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Cue-based facilitation of self-regulated learning: A discussion of multidisciplinary innovations and technologies

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ABSTRACT

This article discusses the seven contributions to the special issue *Facilitation of self-regulated learning*. We first introduce the cue-utilization framework to study self-regulated learning; the basic idea of this framework is that learners use whatever cues are available to monitor and control their learning processes. This framework is then used to position, discuss, and critically compare the seven contributions, which represent a wide variety of approaches to self-regulated learning. Based on our analysis, five main conclusions are presented: (1) there is a tendency to focus investigations on learners' monitoring and reflection whereas it might be more fruitful to take the full learning cycle into account, (2) there are strong indications that learners' use cues to regulate their learning but which cues they are actually using depends on many different factors including the type and level of learning, (3) there is a clear need for the provision of *metacognitive prompts* to learners that stimulate them to use more diagnostic cues and make better control decisions, (4) on the instructional-sequence level, facilitation of self-regulated learning might include 'second-order' scaffolding where the number of prompts decreases as learners acquire more self-regulated learning skills, and (5) affective states may serve as cues but how they interact with cognitive cues is still unknown. We conclude that a design approach to self-regulated learning might help to acknowledge its enormous complexity.

1. Introduction

Learning environments in contemporary education are quickly changing. New technologies are used to make them more flexible and to realize individualized learning trajectories that meet the demands of an increasingly diverse group of learners, with different educational profiles, learning needs, and interest. These new, more flexible learning environments typically make a greater demand on students' self-regulated learning skills (Van Meeuwen, Brand-Gruwel, Kirschner, de Bock, & van Merriënboer, 2018). That is a potential problem, because research has shown that learners often have faulty ideas on how they learn and remember which leads to ineffective forms of self-regulated learning and overconfidence in own learning capabilities (Bjork, Dunlosky, & Kornell, 2013). Therefore, a development towards more flexible technology-enhanced learning environments must go hand in hand with the teaching of self-regulated learning skills, which are both critical to learning in modern education and to lifelong learning in a fast-changing society where learners must be prepared to autonomously acquire new knowledge and skills. Often, teaching self-regulated learning skills entails a gradual transition from external regulation (by a teacher or other intelligent agent) to self-regulation in a system of 'shared control' (Van Meeuwen et al., 2013). The contributions to this special issue presented state-of-the art innovations and technologies to facilitate self-regulated learning and thus addressed an urgent issue in contemporary education.

The aim of this article is to provide a discussion and synthesis of the seven contributions to the special issue. Its structure is as follows. First, we present a theoretical framework to study self-regulated learning. This framework gives a central role to Koriat's idea of *cue utilization* in self-regulated learning (1997; see also De Bruin & van Merriënboer, 2017). Second, this framework will be used to position, discuss, and critically compare the seven contributions. The third section presents the main conclusions and sketches some directions for future research.

2. A framework to study self-regulated learning

This section will describe a framework for investigating self-regulated learning. It starts with a description of self-regulated learning as a basic learning cycle that is made up of two complementary processes: metacognitive *monitoring* of the learning process and, based on the monitoring results, *controlling* the learning process. Second, we will argue that *cues* play a central role when learners monitor and control their learning, and that in the teaching of self-regulation *metacognitive prompts* should help students to use diagnostic cues, that is, cues that are predictive of later performance. Third, we will explain that the effectiveness of cues and prompts depends on the desired type of learning. For example, the ability to provide keywords after reading a text might yield a good cue for elaboration (i.e., constructing new

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knowledge by connecting new information to what you already know) but not for inductive learning (i.e., constructing new knowledge by solving a variety of problems). Fourth, the effectiveness of cues and prompts not only depends on the desired type of learning but also on the level at which learning takes place, either learning from a single topic or task (i.e., the task/topic level) or learning over a series of topics and tasks (i.e., the instructional-sequence level). This section will end with presenting review questions that are based on our theoretical framework and that will then be used to critically discuss each contribution to the special issue.

2.1. Monitoring and control

Two important and complementary sub processes in self-regulated learning are monitoring and control (Nelson & Narens, 1990). Monitoring is the term used to refer to the metacognitive thoughts learners have about their own learning. For example, learners who are reading a study text will monitor their level of comprehension of the text. Control refers to how learners respond to the environment or adapt their behavior based on their metacognitive thoughts. For example, if comprehension monitoring leads to the thought that an expository text is not yet well understood, the learner might ask for extra explanation from a teacher or a peer. Monitoring and control are closely linked to each other in one and the same learning cycle: It only makes sense to ask learners to monitor or reflect on their performance when they are in a position to use their metacognitive thoughts to control or plan future actions. Furthermore, metacognitive monitoring and control play an important role during the phases of acquisition of new knowledge and skills as well as their retention and retrieval (Nelson & Narens, 1990).

