Metacognition and Learning (2022) 17:683–690
https://doi.org/10.1007/s11409-022-09327-6

Introduction to the special issue: the role of metacognition in complex skills - spotlights on problem solving, collaboration, and self-regulated learning

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Received: 20 October 2022 / Accepted: 25 October 2022 / Published online: 22 November 2022

Keywords Complex skills · Metacognition · Self-regulated learning · Problem solving · Collaboration 21st-century skills

Challenges in the 21st century have radically transformed our society and the future of education (e.g., Autor et al., 2003; Cascio 1995; OECD, 2014, 2017, 2021). Students are required to learn, use, and transfer a set of complex skills, such as collaboration, problem solving, and self-regulated learning (e.g., Graesser et al., 2018). There is mounting evidence from both a research and an educational practice perspective that these skills, in addition to core domains such as math and reading, are critical for future success at work and life as a citizen (Graesser et al., 2018; Greiff et al., 2014; National Research Council, 2012; OECD, 2017).

One salient demonstration of these changes is the inclusion of these skills in the Programme for International Student Assessment (PISA; OECD, 2014, 2017), which is a major large-scale educational assessment conducted in over 70 countries by the Organisation for Economic Co-operation and Development (OECD). Self-regulated learning was acknowledged in 2000, whereas both collaboration and problem solving subsequently were adopted in this large-scale assessment. Creative problem solving was included as an innovative domain in PISA in 2012 and collaborative problem solving in 2015, complementing the core domains of reading, mathematics, and science. In addition to these international assessments, the National Assessment of Educational Progress, the "Nation's Report Card" in the US, considers the inclusion of measures of collaboration as an add-on to the existing assessments (NCES, 2017).

It is widely acknowledged that these 21st -century skills are needed for success in today's world requiring specific fundamental *cognitive* skills or processes such as the

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application of effective basic cognitive strategies (Corno & Anderman, 2015; Wüstenberg et al., 2014). In addition, the application of complex skills requires *metacognition* and *self-regulation processes* that include goal setting, planning, monitoring goals and progress, and reflection (Azevedo & Gašević, 2019; Schunk & Greene, 2018; Veenman et al., 2006; Winne, 2018; Winne & Azevedo, 2022).

The role of metacognition is undisputed in learning in domain-specific contexts, such as mathematics, reading, and science. Also, the need to understand the role of metacognition in complex skill sets that span problem solving, collaboration and self-regulated learning is growing in importance because of the disruptive changes in the 21st century (Greiff et al., 2014; Dunlosky & Rawson, 2019). Unfortunately, current scientific knowledge of metacognition in these complex skills is sparse, especially regarding collaboration and problem solving. It could therefore be argued that the role of metacognition in these complex skills should require more attention in future empirical studies (e.g., Graesser et al., 2018; Greiff et al., 2014). Indeed, this is the target of this special issue.

The relationship between metacognition and self-regulated learning has been studied extensively as a complex skill and is included in this special issue besides problem solving and collaboration for three reasons. First, self-regulated learning plays a prominent role in 21st -century learning and has traditionally been viewed as closely intertwined with metacognition (Winne & Azevedo, 2022; Winne & Hadwin, 1998). Thus, examining the role of metacognition in complex skills without considering self-regulated learning would be like fishing without a fishing pole. Second, the complex skills discussed in this special issue overlap in important aspects such as conceptualization, and thus, the findings from self-regulated learning are also relevant to other complex skills such as problem solving or collaboration, and vice versa. Third, this special issue was deliberately open to articles that have metacognition as the main topic (e.g., its assessment, its development) and self-regulated learning is well within the scope. Since self-regulated learning has arguably been the most studied complex skill in the field of metacognition, excluding self-regulated learning would exclude many potentially relevant articles and would prevent incorporating valuable findings for this special issue.

