings indicate that guiding lower secondary school students to personalize and prioritize their goals as well as to monitor and reflect on their progress by means of metacognitive prompting helps them to engage in SRL skills.

The metacognitive prompting did not, however, increase the learners' time management abilities measured by means of the second scale in the self-report and the learners' online behavior. These findings may shed light on the *goals planner*, in particular, that had been created to support learners in their strategic planning. It has been noted previously that time management is an essential self-regulatory process, by which students actively determine when and for how long they will pursue activities deemed necessary for the achievement of their academic goals (Wolters & Brady, 2021). However, planning activities, in particular, can lead to cognitive load (Seufert, 2018), hindering the students' learning process if instructions are created too complex (Sweller et al., 1998) Reducing the complexity of planning features in CBLEs may be achieved by providing a training phase prior to sole calendar use ensuring basic knowledge of calendar use.

Surprisingly, the control group made significantly more progress in the lesson than the experimental group. Prior studies have suggested that while gamification elements have been shown to enhance desired motivational, behavioral, and learning outcomes (Zainuddin et al., 2020), some can overlap with elements of SRL support (Raleiras et al., 2020). Rewards such as badges, coins, or stars can be used to support planning, self-monitoring, collaboration and comparison, and self-evaluation (Tang & Kay, 2014). Higher learning progress among those without metacognitive prompting may indicate that the gamified elements may not have been well aligned with the SRL support, causing unnecessary confusion for the experimental group. Although the advanced learning progress of the control group did not result in significantly improved learning outcomes, future research requires a more rigorous exploration of factors that interact with the SRL support in the CBLE.

7.2 Implication on findings on learning performance

Regarding the second research question, findings show that learners supported by metacognitive prompting did not significantly improve their learning performance compared to learners who did not receive prompts. While these results concerning the effects of SRL support on recall knowledge are in line with previous studies (Bannert & Mengelkamp, 2008; Bannert et al., 2015; Engelmann & Bannert, 2021), the findings in terms of SRL support on transfer knowledge contradict previous research (Lim et al., 2021; Müller & Seufert, 2018; Sonnenberg & Bannert, 2015). These analyzes of previous research were, however, conducted mainly in settings with learners in higher education. Among younger learners, it was previously found that while SRL strategies were fostered, no transfer effects on achievement were detected (Benick et al., 2021). The present research focused on a language learning context. Future research may include this intervention in a CBLE context of mathematics as higher effect sizes were found in intervention studies in the context of well-structured subjects (Dignath et al., 2008).

Post-hoc interaction analyzes indicate differential effects of the adaptive metacognitive prompts for high and low achieving learners. While high achieving learners seem to have rather profited from the support of prompts in terms of transfer knowledge, as reported previously (Hsu et al., 2017; Kramarski et al., 2013; McCarthy et al., 2018; van Dijk et al., 2016), the significantly negative effects on transfer performance for low achieving learners point to a result discussed as the Matthew effect. Previous studies that described the Matthew effect hypothesized that SRL instructions are more likely to help high achievers in general, resulting in even greater inequalities (Dörrenbächer & Perels, 2016; Lau, 2022). The assumption that low-achieving learners require more support to benefit from SRL instructions because they show lower SRL competencies (Bai et al., 2021; Lau, 2022) was, however, not substantiated by the results of the study. Post-hoc analyzes indicate no significant moderation of SRL competencies between the condition and learning performance. Other studies have suggested that prior knowledge influences the students' learning performance (e.g., Thompson & Zamboanga, 2003), however, no interaction effects of prior knowledge were found in the present study. Prior achievement levels have been widely shown to influence future achievement levels (Hemmings & Kay, 2010), however, to reduce these inequalities, support for low-achieving students in particular needs to be addressed in future research.

In order to effectively support all students by means of metacognitive prompting, adjustments especially valuable for low-achieving students can be realized within the design of the prompts. Van Dijk et al. (2016) found that average and low-ability students rarely made use of the prompts. The absence of effects on learning performance due to student compliance has been suggested before (Müller & Seufert, 2018; van Alten et al., 2020). In the present study, it cannot be ruled out that this might have affected the results. However, as it has been shown that compliance is increased when students interact with the prompts (Bannert et al., 2015), the prompts in the present study were created highly interactive. In order to effectively use the prompts, learners may first need to realize that the help offered is necessary, which they cannot if they lack self-assessment skills (van Dijk et al., (2016). Future research should integrate measures in the design of the prompts that control the quality of the prompts use by means of checks for inadequate behavior, as exemplified by Kautzmann & Jaques (2019).

In addition, the relationship between motivational variables, metacognitive prompts, and learning performance remains to be explored. Bai and colleagues (Bai et al., 2021) found that self-efficacy and a growth mindset were crucial predictors of strategy use, indicating that students who believe that their skills can be improved through effort and practice are more likely to undertake efforts, seek challenges, and persevere in the face of setbacks. Some initial findings indicate that growth mindset interventions may be particularly helpful for struggling students (Yeager et al., 2019; Macnamara & Burgoyne, 2022); however, this and its influence on the effective use of metacognitive prompts, needs further investigation.