2.2. Cues and metacognitive prompts

When students regulate their learning, their monitoring judgments are typically based on cognitive cues that are more or less predictive of future performance, that is, they differ in their *diagnosticity* (Koriat, 1997). One example of a cue with low diagnosticity is that information is easily recallable immediately after studying a text; it is then easily recallable because it is still active in working memory but not because it can be readily retrieved from long-term memory as will be required in a future test. Thus, a much better cue is whether the information is easily recallable a few hours after study (this is called the 'delayed judgment-of-learning effect'; Dunlosky & Nelson, 1992). Unfortunately, the recallability of information directly after study is a cue with low diagnosticity but high *utilization*, that is, students are inclined to actually base their regulation decisions on this particular cue.

To regulate their learning, learners use whatever cues are available as to their current level of learning. A problem here is that they tend to use invalid and/or superficial cues (i.e., high utilization combined with low diagnosticity), which may also explain why they are typically overconfident when predicting their future performance. When learners use invalid cues and/or are overconfident, this has negative consequences for their control decisions, for example, they use surface rather than deep learning strategies, they terminate practice or study too early, or they skip particular elements during practice or study. In turn, this will also have negative effects on their learning outcomes (Zimmerman & Schunk, 2001). To improve self-regulated learning, students need to be stimulated to use cues with a higher diagnosticity. This typically requires providing *metacognitive prompts* that should be carefully designed and situated before monitoring and control tasks (Taminiau et al., 2015; van den Boom, Paas, & van Merriënboer, 2004; 2007). Table 1 provides some examples of metacognitive prompts.

2.3. Regulating different types of learning

Accurate monitoring must, thus, be based on diagnostic cues. While metacognitive prompts can stimulate learners to use such cues and facilitate self-regulated learning. What valid cues are and what good metacognitive prompts are depends on several factors. A first factor is the desired type of learning. Van Merriënboer's four-component instructional design model (4C/ID; Van Merriënboer & Kirschner, 2018a, 2018b; for its relation with self-regulated learning, see also Van Merriënboer & Sluijsmans, 2009), for example, distinguishes four different types of learning which correspond with four instructional components that should be interrelated to each other in order to promote a process of 'complex learning': (1) learning tasks aim at *inductive learning*, (2) supportive information aims at *elaboration*, (3) procedural information aims at *rule formation,* and (4) part-task practice aims at *strengthening* cognitive rules.

Inductive learning and elaboration are sub processes of *schema construction*, that is, the construction of general and/or abstract cognitive schemas in long-term memory (Van Merriënboer, 2016). When new problem situations are encountered, well-developed cognitive schemas can be flexibly used by the learner; thus, they allow for transfer of learning because the same schema can be used in different situations. When learners perform tasks aimed at inductive learning (i.e., inducing schemas from a variety of concrete experiences), they may be inclined to use monitoring cues with a low diagnosticity for transfer of learning. Fluency, accuracy and speed, for example, might be good indicators of their current performance but they are *not* good diagnostic cues for the construction of rich schemas. Just because performance on a task is fluent, accurate and fast does not mean that the learner will be able to carry out transfer tasks (Bjork et al., 2013). Being able to perform a task in different ways or by using different approaches, in contrast, is a better diagnostic cue for transfer of learning. We may, thus, prompt learners to try to perform a task in different ways so that they receive cues that are more diagnostic for their future performance on transfer tasks. Yet, such prompts may have negative effects on immediate performance (e.g., errors are made and/or it may take more time to complete the task) but have positive effects on learning and transfer, an effect known as the 'transfer paradox' (Van Merriënboer, de Croock, & Jelsma, 1997).

When learners study supportive information aimed at elaboration (i.e., elaborating schemas by enriching newly presented information with already existing prior knowledge), immediate recall of only the presented factual information is not a good indicator of the construction of rich schemas because the fact that studied information can be readily recalled does not predict performance on future tasks requiring deep understanding. The ability to self-explain the information, to generate keywords, or to make diagrams of it provides, in contrast, better diagnostic cues for future performance. We should thus prompt learners to self-explain information or to provide keywords or diagrams of it so that they receive diagnostic cues. Yet, such prompts may have negative effects on the immediate study process (e.g., study costs more time and effort) but positive effects on deep understanding and future performance, a process that is closely related to the transfer paradox and that is caused by so-called 'desirable difficulties' (Bjork & Bjork, 2011).