For this special issue, articles were sought from researchers addressing the role of metacognition in any of the complex skills addressed. Specifically, contributions were solicited on one or more of the following research questions, all related to any of the complex skills:

1) *Interplay*: Which metacognitive aspects are involved and what role do they play in the respective skill set(s)?
2) *Methods*: By means of which methods can metacognitive aspects be assessed?
3) *Development*: How do metacognitive aspects develop?
4) *Training and instruction*: How can metacognitive aspects be trained and instructed in the long run?

In terms of interplay, we asked that the relevant metacognitive aspects be properly defined, based on a solid theoretical foundation, and integrated with the complex skills investigated. Many metacognitive aspects (e.g., metacognitive skills, metacognitive knowledge, metastrategic knowledge) can be subsumed under the umbrella term "metacognition" so a clear definition of which aspects are under focus is imperative (Alexander et al., 2008; Veenmann et al., 2006).

Regarding methods, we sought articles that had new advances in both assessments for metacognition in complex skill sets and methodologies. For instance, recently emerging

data-intensive process-oriented methodologies (e.g., log files, learner-system interactions, physiological arousal) have the potential to shed additional light on the processes underlying those core aspects of human performance (e.g., Greiff et al., 2015, 2018).

Regarding development and training, we sought contributions that described how metacognitive aspects develop over time or how they can be fostered and transferred to different tasks or domains. For instance, we looked for contributions that examined how training complex skills, including metacognitive aspects, leads to increased performance in the complex skills.

Contributions

This special issue has eight articles, seven empirical articles (including one systematic review) and one theoretical article. All the articles address metacognition in complex skills collectively spanning self-regulated learning, problem solving, collaboration, and related higher-order thinking. The articles are listed and summarized in Table 1, including the complex skill addressed, and an evaluation of the guest editors on how the authors addressed one or more questions of this special issue.

Four articles addressed self-regulated learning. In an intervention study, Stebner et al. (2022) demonstrated how hybrid training of cognitive and metacognitive skills facilitates near transfer and to some extent far transfer of metacognitive skills. Eshuis et al. (2022) reported an intervention study of self-directed learning in which students were engaged in technical problems and asked to create concept maps of their acquired knowledge. Following the concept maps, students received various treatments. Results showed that students who received a combination of different treatments, including class discussions, made higher learning gains. In an exploratory study, van der Graaf et al. (2022) examined how self-regulated learning during learning contributes to different, specific learning outcomes. They provide an initial picture of how considering different levels and structures of knowledge helps to understand the relationship between metacognitive knowledge, self-regulated learning activities, and corresponding learning outcomes. In a theoretical article, Winne (2022) describes how software tools and learning analytics can help support self-regulated learning for learners in N = me approaches and calls for more synergy between research on individual learners and learning science.

Two articles addressed collaboration. Malmberg et al. (2022) presented an approach to using physiological arousal as a proxy for assessing metacognition during collaboration. They demonstrate that students' task perception during collaboration is reflected in electrodermal activity (EDA). Using case vignettes, Melzner et al. (2022) demonstrate how students regulate the use of strategies during collaboration and at what social level (self- vs. co- vs. shared-level) they use these strategies.

Two articles investigated problem solving or higher-order thinking. Nicolay et al. (2022) used a cross-lagged panel design to explore how metastrategic knowledge about a particular strategy and successful use of that cognitive strategy develop from sixth to ninth grade. They analyzed data from a representative sample and report that both metastrategic knowledge and cognitive strategies are strongly intertwined and influence each other during development. Zohar and Ben-Ari (2022) conducted a systematic review of teachers' knowledge and professional development related to metacognitive instruction in the context of higher-order thinking. They point to the importance of metastrategic knowledge in