7.3 Limitations and Future Research

The present study has some clear limitations and should be addressed in future research. Firstly, the generalizability of the present study's findings is limited. The presented data were collected from a single secondary school in Germany, a *Gymnasium*, Germany's highest academic school type. To draw conclusions that are applicable to lower-achieving students, it is essential that future studies incorporate participants from a broader range of school types. Furthermore, the quasi-experimental design of the study required the continuous presence of participants across data collection of three weeks of. However, due to student absences resulting from illness, not all participants who initially took part could be included in the final analyzes. In addition, technical issues reported by some learners while using the CBLE necessitated the exclusion of these cases from the dataset. To support more robust generalizations concerning learner characteristics, future research should include larger and more diverse samples. Given the difficulty of collecting and analyzing data from young learners, the present study provides first exploratory results for future studies with this age group.

Secondly, in order to increase the effects on SRL activities and learning performance, learners should work in the CBLE during school as their main learning task. Due to strict school policies, students voluntarily participated in this study outside of the classroom. For students to adapt to new learning situations (Gašević et al., 2017) and to work within the environment with reduced extraneous cognitive load (Seufert, 2018), learning sessions in the CBLE in the classroom environment seem beneficial to investigate.

Future studies, thirdly, need to include means to measure individual effects of each prompt and quality of the prompt usage. Prior research by De Haas et al. (2022) indicated a decline in children's task engagement over time, aligning with the novelty effect describing learners to be excited in the beginning when using a new technology (Kanda et al., 2004). Using advanced data mining or eye tracking (Fan et al., 2022, Sim & Bond, 2021) of SRL activities combined with think-aloud data to receive multimodal data (Molenaar et al., 2023), may reveal activities that could not be observed in the present study. Furthermore, an SRL questionnaire validated for young learners and digital learning contexts can be helpful. Combining these multimodal data will aid future research that seeks to clarify students' engagement in metacognitive SRL activities and to determine how adaptive SRL support needs to be designed to effectively improve learning in CBLEs.

8. Conclusion

The main purpose of the present study was to investigate the effects of adaptive metacognitive prompts including goal setting, strategic planning, and progress evaluation on SRL activities and learning performance in young learners in an authentic CBLE. Results show that the learners' self-reported metacognitive SRL skills were significantly enhanced by means of metacognitive prompting. However, no effects of the metacognitive prompts were found on recall or transfer knowledge when all learners were included. Findings from moderation analyzes indicate that performance level significantly moderated the relation between the condition and the transfer learning performance, surprisingly negatively impacting especially students with low-performance levels. These findings highlight the importance of adaptivity of SRL support to the students' prior achievement levels, emphasized by the results in the present study that neither prior knowledge nor prior SRL skills moderated the effect of the prompts on learning performance. To further advance research on the development of SRL in young learners, metacognitive prompts need to be more rigorously checked for appropriate usage, additional measures such as mining behavioral SRL data and eye-tracking can be beneficial. Also, motivational variables such as self-efficacy and growth mindset that influence prompt usage remain to be explored.

9. References

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8. Discussion

This dissertation's overall aim is to provide a deeper understanding of the effects of adaptive metacognitive prompting on metacognitive SRL activities and learning performance in a CBLE among young learners in lower secondary school. Previous research has shown that providing support for SRL activities can help learners overcome difficulties in learning and in particular, in digital learning (Broadbent et al., 2020, Heikkinen et al., 2023). In addition to students in higher education, this has also been shown to be true for children and adolescents (Dent & Koenka, 2016; Dignath & Büttner, 2008). Although digital learning in secondary school learners becomes more common and requires more independent and self-regulated learning (Broadbent et al., 2023; Winters et al., 2008), research investigating means to effectively support young learners' SRL activities and learning performance in CBLEs remains scarce.

In the research of this thesis, two quasi-experimental studies were, therefore, conducted to explore the effects of adaptive metacognitive prompting on SRL activities and learning performance in an authentic CBLE for young learners in secondary schools. This general discussion aims to answer three questions: "Is adaptive metacognitive prompting an adequate tool to support SRL in young learners?", "How can young learners be provided with appropriate prompts?" and "How can adaptive metacognitive prompts meet learners' individual needs?". By answering these questions, this section will discuss the main findings of the two studies, limitations as well as implications for research and practice, and point to future research directions in SRL research.

8.1 SRL Support: Metacognitive Prompts as an Adequate Tool for Young Learners

This section is aimed at discussing the effects of adaptive metacognitive prompting on the young learners' SRL activities and thereby, answers to the question "Is adaptive metacognitive prompting an adequate tool to support SRL in young learners?". By looking at the main findings of the two empirical studies and the limitations in terms of context-specificity, implications for SRL theory and the development of SRL skills are presented.