Rule formation and strengthening are sub processes of *schema automation*, that is, the automation of highly specific cognitive schemas (also called 'cognitive rules') in long-term memory, which the task performer can use fast and effortlessly to perform routine aspects of tasks (Van Merriënboer, 2016). When learners consult procedural information aimed at rule formation (i.e., they follow 'how-to' instructions), the ability to perform the current task with the procedural information at hand is not a valid cue for rule formation; instead, learners should ask themselves whether they will be able to perform the same task a next time *without* consulting the procedural information. In other words, being able to operate a computer program by following the instructions in a manual is not a good cue for available cognitive rules; a better cue is provided by trying to do the same operations at a later time *without* using the manual. Metacognitive prompts should thus invite the learner to perform routine aspects of a task *without* having the procedural information (how-to instructions) at hand, so that diagnostic cues

Table 1
Examples of metacognitive prompts for facilitating self-regulation of different types of learning at the task/topic level and the instructional-sequence level.

	Examples of Metacognitive Prompts		
	Type of learning/instructional component	*Task or topic level*	*Instructional sequence level*
Schema Construction	Inductive learning/learning tasks	• Would you be able to perform this task in an alternative fashion? • Can you indicate any risks or suboptimal approaches for performing this task?	• Can you explain how this task is different from previous tasks you performed? • Which future task will help you work on points of improvement?
	Elaboration/supportive information	• Can you self-explain the information you just studied? • Can you summarize or build a diagram of the information you just studied?	• What additional learning resources might help you to increase your understanding? • What resources should you re/study in order to be able to perform future tasks?
Schema Automation	Rule formation/procedural information	• Would you be able to perform this routine aspect of the task *without* the availability of just-in-time instructions? • If you make an error, would you be able to recover from this error without asking for help?	• Which how-to instructions can help you become more accurate and make less errors? • Will you be able to perform this task next time *without* the learning aid?
	Strengthening/part-task practice	• Does it cost you any mental effort to perform this task? • Would you be able to perform it simultaneously with other tasks?	• Did your investment of effort decrease over the last practice sessions? • Should you continue practicing under higher speed stress and time sharing conditions?

for schema automation become available.

Finally, when learners do part-task practice aimed at strengthening cognitive rules (i.e., repetitive practice aimed at the full automation of rules such as drilling multiplication tables in primary school or recognizing dangerous situations on a radar screen in a training program for air traffic controllers), the ability to perform the task accurately and without errors is not a valid cue because this does not properly inform the learner about the achieved level of automaticity; instead, learners should use speed, invested mental effort (Blissett, Sibbald, Kok, & van Merriënboer, 2018), and time-sharing abilities as more valid cues for the achieved level of automaticity, because an automated task can be performed very fast, effortless, without conscious control and thus together with other tasks (Sweller, van Merriënboer, & Paas, 2019). Metacognitive prompts should thus invite the learner to perform the routine aspects of a task simultaneously with other tasks or to rate their performance on speed and mental effort, so that diagnostic cues for the strength of acquired cognitive rules become available. The four rows in Table 1 give some examples of metacognitive prompts for the four different learning processes.

2.4. Regulating learning at different levels

A second factor determining what good cues and good metacognitive prompts are relates to the level of learning. Self-regulated learning can take place at different levels. First, at the level of tasks or topics, learners monitor how well they master a particular task which affects how and how long they continue practicing it, or they monitor how well they comprehend, for example a piece of text, animation or video which affects how and how long they engage in studying or restudying it. At this level, cues and metacognitive prompts primarily concern comprehension and mastery.

Second, at the instructional-sequence level, learners monitor how well they performed on one or more learning tasks after completing them which then affects their selection of next suitable tasks and/or other learning resources (Nugteren, Jarodzka, Kester, & van Merriënboer, 2018; Raaijmakers, Baars, Paas, van Merriënboer, & van Gog, 2018; Raaijmakers, Baars, Schaap, Paas, van Merriënboer, & van Gog, 2018). Self-regulated learning at the task-sequence level is often described as *self-directed learning* (rather than self-regulated learning) and cues and metacognitive prompts primarily indicate progress, that is, the increase of comprehension and/or mastery over tasks/topics and over time. Electronic development portfolios that keep track of performed tasks as well as assessment results on those tasks (e.g., Kicken, Brand-Gruwel, & van Merriënboer, 2008; Kicken, Brand-Gruwel, van Merriënboer, & Slot, 2009a; 2009b) are often used as a basis for coaching meetings in which a student and a teacher together discuss progress, points of improvement and future plans for learning (for a review of electronic development portfolios, see Beckers, Dolmans, & van Merriënboer, 2016). The two columns in Table 1 provide examples of metacognitive prompts for the task/topic level and the instructional-sequence level.

2.5. Framework and review questions

To briefly summarize our framework: self-regulated learning consists of two processes that complement each other in one learning cycle: monitoring and control. To monitor and control their learning (i.e. self-regulation), students use whatever cues are available as to their current level of learning. These cues vary in diagnosticity (how accurately they predict actual learning and future performance) and in utilization (the extent to which students actually base their monitoring and control on these cues). Unfortunately, learners are inclined to use cues with low diagnosticity, often leading to overconfidence (Dunlosky & Rawson, 2012). To facilitate self-regulation, metacognitive prompts may help learners to use more diagnostic cues during monitoring and control. However, what good cues and good prompts are depends on the type of learning, the level of learning as well as other factors. Therefore, prompts need to be carefully designed and situated before monitoring and control tasks.