Table 1 Overview of the contributions in this special issue

Authors	Complex skill	Addressed question(s) of this special issue
Eshuis, ter Vrugte, & de Jong	SRL *electricity-related topics*	Present a **training** approach to promoting the quality of (certain) metacognitive skills and learning gains through various interventions using concept maps, showing that a combined intervention including expert examples of concept maps, reflection prompts, and classroom discussions are most effective.
Stebner, Schuster, Weber, Greiff, Leutner, & Wirth	SRL *different contexts*	Provide evidence of when metacognitive skills **training** is beneficial for transferring metacognitive skills to tasks of different transfer distances and for acquiring content knowledge in these tasks.
van der Graaf, Lim, Fan, Kilgour, Moore, Gašević, Bannert, & Molenaar	SRL *learning in a digital learning environment*	Provide insights on the **interplay** of metacognitive knowledge, metacognitive skills/self-regulated learning for relevant learning outcomes.
Winne	SRL	Provides in a theoretical article how software tools and learning analytics help to support self-regulating learners' metacognition in N = me approaches, with implications for **training** and **methods**.
Malmberg, Haataja, & Järvelä	Collaboration *collaboration on physics tasks*	Provide data on how the student's perceived task difficulty of a collaborative task was reflected in electrodermal activity, thus providing **methods** on how additional physiological data can be used to measure metacognition during collaborative learning.
Melzner, Dresel, & Kollar	Collaboration *case vignettes*	Provide implications on how strategy usage varies between different demands in certain problems requiring collaboration, and thus, demonstrate one showcase how strategies usage, metacognitive skills, and task demands **interplay** during collaboration.
Nicolay, Krieger, Stadler, Vainikainen, Lindner, Hansen, & Greiff	PS *complex problem solving*	Provide implications on how strategy application and metastrategic knowledge during complex problem solving **develops** from sixth to ninth grade.

Table 1 (continued)

Authors	Complex skill	Addressed question(s) of this special issue
Zohar & Ben-Ari	HOT	Provide in a systematic review that metacognition, and especially metastrategic knowledge, are rarely addressed in a teacher's professional development in the context of teaching HOT, which stays in contrast to the high relevance of metacognition for the **instruction** of HOT.

Note: Complex skill describe the complex skill addressed in the respective articles. If a complex skill covers a certain context/domain/task, this was further specified in italics. The fit between the implications of the article to the targeted question(s) of this special issue was evaluated by the guest editors. SLR = self-regulated learning, PS = problem solving, HOT = higher-order thinking.

teachers' ability to teach higher-order thinking, so they argue for more systematic and comprehensive efforts to incorporate metastrategic knowledge into teacher education.

In sum, this special issue contains articles that examine the underlying processes empirically and theoretically, using multimodal techniques such as process data, physiological arousal, or other observational data. The authors focused on rigorous and replicable research methods, providing valuable insights for further research and educational practice in the context of metacognition in complex skills. In conclusion, we believe that these contributions demonstrate that the value of research in this area is not asking "either/or" questions (i.e., "metacognitive skills or metastrategic knowledge", "quantitative or qualitative measurement", "collaboration or self-regulated learning") but rather a search for synergy among research, learners, practitioners, and scholars from different perspectives to equip the next generation with the best opportunities we can all collectively provide.

Acknowledgements We would like to thank the journal managers and the journal staff of *Metacognition and Learning* for their support in all practicalities. We would especially thank the editor-in-chief, Dr. Anastasia Efklides, for her support of the special issue. We also thank all authors for their contributions, and reviewers for their critical comments and valuable suggestions on the respective contributions - without the contributions and the critical reflections, this special issue would not be assembled. Finally, we would like to express our gratitude to Dr. Susanne Narciss for the fruitful discussions on an earlier draft of this editorial.

Funding Open Access funding enabled and organized by Projekt DEAL. This article and special issue were supported by funding from the National Science Foundation (DUE#1761178, DRL#1916417, and BCS#2128684) awarded to Roger Azevedo. All statements expressed in this article are those of the authors and do not reflect the official opinions or policies of the authors' host affiliations or any of the supporting institutions.

Declarations

This study did not involve human data, and no ethics committee approval was required. All authors were in agreement with the submission of this manuscript.

Conflict of interest The authors declare that they have no conflict of interest.

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