8.1.1 The Positive Influence on Young Learners' SRL Activities

The two studies in the present thesis extended prior research by investigating the effects of adaptive metacognitive prompting on metacognitive SRL activities among young learners. Positive effects of the prompts on the learners' metacognitive SRL activities were found in both studies.

The first study gained, by means of the think-aloud method in the 30-minute learning session, in-depth insights into the learners' prompted and unprompted metacognitive SRL activities and the sequential structure of these activities using process mining. Following the first research question of this thesis, the results showed that the prompts encouraged learners to engage in significantly more *domain-general* metacognitive SRL activities in terms of *goal setting* and *planning*. Two findings of the process mining that analyzed the learners' sequential structure of the SRL processes need to be highlighted. Firstly, the control group's sequential structure showed better integrated *reflection* activities. Secondly, the experimental group's process model reflected more closely the cyclical phases proposed by traditional SRL models by Zimmerman (2000) and Winne and Hadwin (1998).

The second study of this thesis examined the effects of the adaptive metacognitive prompts on SRL activities by means of the learners' online behavior including logfiles and an adapted version of the self-report questionnaire MSLQ by Pintrich (1991). In order to comprehensively and unobtrusively capture these effects, a three-week data collection phase was scheduled allowing the learners to independently work in a 3.5-hour learning unit outside of school. Findings show that metacognitive prompting led to significantly higher values in the scale *Metacognitive Self-Regulation* of the self-report questionnaire, referring to the first research question of this thesis. No differences between the groups were found in the scale *Time Management* of the self-report questionnaire, nor in the learners' online learning behavior within the CBLE.

These findings from the studies show that the young learners in lower secondary school applied basic metacognitive activities to language learning tasks in a CBLE, referred to in the present research of this thesis as *task-specific* metacognitive SRL activities. By means of adaptive metacognitive prompting, the learners made use of *domain-general* metacognitive SRL activities that allow metacognitive strategies to be transferred across domains. This finding is in line with prior research showing that learners possess elementary forms of metacognitive skills in primary and lower secondary school (van der Stel & Veenman, 2014). Aged ten to twelve years old, students were found to be in a transitional phase in which they start to apply metacognitive skills across tasks (Veenman & Spaans, 2005). This ability to transfer metacognitive skills across tasks has been found to be a strong predictor for academic performance (van der Stel & Veenman, 2008, van der Stel et al., 2010). From a theoretical point of view, this scenario aligns with what is referred to as the production deficit (Flavell, 1977; Veenman et al., 2000). The underlying assumption that learners possess the strategies, yet refrain from using them until prompted, was shown for *goal setting* and *planning*, in the first study, and for metacognitive SRL skills, in the second study. The learners, thus, possess elementary forms of metacognitive SRL skills and by means of the prompts exhibit more advanced levels of these skills. In terms of *domain-general and task-specific reflection* activities in the first study and *Time Management* in the second study, no group differences were found, allowing some careful assumptions that more training for reflecting and time management activities may be needed.

Overall, the findings of the presented research provide a positive answer to the posed question. The findings in this thesis indicate that the adaptive metacognitive prompts are a promising tool to support young learners' metacognitive SRL activities in CBLEs. For future research, it is necessary to address some limitations of this research.

8.1.2 Limitations

In terms of SRL activities, the research in this thesis encompasses the limitation of generalizability of the results that should be considered in future research. The results are generalizable in a limited way, as the adaptive metacognitive prompts have been investigated in a learning environment with particular features and learning material using process and product measures adapted to this context.

The context-specific nature of this research can be integrated into the discussion on the context-specific nature of SRL and metacognition (Rotgans & Schmidt, 2009). A first perspective postulates that self-regulated learners are able to adapt their skills to different learning contexts (Siegler, 1988). This would imply that SRL activities are relatively consistent across subjects, and that findings conducted in one learning context can be transferred to others. A second perspective proposes that the underlying structures of SRL are relatively stable and do not undergo significant alterations in response to subject domain variations (Wolters & Pintrich, 1998). The most widely accepted and third perspective holds that SRL is highly dependent on the context of the learning situation, and demands that SRL research is conducted at course level (Pintrich, 2004; Rotgans & Schmidt, 2009).

Furthermore, values in measurement methods can be dependent on the learning environment, thereby being a source of variability and limiting the generalizability of results. While self-reports may be more independent of the domain (Rotgans & Schmidt, 2009), process measures such as the think-aloud method include domain-specific and task-specific utterances as a basis for the coding scheme (Chi, 2006; Ericsson & Simon, 1993). This is true also for learning analytics and trace data, measuring the learners' interaction in the CBLE and thereby, following the conditions of the CBLE to some extent (Du et al., 2023). The granularity differences derived from SRL models and processes pose a further challenge to the measurement of SRL (Rovers et al., 2019), and thereby render the comparison of SRL research and the generalizability of the findings difficult.