Our theoretical framework will serve as a lens to study the seven contributions to this special issue. For each contribution, three questions will be answered:

1. What type of learning is at stake?
2. At which level does the self-regulation occur?
3. What cues were used by the learners and were these cues elicited by particular metacognitive prompts?

3. Discussion of the contributions to this special issue

Table 2 positions the seven contributions to this special issue in our theoretical framework. The first contribution by Noroozi, Alikhani, Järvelä, Kirschner, and Juuso (this issue) described a tool for visualizing and processing multimodal data. The tool, SLAM-KIT, is a Graphical User Interface developed in MATLAB that helps researchers to collect and analyze rich self-regulated learning data originating from individual learners, pairs of learners (CoRL; Co-Regulated Learning), and groups of learners (SSRL; Socially Shared-Regulated Learning). The

Table 2
Positioning the seven contribution in our theoretical framework.

Study	Type of Learning	Level of Learning	Prompts provided	Cues elicited (with or without prompt)
1. Noroozi, Alikhani, Järvelä, Kirschner, and Juuso	Not specified, all types of learning	Task or topic-level	No prompts provided but these can be developed. E.g., prompt students to use 'synchronicity' as a cue for co- or shared regulation	Multimodal data collected and visualized with SLAM-KIT could, in principle, also be presented to students and serve as cues
2. Cui, Wise, and Allen	Not specified, all types of learning	Instructional-sequence level	Fixed and given by the online reflection system: Personal, professional, ethics, progress	Statements reflect use of different types of cues for different types of statements/prompts
3. Verstege, Pijeira-Diaz, Noroozi, Biemans, and Diederen	Inductive learning	Task or topic level	Accessing the virtual teacher for feedback on experimental design; accessing background information units; requesting the answer to a calculation; accessing hints	Accuracy of experimental design; accuracy of students' background knowledge; accuracy of students' calculation; accuracy of students' knowledge; number of attempts to complete preparation questions; number of meaningful clicks in the simulation; number of attempts to answer all questions
4. Dindar, Alikhani, Malmberg, Järvelä, and Seppänen	Elaboration (task 1) and inductive learning (task 2)	Task or topic level	No explicit prompts provided, but indications that different prompts might be needed for collaborative learning (e.g., synchronicity) and cooperative learning.	Cognitive cues; motivational cues; emotional cues; behavioral cues
5. Rienties, Tempelaar, Nguyen, and Littlejohn	Inductive learning	Instructional-sequence level	Study aims at the development of prompts (adaptive feedback) for subgroups of learners	Different groups of learners seem to use different types of cues, based on scheduled group meetings, performance on quizzes, and scheduled examinations
6. Spann, Shute, Rahimi, and D'Mello	Inductive learning	Task or topic-level	What did you do to manage your strongest emotion? Effort ratings	Dominant affective state (one of nine options); chosen affective regulation strategy (one of six options); experienced effort
7. Lund	Elaboration (case 1) and inductive learning (case 2)	Task or topic-level	Prompts aimed at regulation of learning are rarely given but seem to be different for elaboration and inductive learning	Verbalizations and actions in the context of collaborative knowledge construction

data may include time-stamped video and audio recordings of the teaching-learning process and corresponding physiological data such as electrodermal activity, heart rate, eye movements, and facial expressions. A major claim of the authors is that a deep understanding of self-, co- and shared regulatory processes in - collaborative - learning requires the measurement, visualization and triangulation of multimodal data. We fully agree with that idea, but it should be noted that SLAM-KIT is “just a tool” and as indicated by the authors, coding and interpretation of the combined data channels still needs to be done by the researchers.

In our framework, the tool will be most useful to collect multimodal data on the task or topic level, that is, when learners work on a collaborative problem-solving task or when they discuss a study text together. Then, a first step will be to investigate which patterns of signals are actually related to the *regulation* of learning; a very interesting idea presented in this paper is, for example, that the synchronicity of physiological signals from collaborating students informs us about the level of co-regulation or socially shared regulation. Particularly interesting in this regard is recent research on brain synchronicity: Research by Dikker et al. (2017) shows that more synchronicity in EEG waves during classroom activities correlates with higher classroom engagement in students. See also the study by Dindar et al. (this issue) for an innovative measurement and analysis of physiological synchronicity (i.e., electrodermal activity). Second, it seems necessary to disentangle - patterns of - signals that either relate to monitoring and monitoring cues (e.g., looking at or paying attention to particular objects in the environment, effort and speed related measures) or to control and control cues (e.g., use of particular learning resources, keystrokes and mouse movements). Here, it might be interesting to study if there are differences in regulation patterns between different types of learning, for example, between collaboratively learning from a study text (elaboration) or cooperatively solving a problem (inductive learning; see also our discussion below of Dindar, Alikhani, Malmberg, Järvelä, and Seppänen, this issue). Third, it would be interesting to find out which regulation patterns indicate the use of cues with high diagnosticity, by comparing groups that show a low versus high level of regulation and/or groups that show low versus high performance. We think that more knowledge about effective regulation patterns is needed before SLAM-KIT can be sensibly used with learners (or teachers). Just presenting learners with a wealth of multimodal data is, in our opinion, not helpful for learning: we should at least be able to provide metacognitive prompts to learners that help them focus on diagnostic cues in these data.