While these perspectives are important to be considered in terms of construct and external validity, the present research views the predictive validity of SRL as the main goal of SRL research, following Rotgans and Schmidt (2009). By investigating SRL activities and ways to support these, the key objective of SRL research remains to make predictions about academic achievement and which measures can be put in place to improve learners' SRL. As academic achievement is highly context-specific and more accurate on course-specific level (Rotgans & Schmidt, 2009), predictions are assumed to be more accurate if SRL activities are investigated at course-specific level. It remains yet to be determined whether these assumptions are accurate.

However, as research in SRL support in CBLEs for young learners remain rare, the research of this thesis offers a promising path for future research showing that adaptive metacognitive prompting can be successful in fostering young learners' SRL activities. Future researchers may investigate the effects of metacognitive prompting by comparing two different domains, allowing for more precise implications in terms of the domain-generality of SRL activities. Despite this limitation, some implications from this research for development of SRL and SRL theory can be drawn.

8.1.3 Implications for SRL Development and SRL Theory

The findings on SRL activities presented in this thesis suggest that, from a theoretical and empirical perspective, a higher focus needs to be placed on the nuances in skill development of SRL among younger learners and how these nuances in SRL development can be supported individually adapting to the current needs of the learner. Prior research in SRL has focused on the development of SRL and metacognition, yet mainly in laboratory settings (Perry et al., 2017). The cognitive and metacognitive development of learners in lower secondary schools when creating and evaluating SRL support for authentic learning environments has been in the center of the discussion scarcely (Dörrenbächer-Ulrich et al., 2024). Especially with the growing use of CBLEs in schools (OECD, 2021), and increased SRL demands when learning in CBLEs (Cerezo et al., 2017), young learners and their cognitive and metacognitive development needs to be emphasized when creating adequate tools to support young learners' SRL.

The present research in this thesis placed young learners and their development of SRL at the center of the investigations, with a focus on prompting as a means of supporting SRL in CBLEs. The findings of this thesis indicate that offering SRL support that co-regulates certain SRL strategies can be beneficial for learners in lower secondary school in developing their SRL skills. The concept of co-regulation is derived from Vygotskian perspectives on learning, building on the idea that learners require interactions with a knowledgeable person or system that assists them in gradually developing their own SRL skills (Perry et al., 2017). Schunk and Zimmerman (1997) propose a four-phase model in which they describe how SRL develops from *other regulation* to *self-regulation*, including the phases of *observation, imitation, self-control* and *self-regulation*. Prompting young learners to engage in metacognitive SRL activities can therefore be seen as part of the journey towards becoming a self-regulated learner.

In order to provide young learners with valuable SRL support in CBLEs, more research is needed investigating the critical phase of developing metacognitive skills. Focusing on lower secondary school students in the research presented in this thesis allowed insights into the spontaneous application of SRL strategies and as well as their prompted SRL activities. Future research is needed to explore the different phases of SRL skill development depending on the educational and cognitive stage of the learners. This can be realized in future research by focusing on this specific age group in particular, as done by Heirweg et al. (2020), or by exploring how metacognitive skills develop over time, investigating differences between primary and secondary school students, as exemplified by Alvi & Gillies (2023). By comparing learners' SRL development in different educational stages, SRL support can be more adapted to the learners' needs.

The research in this thesis illustrates that young learners in lower secondary school engage in basic forms of SRL activities and by means of adaptive metacognitive prompting, they showed more complex metacognitive SRL activities. This research was conducted in the learners' natural learning settings, proposing that in order to develop appropriate forms of SRL support, research needs to investigate the effectiveness of this support in the authentic areas of application. Through replication in other contexts concerning learning material and learning environment, yet with a continued focus on developmental aspects of young learners' SRL, these results can be further explored in future research.

8.2 Beyond Prompt Effects: Providing Young Learners with Appropriate Prompts

The goal of this section is to address the effects of adaptive metacognitive prompting in terms of prompt compliance, the act of responding appropriately to the prompts (van Alten et al., 2020), and learning performance. By considering the main findings of the two empirical studies and the limitations of measuring prompt compliance, implications for prompt design are identified. This section, thus, attempts to answer the question "How can young learners be provided with appropriate prompts?".

8.2.1 The Challenge with Prompt Compliance and Learning Performance

The research in the present thesis extended prior findings on prompt development by exploring the learners' prompt usage with regard to their learning performance. This was enabled by the fine-grained analysis of think-aloud protocols in the first study, and the learners' interactions via trace data in the second study. Additionally, learning performance measures were integrated into the experimental design to determine the effectiveness of the prompts. The creation and implementation of the three prompts and a calendar in the present research followed the theoretical underpinnings of SRL research and the Design Thinking Approach (Plattner et al., 2009), a user-centered approach guided from design principles. A pilot version of the prompts was subsequently evaluated with ten students as well as teaching experts and software developers. However, the analysis shows that some learners did not comply with the prompts.