Cui, Wise, and Allen (this issue) focused on student reflections which were systematically collected in an online reflection system. They described a conceptual framework distinguishing six reflection elements: (1) description, where students describe their observations, (2) analysis, where students make sense of their learning events, (3) feelings, where students describe their affective reactions, (4) perspective, where students demonstrate changes in perspective, (5) evaluation, where students identify their strong and weak points, and (6) outcomes, where students describe lessons learned and future plans for learning. In our terminology, the first five elements pertain to ‘monitoring’ and the sixth one to ‘control’. Students' reflective statements at the beginning and at the end of a four-year dentistry program were collected and automatically analyzed using Linguistic Inquiry and Word Count (LIWC) indices. It was found that different types of reflection statements (e.g., personal reflection statements, reflections on becoming a professional, ethical reflections, reflections on professional progress) elicited the use of different reflection elements. Furthermore, there were changes over time, for example, statements of fourth-year students were longer than statements of first-year students and, surprisingly, fourth-year students were less oriented to making future plans (i.e., made fewer statements categorized as 'outcomes') than first-year students.

This study made an important contribution to the automatic analysis of self-regulated learning processes. When the study is interpreted in our framework, it is clear that the focus is on the instructional-sequence level while the type of learning is not specified. Making a distinction between types of learning the reflections are about might be useful for future work, for example, reflections on 'becoming a professional' might be relevant to learning from learning tasks (i.e. inductive learning) but less relevant to learning from supportive information (i.e. elaboration). Metacognitive prompts were not named as such, but they were actually provided through the online reflection system that prompted students to use different types of statements (personal, becoming a professional, ethical, progress). Different types of statements elicited the use of different reflection elements, which suggests that students used different monitoring cues as a result of the different prompts. An obvious example is the more extensive use of the element 'feelings' in personal and ethics statements, which suggests that affective cues play a central role here. Including the role of cues in the self-regulated learning process and, even more importantly, looking at the diagnosticity of the used cues (i.e., are they predicting future performance?) is an important direction for future research. Only then, can student reflections become truly informative for the quality of their self-regulated learning. As a related issue, it might be helpful to make a clearer link between monitoring statements and control statements to consistently close the learning cycle. Now, the online reflection system did not explicitly ask student to link monitoring statements to control statements (i.e., the reflective element 'outcomes') and even the use of the word 'reflection' might have prompted students to look more into the past than in the future. Possibly, this might also explain why year-4 students were less oriented to making future plans than first-year students.

Verstege, Pijeirra-Diaz, Noroozi, Biemans, and Diederen (this issue) examined the relation between self-perceived self-regulation and learning behavior in a virtual experiment environment (VEE). Master students in an enzymology course engaged in a simulated learning environment preparing them for laboratory class. The goal of the VEE was to learn and apply concepts related to the ensuing laboratory class. Students needed to answer research questions by following the scientific cycle (i.e., formulating a hypothesis, designing an experiment, testing the hypothesis, interpreting findings). Students had help options when doing so: They could request feedback from the virtual teacher, the correct calculation to a problem, or hints on how to continue. Moreover, students' attention was cued to important information by a blinking signal. Results showed that students with low self-regulated learning skills (low-SRL) differed from medium-SRL students in number of attempts to answer the preparation questions, number of meaningful clicks in the VEE, and number of answers to calculations requested, but no differences were found in the remaining four learning behavior variables. The low-SRL and high-SRL students outperformed the medium-SRL students on the post test.