In the in-depth analysis enabled by the think-aloud protocols of the first study, it was shown that when learners were not required to answer to the prompts, some did not respond and simply continued with the next exercise. Prior research with university students has also shown that prompt compliance can be a challenging factor in providing learners with adequate SRL support (Bannert & Mengelkamp, 2013; Braad et al., 2022; Moser et al., 2017; Pieger & Bannert, 2018). Guo (2022) concluded in her meta-analysis that the prompt feature of response versions, namely click buttons, elaboration or not required, did not make a significant contribution in the effect sizes. However, many of the included studies focused on higher education students, with only two of the included studies utilizing click button prompts. In line with van Alten et al. (2020), who used a forced open answer format for secondary school learners to respond to the prompting questions, the prompts were modified for the second study, requiring the learners to respond.

Therefore, for the second study, interactive elements were included into the design of the prompts with the aim of encouraging and requiring learners to respond to the prompts. The analysis of the second study showed that by means of the new interactive design, learners responded to the set goal prompt appropriately by choosing a learning goal for them, and that the calendar was used frequently. It did not, however, influence the overall effects of the metacognitive prompting on recall and transfer learning performance. Future research may additionally focus on the investigation of the number of the prompts, the intensity of prompted cognitive or metacognitive processes (Nückles et al., 2009), as well as the presentation time (Thillmann et al., 2009) and thereby, enter the discussion on temporality of regulation and SRL as a cyclical process (Molenaar & Järvelä, 2014).

All in all, to answer the question of how learners can be provided with adequate prompts in CBLEs, an extensive concept is needed, firstly, to require an appropriate response to the prompt and, secondly, to measure the quality of the prompt response. The two studies partly fulfilled this. The qualitative analysis through the think-aloud protocols in the research of this thesis allowed fine-grained insights in the learners' compliance with the prompts. Unobtrusively measuring the learners' interaction with the learning environment and assessing their learning performance by means of a recall and transfer test allowed the drawing of conclusions in terms of the effectiveness of the prompts. Engaging learners in educational activities is seen, however, as one of the biggest challenges in the educational field, and becomes particularly critical in CBLEs in which learners are outside of the supervision or guidance of teachers (D'Mello et al., 2012). Future research is, therefore, needed to determine further requirements in terms of design and evaluation for appropriate prompting for young learners and to address the following limitations.

8.2.2 Limitations

The research in this thesis is limited in the view that prompt compliance could not be fully observed, and thereby the quality of the prompt usage could not be fully determined. By means of two approaches, future research investigating the effects of metacognitive prompting on young learners' SRL activities and learning performance can be improved.

By means of concurrent think-aloud used in the first study, the learners' utterances were analyzed, thereby including their active and conscious processes. The think-aloud method has been demonstrated to be a non-reactive method, in which uttering one's thoughts does not interfere with the learning process (Bannert & Mengelkamp, 2008; Ericsson & Simon, 1993). However, processes that the learner is not aware of may have remained undetected in the first study of this research project. The use of eye-tracking as an additional method to better understand the learners' compliance with the prompts appears to be a promising avenue for further investigation using it to capture the students' attention to prompts as exemplified by Conati et al. (2013) or D'Mello et al. (2012). Using eye-tracking enables the detection of learners' eye gaze patterns, which can be used to identify attentional deployment and failures (D'Mello et al., 2012) and may be of great value in combination with the think-aloud method to complement the conscious with the unconscious processes.

Another way to determine the quality of the prompt use is to analyze the learners' response to the prompts using advanced trace data. In the second study in the present research, trace data to track the learners' navigational behavior within the learning environment was used, yet it did not allow to investigate the specific interactions with the prompts. An example, in which advanced measures were implemented that tracked the learners' SRL activities as well as the prompt interactions, can be found in Kautzman and Jaques' (2017) work. They measured the learners' knowledge monitoring ability, and provided personalized support dependent on the current metacognitive index. Additionally, any instances of inadequate behavior were identified and addressed. This form of precise measurement of the learners' interaction within the CBLE enables real-time adaptation to the learners' behavior and their needs.

These challenges are to some extent the reason why current research emphasizes that in order to fully understand the critical SRL phases, multimodal data collections are needed to gain insights into the full spectrum of SRL (Reimann et al., 2014). By means of data triangulation, different data streams can be combined to gain insights onto the learners' processes as the learning occurs (Järvelä et al., 2019). Although these multichannel data collection methods present new challenges, they can enable further insights into prompt usage, young learners' prompted and unprompted SRL activities and the effect on learning performance.

Despite these methodological limitations, the research in this thesis provides insights into the use of adaptive metacognitive prompts among young learners and allows for conclusions and implications in terms of prompt design.

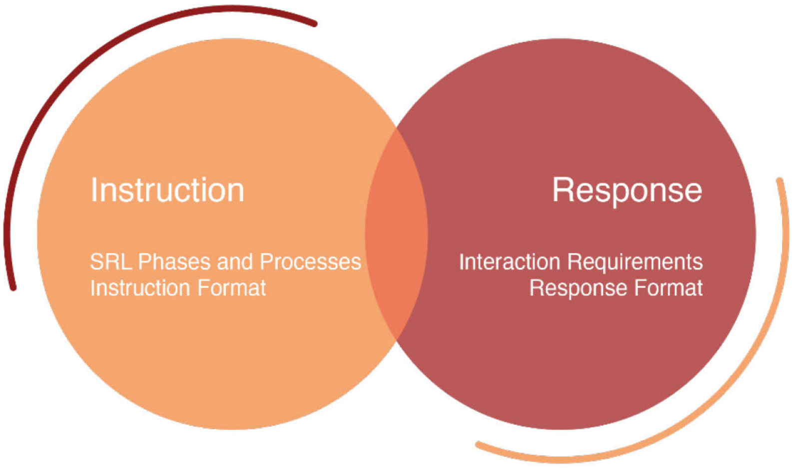
8.2.3 Implications for Prompt Design

The findings on prompt compliance and learning performance indicate that there is a need for greater attention to be paid to prompt design and its targeted users. Previous research investigating SRL support displays considerable variation in terms of target group, type of prompts, timing of prompts, learning tasks and learning environments (Wong et al., 2021). The findings of the present research demonstrate the significance of appropriate learning design in metacognitive prompting, which serves as the central connector between the learning environment and the learners, including their individual development of SRL. In order to enhance the development of SRL support in CBLEs for young learners, further research in SRL and its complex composition of subprocesses need precise guidelines to better integrate prior findings and make predictions for the enhancement of academic achievement.

Based on the development of the metacognitive prompts for this research, it seemed beneficial to develop a schematic perspective on the creation and implementation of SRL support. This section, therefore, includes a framework, derived from iterations during prompt development in the present research, that allows future creations of SRL support. Figure 2 presents this framework, called the *Prompt Design Scheme,* in which a prompt is defined as a combination of an instruction mode and a response mode. The instruction mode of the prompt is created through the two aspects of the targeted SRL phase and processes as well as the instruction format. The response mode of the prompt is created through the two aspects of interaction requirements and response format. Ideally, it should be based on accurate and comprehensive measurement tracked within the CBLE, allowing this kind of SRL support to be adaptive to the learners' needs and preferences.

Figure 2.

The Prompt Design Scheme



To create the instruction of the prompt, targeted SRL phases and processes as well as the instruction format need to be chosen. When focusing on young learners, it may be useful for future research to use the *Cyclical Framework of Metacognitive SRL in Young Learners* developed in the present research to differentiate between macro-processes, including forethought, performance and appraisal phase (Panadero, 2017), as well as the micro-processes, the cognitive, affective, metacognitive and/or motivational processes (Azevedo et al., 2012; Azevedo et al., 2022). This will allow to base the prompts in SRL theory.

Furthermore, choosing the suitable instruction format is crucial. Prior studies have reflected on the format of the prompts using the differentiation between questions and recommendations (Wong et al., 2021), instruction, application, and prompting (Jansen et al., 2019), or guiding questions, reflective questions, and suggestions (Guo, 2022). For the creation of SRL support, researchers need to consider the aim of their research to decide which format fits best their target group and their learning context. The findings in the research in the present thesis suggest that metacognitive prompts as an invitation to reflect combined with visualizations are promising for young learners and allowed to grasp the idea of the metacognitive prompts from the visuals. Different colors, letter size, icons and symbols were used. Molenaar et al. (2022) made use of a learner-faced dashboard to visualize the learners' learning progress using the analogy of a submarine world to display a learner's individual learning status. It is a valuable example of SRL support that uses strong visualizations to offer a different perspective on learning dashboards for young learners.

To determine the response mode of the prompt displayed in the *Prompt Design Scheme,* interaction requirements and the response format need to be developed. It is the aim of the prompt to invite learners to respond to the prompt, and ideally, through this form of intervention, promote their cognitive, emotional and behavioral engagement (Antúnez et al., 2020). Depending on whether a response interaction is required or not, and whether the response format is closed or open, learners may engage differently with the prompt. The research in this thesis indicates that among young learners, it is essential to include a required response format for learners to appropriately respond to the prompts.

These analysis of the effects of adaptive metacognitive prompting in terms of prompt compliance and learning performance indicate that prompts designed for young learners need to be created with different prompt modes compared to those designed for university students. These findings have been incorporated into the presented framework that provides guidelines for the development of such prompts. Further research is required to evaluate the *Prompt Design Scheme*, it may, however, already assist future SRL researchers and CBLE designers to tailor their SRL support more to the needs of young learners.

8.3 Tackling Inequalities in SRL Support: Learners' Individual Needs in CBLEs

The present research in this thesis has shown that person-centered variables influence the interaction between adaptive metacognitive prompting and transfer learning performance. Despite the limitations in terms of the sample and the measurement of person-centered variables introduced in the following section, these research findings allow for practical implications on SRL support in CBLEs and learners' individual needs. This section thereby addresses the question "How can adaptive metacognitive prompts meet learners' individual needs?".