When analyzing these findings in light of the cue-utilization framework, we see that students were provided several potential prompts, such as help from the virtual teacher, hints, and feedback on the correct answer, but had to self-decide whether to use the prompts. This autonomy in prompt use created variance in cue availability for monitoring and regulation, and added an extra level of self-regulation that may have unwantedly affected task load: students not only monitored and regulated their learning, but also monitored and regulated the need for prompts. Some of these prompts provided potentially diagnostic cues about the level of learning. For example, feedback from the virtual teacher on the correctness of the experimental design or feedback on the correct answer to a calculation should help learners diagnose the correctness of their design and calculation and inform further regulation steps to take (i.e., to proceed to the next step or redesign/recalculate). The other two prompts (accessing background information units and accessing hints) may have provided diagnostic cues, but since these prompts were more indirect as to feedback on students' learning, it was more difficult for students to actually *use* these cues to monitor and regulate further learning. Finally, the monitoring cues that were elicited *without* the use of prompts were most indirect to inform students' monitoring and regulation and probably went unnoticed by students. Unfortunately, the design of the study does not allow for actual cue utilization, and for measurement of cue diagnosticity. Incorporating, in future research, explicit measures of monitoring and regulation (e.g., judgments of learning, regulation choices) and the use of metacognitive prompts that elicit cues will allow for measurement of cue diagnosticity and cue utilization, which will help understand how low-, medium-, and high-SRL students differ in metacognitive processes when engaging in a VEE.

Dindar et al. (this issue) unraveled how shared monitoring during collaborative learning relates to physiological synchrony between group members. Three students from a secondary school advanced physics course collaborated to write a group essay on the speed and intensity of light (session 1), and to cooperatively experiment with interference and diffraction (session 2). The authors describe in detail how Multidimensional Recurrence Quantification Analysis (MdRQA) is suitable to measure physiological synchrony among the collaborating students. In the writing task, students' physiological response was correlated with monitoring duration. However, this was not the case for the second session, where no relation was found between the MdRQA indices and shared monitoring.

The small sample size and limited number of tasks asks for caution in interpretation of these findings, but the different types of learning in the two sessions (elaboration versus inductive learning) may possibly explain this discrepancy. The first session, emphasizing jointly searching for information and writing this up, can be described as *collaborative* learning/elaboration, whereas the second session is a case of *cooperative* problem solving/inductive learning. In the first collaborative task, participants work in a coordinated effort on a joint product and aim to construct the same knowledge through elaboration; in the second cooperative task, learners may divide labor to work towards a common goal and construct knowledge through inductive learning (Dillenbourg, Baker, Blaye, & O'Malley, 1996). This difference may explain discrepancies in findings; working on a joint product versus a joint goal will entail more synchronicity, as students will be working together in space and time to a greater extent. This difference in synchronicity will also require different monitoring cues to self-assess progress. In the first task, speed and fluency of completing the task are probably more diagnostic and also more utilized as these types of cues tend to be more available. This match between availability and diagnosticity makes it easier to monitor progress and to stay 'in sync'. The second, inductive learning task where students work less in collaboration and more in cooperation requires different metacognitive prompts, for instance, trying out an alternative approach, or trying the same approach on a new task. These types of prompts are also more difficult to jointly engage in, leading to less shared monitoring.

Rienties, Tempelaar, Nguyen and Littlejohn (this issue) explored distinct clusters of behavioral engagement in a blended learning environment encompassing an online tutorial called Sowiso at different time points: before face-to-face tutorial group meetings (phase 1), before self-quizzes (phase 2), and before the final exam (phase 3). Sowiso contained hundreds of exercises on quantitative methods in business and 'temporal learning analytics' were used to explore when and how the students worked with these exercises. Four clusters of students were identified: (1) 'early-mastery students' who started to work with the exercises right before the first tutorial group meeting and who mastered 95% of all topics at the self-quizzes, (2) 'strategic students' who formed the largest group and concentrated their work on the exercises before the self-quizzes and who reached almost full mastery before the final examination phase, (3) 'exam-driven students' who started to work on the exercises before the examination and who did not reach full mastery, and (4) 'inactive students' who were consistently inactive and who achieved relatively low levels of mastery during the three phases. The clusters were predictive for final course performance: early-mastery students and strategic students did relatively well while exam-driven and inactive students underperformed. In addition, the student clusters differed from each other on several other characteristics, for example, the early-mastery students showed the highest level of external-regulation while the inactive students showed the highest level of lack-of-regulation.

Placed in our framework, this contribution clearly focused on the instructional-sequence level and the online tutorial Sowiso facilitated a process of inductive learning, because students mainly learned by practicing on exercises and studying worked examples. It seems highly plausible that different student clusters used different cues to monitor and control their learning. For the early-mastery group, who showed a high level of external regulation, it seems that a dominant cue to start working on the exercises were the planned tutorial group meetings. This seems to be a disciplined group that 'just prepares' for all planned meetings. The strategic learners orientated their practice on the self-quizzes, which is a successful strategy because self-testing has been found to be an effective way to assess own performance and self-regulate learning (e.g., Fernandez & Jamet, 2017). A systematic review on blended learning (Spanjers et al., 2015) also showed that self-quizzes are an important moderator variable for the effectiveness of blended learning: Blended learning environments that make frequent use of self-quizzes are as effective as face-to-face learning environments, probably because the quizzes help students to self-regulate their learning. For the exam-driven group, the examination at the end of the course seems to be the main cue to start working on the exercises, leading to procrastination, cramming and low final course performance. Finally, the inactive group which scored high on lack-of-regulation does not seem to use any diagnostic cues at all. An important aim of this study was to provide automated feedback to students. Such feedback might well take the form of metacognitive prompts that stimulate students to use more diagnostic cues, which seems to be especially important for the examination-driven and inactive learners.