8.3.1 Prior Performance Levels as a Moderator

The studies in the present research showed no effects of the prompts on learning performance. However, post-hoc moderation analysis revealed that prior performance moderated the effects of metacognitive prompting on transfer performance. This extended prior research by showing that the certain learners' prerequisites are crucial to effectively apply the metacognitive prompts in their learning process with the aim to enhance transfer knowledge performance.

The importance of learners' characteristics in SRL has been established before; Zuh and Mok (2018), for instance, found that primary school students' prior achievement predicted the learners' planning, monitoring and adaptive reactions, thus, their metacognitive SRL activities. However, limited attention has been paid to learners' characteristics that may influence metacognitive prompting. While many empirical studies have shown positive effects of these prompts (Guo, 2022), some were unable to find beneficial effects (K. Engelmann & Bannert, 2021; McCarthy et al., 2018; Pieger & Bannert, 2018; van Alten et al., 2020). Winne and Hadwin (1998) have postulated the importance of conditions in SRL in their COPES model, referring to the learners' variables. Notwithstanding this theoretical model, previous research has primarily focused on the timing and design of prompting as the underlying cause of observed differential effects (Guo, 2022; Zheng, 2016). The findings of the second study in this thesis extends this line of research showing that the learners' prior performance levels play a crucial role in the effective use of metacognitive prompts among young learners.

In the present thesis, the findings of the post-hoc analysis demonstrate, in particular, that low prior performance level students were negatively impacted by the metacognitive prompts in terms of their transfer performance. The findings that high achievers profit more from SRL support have been detected previously (Lau, 2022; Otto & Kistner, 2017) and is known as the "Matthew effect" (Walberg & Tsai, 1983). An underlying assumption of this effect is that high achievers possess higher SRL skills than low achievers (Bai et al., 2021), use SRL strategies more strategically and flexibly compared to low achievers (Heirweg et al., 2020) and, therefore, can integrate SRL instruction better into their learning. This assumption was not confirmed as the additional moderation analyzes of prior SRL skills and prior knowledge showed no significant influence on the relation between the condition and learning performance measures. Other studies have demonstrated that SRL instruction can result in positive effects on low achievers (Zohar & Peled, 2008), moderate achievers (Dörrenbächer & Perels, 2016) or have found no differential effects (Donker, et al., 2014). It, thus, remains to be investigated how adaptive metacognitive prompts can be created to be beneficial for low achieving young learners in order to address existing inequalities in education and prevent them from being further deepened.

In sum, the findings on performance level as a moderator indicate that adapting SRL support to the learners' needs is a complex process and call for attention on aptitude-treatment-effects in SRL research. The present findings indicate that for CBLEs to better meet the learners' individual needs, referring to the question of this section, SRL support needs to be created in a way that it takes into account the learners' individual characteristics.

Thereby, a particular focus should be put on the learners' prior performance and low achieving learners. In terms of the sample and the measurement of the person-centered variables in the research of this thesis, some limitations need to be addressed for future research.

8.3.2 Limitations

The presented findings in terms of learning performance and prior performance were limited in two ways in the present research. Firstly, the sample of the two studies conducted in this research contained only learners from the highest level of secondary schools in Germany, the Gymnasium. With the objective in this research to implement and evaluate the adaptive metacognitive prompts in an authentic CBLE, the learning materials for the empirical studies were mapped onto the levels of the 6th grade learners in Gymnasium. Given the findings that within this learning situation, the adaptive metacognitive prompts encouraged all students to engage in SRL activities, but tended to improve transfer learning performance only for some of the students, more research is needed to extend these results. Future researchers may, therefore, target learners in other levels of secondary schools in Germany, thus, Mittelschule and Realschule, with the aim of investigating a more representative sample.

Secondly, future research may include more comprehensive measurements of person-centered variables to determine their influence on the successful use of metacognitive prompts and the effects on learning performance. In an attempt to conduct an ecologically valid research, the effects of adaptive metacognitive prompting were investigated in an authentic CBLE and the students' natural learning contexts. This included a collection of prior learning variables focusing on SRL skills, prior subject knowledge and prior performance level. To measure the learners' SRL skills, a self-report was used. Although reliability scores were appropriate and allowed comparisons between the prompted and unprompted groups, self-reports remain being subject to criticism, pointing out the subjectivity and the risk of socially desired answers (Greene & Azevedo, 2010). In future research in CBLEs, Broadbent et al.'s (2023) questionnaire called Self-Regulation for Learning Online (SRL-O) may be of help. To assess the learners' prior knowledge, a knowledge test was developed by teachers and learning experts. While it allowed the comparison of the groups and pre- and post-values to determine learning gain, this knowledge remains domain-specific (Rotgans & Schmidt, 2009). Concerning the prior performance level, learners' overall subject grades were collected. Due to the age of the learners, future research may use firstly, teachers' grading reports and secondly, combine grades from the tested subject in the CBLE learning unit with overall school year grades as a means to represent the overall performance level in an improved way.

Given the difficulty of conducting research with young learners, the present research in this thesis offers detailed insights into the importance of person-centered variables for the creation of adaptive metacognitive prompts and allows to draw implications for SRL support in CBLEs.

8.3.3 Implications for SRL support in CBLEs

The findings on prior performance as a moderator in the present research suggest that a person-centered approach within SRL support research can be valuable. It calls for learning environments to be more sensitive to the young learners' individual conditions when providing learners with adaptive metacognitive prompts as a means to support SRL. This sensitivity can be achieved through the integration of high adaptivity of the SRL support and the CBLE.

In order for high adaptivity to be available for metacognitive prompts and CBLEs, it is necessary to enable precise measurements of the learners' individual characteristics in the CBLEs. Prior performance has been shown to influence the effective use of the metacognitive prompts in terms of transfer learning performance in the present research and may, therefore, be in the center of measurements and adaptivity in future research. To determine how these prior abilities implicated transfer learning performance, future research may focus on exploring young learners' basic executive functions, following Diamond (2016). The developmental perspective in her work shows that differences in working memory, focused attention or inhibitory control may influence cognitive flexibility and thereby impact higher level executive functions including SRL processes (Perry et al., 2017). This will allow to further investigate personalized SRL support among young learners, following the example of Lim et al (2023) who examined personalized SRL support among university students.

With the emergence of AI in the educational sector in recent years (Molenaar, 2023; OECD, 2021), it seems feasible in the future to integrate precise measurement and advanced adaptivity of learning contents to tailor SRL support to the learners' needs. While the use of AI to create adaptive SRL support is still limited (Sharma et al., 2024), its unique opportunity when successfully integrated in future technologies can no longer be denied (Khalil, et al., 2024). Two exploratory studies show the potential of adaptive SRL support in adaptive learning environments. Firstly, the work by Mejeh and Rehm (2024) shows that using data analytics and machine learning algorithms in combination with natural language processing enables adaptive SRL support in computer-based learning. Secondly, Ng et al. (2024) employed a ChatGPT enhanced bot to provide adaptive SRL support and compared it to a rule-based AI chatbot. Their work demonstrate that generative AI supported technologies have great potential to enhance learning and SRL. Future research is needed to better understand the use of rule-based and generative AI in SRL support and how it can be used to generate responsible responses. Following Mejeh and Rehm (2024), the present research project highlights the importance of collaboration between disciplines to provide personalized learning contents with adaptive SRL support in CBLEs. It is suggested that learning researchers work closely with CBLE developers and the school community to enable these technologies to successfully support learning.

The idea of scaffolding, in which an expert facilitates a learner's progression from the current level of comprehension to the next level (Vygotsky, 1997) can be extended to CBLEs through adaptivity. Adaptive metacognitive prompting, therefore, presents an evolved form of scaffolding, in which the process of scaffolding is no longer limited to interactions between a more knowledgeable human and a learner (Devolder et al., 2012). Instead, as demonstrated by the present research of this thesis, adaptive metacognitive prompting presented a promising solution for young students with SRL supported learning in CBLEs. As shown in the findings of this thesis, future research is needed to further investigate which form of adaptivity within the metacognitive prompts and the CBLEs is needed to also provide low achieving students with SRL support. In the future of computer-based learning, high adaptivity in sophisticated CBLEs may provide personalized SRL support that is comparable to one-on-one instruction. These CBLEs with personalized SRL support can then assist educators reach their goal of individually supporting their students' learning process.

9. Conclusion

This thesis has emphasized the importance of SRL and how a lack of these skills can be a challenge when learning in CBLEs and in the process of lifelong learning. Metacognitive prompting, a form of SRL support for CBLEs, has been identified in previous research as a protective factor for successful learning in university students' computer-based learning. The present research in this thesis, therefore, investigated whether adaptive metacognitive prompting can be beneficial for young learners. Two empirical studies have been conducted with learners in lower secondary school. The between-subject design of the two studies allowed to gain deep insights into young learners' prompted and unprompted SRL activities and enabled conclusions, firstly, on the effects of the prompts in terms of the development of SRL, prompt compliance, and prompt design. Secondly, the analyzes on the effects of metacognitive prompting on recall and transfer performance allowed for the exploration of the influence of learners' characteristics on the successful use of the prompts and highlighted the importance of prior performance. Taken together, the adaptive metacognitive prompts positively influenced the learners' metacognitive SRL activities, which can be seen, despite the addressed limitations, as a promising result. Future investigations are needed to shed light into the effects of adaptive metacognitive prompting on learning performance, particularly among low-achieving young learners. As technological developments, including data analytics and AI, continue to advance, research in SRL should continue to explore how future CBLEs can provide personalized SRL support that is closely aligned with the individual needs of learners.

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