Spann, Shute, Rahimi, and D'Mello (this issue) investigated affective states, effort, and affect regulation in a challenging game-based physics learning environment. College students participated through Amazon Mechanical Turk and learned qualitative physics principles in a virtual physics world. The most often reported affective states were determination and frustration, the most often reported regulation strategies were cognitive reappraisal or acceptance. Students were more likely to engage in cognitive reappraisal for the easy levels than for the medium and difficult levels of the game. Students were more likely to solve a level if their dominant state was determination/curiosity compared to frustration/confusion. For posttest scores, cognitive reappraisal only had a positive effect for those who put in high effort and who were highly frustrated/confused. Acceptance had a positive effect when effort was low and frustration was high or vice versa.

This study focuses on an underemphasized aspect of self-regulated learning, monitoring and regulation of affect. It shows that affective cues are (also) determining in regulating further learning, particularly in relation to effort regulation; a clear determinant of problem-solving success. Until now, cognitive empirical research on cue diagnosticity and cue utilization has failed to incorporate affective cues (but see Efklides, 2006, for a theoretical framework), but to fully comprehend how learners monitor and control learning, affective cues need to be taken into account. Note, however, that the measurement of affective cues as presented in the paper by Spann et al. (this issue) limits conclusions about causality; for example, it is not possible to know whether the higher problem-solving success is a result or cause of determination/curiosity. Future research could include multiple measurements of affect at different moments during the problem-solving exercise or experimentally induce affective states to unravel causality.

The final contribution by Lund (this issue) presented and illustrated the multigrain collaborative knowledge construction model. This model elegantly intertwines knowledge construction and regulation: On the one hand, both *individual* and *collaborative* knowledge construction can be individually regulated, co-regulated, or socially shared regulated; on the other hand, both an *individual* can construct and a *group* can co-construct knowledge about individual regulation, co-regulation, and socially shared regulation. When we focus on regulation, the model assumes that this is based on both verbalizations and actions and the role of monitoring and control is expressed as follows: "Regarding self-monitoring, people will not be effective at *influencing their own motivation and actions* unless they pay good attention to what they are doing, the conditions under which their actions occur, *and the effects these actions produce*, either immediately or by keeping the causal link in mind for the future" (*italics* added). Thus, control (influencing own motivation and actions) requires careful monitoring of diagnostic cues (not only actions but also the effects these actions produce under particular conditions). The same principle applies for monitoring and control in pairs and groups of learners.

The model is illustrated by two case studies on collaborative learning: (a) conceptual learning in physics, and (b) learning to play a strategic card game. In our framework, the dominant type of learning is elaboration in the first case study and inductive learning in the second case study; both are at the task/topic level. An important finding from the first case study is that little self-regulated *learning* occurs: " … even if students correctly drew models and were able to make a bulb or bulbs shine with their experiments, they did not connect these activities to theoretical concepts of physics, so learning was incomplete". Lund suggests to teach students a 'metaview' of what learning consists of and to provide them with guidance that might well take the form of metacognitive prompts. In the second case study, one learner was teaching three other learners to play a card game. Again, not much regulation of *learning* could be observed. But as we would expect on the basis of our framework and on the basis of the results reported by Dindar et al. (this issue), regulation in the second case study, which studied inductive learning, was different from regulation in the first case study, which studied elaboration. To illustrate this, a quote of one learner in the second case study is: "Are we supposed to first listen to the rules and then play or can we play right away?" (i.e., individual regulation aimed at collaborative knowledge construction). This question makes sense, because learning the rules of the game (rule formation) is best done in the context of actually playing the game (inductive learning); in 4C/ID (Van Merriënboer & Kirschner, 2018a), this corresponds with the guideline to present procedural how-to information just-in-time, precisely when learners need it in order to perform the task. Thus, differences between both case studies strongly support the idea to distinguish different types of learning when doing research on self-, co- and socially shared regulation of learning. Another interesting observation is that some verbalizations or actions can fulfill a double role for monitoring and control: When a student says "I do not understand" (i.e. individual regulation aimed at individual knowledge construction) in the context of playing the game, it expresses self-monitoring but also a request for further explanation by a peer (i.e., control) at the level of co-regulation.

To recapitulate this section: the presented cue-utilization framework for studying self-regulated learning proved fruitful to interpret the findings presented in the contributions to this special issue. The following observations support the value of the framework:

1. Students' use of cues determines their regulation of learning processes.
2. Cues can be external, such as planned meetings or exams, or internal (cognitive, physiological, affective).
3. The use of cues with low diagnosticity seems abundant.
4. Students show important differences in their use of cues.
5. There are strong indications that cues are different for the regulation of collaborative learning (i.e., elaboration) and cooperative learning (i.e. inductive learning).
6. Metacognitive prompts are needed to affect the use of cues, but are not (always) designed with the goal to elicit specific cues in mind.

4. Conclusions

This special issue included a wide variety of studies on self-regulated learning. In spite of this variation, we think the presented cue-utilization framework offered a valuable basis for analyzing and comparing the different studies. Taking our findings on the separate studies together, we reach five overarching conclusions. First, a majority of the studies paid more attention to monitoring and reflection than to control. This is a potential danger because good monitoring and/or reflection are a necessary but not a sufficient condition for effective self-regulated learning: Monitoring is of no use, and may even be experienced by learners as a pointless exercise, when it does not actually enable them to respond to their environment or adapt their behavior. It is thus important to take the whole learning cycle into account and to acknowledge that planning and control should always complement monitoring and reflection.

Second, the presented findings suggest that students use a diversity of cues to monitor their learning and to make control decisions and, moreover, that these cues are dependent on the desired type of learning (inductive learning, elaboration, rule formation, strengthening of rules), the level of learning (on topic/task level or instructional-sequence level), and a range of other factors. For example, both the results of the studies of Dindar et al. (this issue) and Lund (this issue) strongly suggest that cue use is different for learners that cooperate in a process of inductive learning (component 1 in the 4C/ID model) and learners that collaborate in order to elaborate newly presented information (component 2 in the 4C/ID model; see two upper rows in Table 1). Furthermore, in the studies included in this special issue the diagnosticity of cues is often not explicitly taken into account and a distinction between monitoring cues (predicting future performance) and control cues (what to do to improve learning) is often not explicitly made. For future research, it will be helpful to analyze learners' actual use of cues in depth and to relate them to the quality of their monitoring and control decisions. It should be acknowledged that there is not one ‘ideal form’ of self-regulated learning: Depending on the desired type of learning, level of learning and many other factors, different types of cues need to be used by learners for effective self-regulated learning.

Third, several studies in this special issue showed that – particular groups of – learners struggle with self-regulated learning. There is a clear need for the provision of metacognitive prompts to learners that stimulate them to use diagnostic cues and that help them to make better control decisions. To optimize diagnostic cue use it is also important to study how learners actually interpret such prompts. Dunlosky and Rawson (2015), for example, had students learn definitions and gave them feedback prompts asking them to compare their own definition with a golden standard. But despite these prompts, even after comparing their own incorrect definitions with a golden standard, students still overestimated the correctness of their own definitions. Thus, in order to positively affect self-regulated learning, prompts and feedback should not only focus on learning but also on the use and interpretation of diagnostic cues because otherwise we miss an important step in between. Metacognitive cues will only have a positive effect on self-regulated learning when they are carefully designed.

Fourth, it is surprising that studies on the instructional-sequence level did not apply any form of ‘scaffolding’, that is, providing a high level of support and guidance to learners early in the learning process and gradually decreasing that amount of support and guidance as learners acquire more expertise. Scaffolding is an exceptionally strong instructional method when learners acquire complex skills (Reiser, 2004). Van Merriënboer and Kirschner (2018) use the term first-order scaffolding for gradually decreasing support and guidance when teaching domain-specific skills and *second-order* scaffolding when teaching domain-independent/metacognitive skills such as self-regulated learning. Then, learners might receive more, and more direct metacognitive prompts in the beginning of the learning process and gradually receive less prompts as their self-regulated learning skills develop.

Fifth, the studies by Spann et al. (this issue) and Cui, Wise and Allen (this issue) clearly indicated that affective states may serve as cues during monitoring and regulation of learning. No specific prompts are needed, except asking students how they feel. This has been a blind spot in cue-utilization research, and it is relevant to continue research combining affective cue use and (meta)cognitive cue use. Both should be driving monitoring and control, but research as to how to balance these cues is lacking.

To conclude, this special issue presented a varied set of high-quality papers that all contributed important pieces to the jigsaw of self-regulated learning. Our cue-utilization framework proved to be helpful to analyze and synthesize the set of papers. The main lesson learned is that the general idea of “facilitation of self-regulation” might be an over-simplification, because it suggests that there is a limited set of instructional methods that help to reach this goal. It might be more fruitful to acknowledge that self-regulation can take countless different forms. Then, a design approach is needed where we first analyze what type of learning needs to be regulated, what the current regulation skills of learners are, and under which conditions regulation takes place before investigating specific instructional methods, that is, methods that help learners to use diagnostic cues and adaptive control strategies.

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