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Designing a Computer-Supported Collective Regulation System: A Theoretically Informed Approach

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Design-based research argues for the importance of integrating theory with design, but how design decisions are made is rarely documented in educational research. As the interdependence of technology design and education increases, these forms of documentation are becoming more important. To address this need, we present a design narrative describing how we drew on learning theories to design and empirically test a system to help students develop socio-metacognitive expertise (expertise in understanding and regulating collaborative sense-making processes). We end the paper by reflecting on the trade-offs associated with the design decisions we made, the divide that exists between theory and implementation, and the need to further document our design processes to bridge this gap.

Keywords: group processes, socio-metacognition, co-regulated collaborative learning, measurement, collaborative scripts

Within the field of education technology, researchers generally agree that educational software design should be informed by theory, but lack agreement in how theory should inform design and whether designers should document their

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processes. The lack of design documentation is problematic for various reasons, two of which include the inability to build on previous design work and the inability to identify inconsistencies in the design.

Without design documentation, we are limited in our understanding of how the design came to be and therefore also limited in our ability to build new design knowledge (Hoadley, 2002). There are many decisions that need to be made throughout the design cycle. These decisions include how to apply theory, which design idea to pursue, which design idea to leave behind, and how to refine the core ideas behind a system over time. As different design paths compete against each other, designers formulate rationale based on experience or field testing to decide between different options. Design documentation captures these decision-making processes and allows others the benefit of learning from previous designers, the decisions they made, and the impacts that those decisions had on learners. Design documentation contains valuable information that can prevent designers from repeating mistakes, facilitate the pursuit of novel design paths, and thereby promote knowledge building.

Unpacking design decision-making processes is also important to ensuring consistency between the intent of an original design idea and the actual design product. There are many known trade-offs associated with different educational designs and each can impact the type, quality, and transferability of learning (Collins, 1996). It is possible that designers could draw on relevant theories to develop a useful concept for a collaborative system, but make design decisions down the line that negatively impact learning processes or contradict learning theories. Without design documentation, such inconsistencies could go undetected.

Design documents that note design requirements, including the initial conceptions of the design problem and commitments to specific users or theories, help ensure coherence between the initial design and the outcomes. Early in the design process, the goal is to understand the problem that technology is intended to address from multiple perspectives in order to prioritize design commitments as a set of design requirements. These requirements documents are used as a cognitive tool to prevent designers from making poor decisions by drawing on the documents to check ideas and identify trade-offs associated with different design paths. This type of analysis is an effective way for designers to pick between design options to ensure that the final design meets as many of the initial design commitments as possible (Rosson & Carroll, 2002). Later in the process, these requirements documents are also a useful tool for assessing the coherence between design intents and design outcomes.

This type of design documentation is more common in computer and information sciences than in the field of education. However, documentation in computer and information sciences fields relies more on a bottom up approach to design through which developers examine situated practices and focus on making users happy. As a result, learning theories do not play a central role in these design narratives.

As Quintana, Shin, Norris, & Soloway (2006) point out, learning theory must be central to the design of educational technologies because these technologies focus on helping a learner attain specified learning outcomes rather than simply enhancing a user's ability and experience when carrying out work tasks. By examining the role that theory plays throughout the educational design processes, instructional designers can better understand the existing limitations of theory as well as those of the design.

Toward this goal, we present a design narrative focusing on the role that different theories played in designing a learning technology. We do not focus on reviewing previous systems that support collaborative interactions because that is not a main aim of the paper. Our system, designed to help students learn how to monitor and regulate group cognition, is named CREATE: Collective Regulation & Enhanced Analysis Thinking Environment. We begin by discussing our design methods and theoretical assumptions and how these assumptions influenced our initial design ideas. Our aim in presenting the CREATE system first is to help the reader envision different aspects of the system when reading the design narrative that follows. In this narrative, we document our design process and the role that theory played throughout. We conclude the paper with an evaluation of the design decisions we made and suggestions for future research on the design of computer-supported collective regulation systems.

DESIGN METHODS AND THEORETICAL FRAMEWORKS

We followed a mix of human-centered (Nielson, 1993) and learner-centered (Quintana et al., 2006) design methods to develop our system. We relied on human-centered design methods that included strategies for getting learner feedback and engaging in co-design with users. Drawing on learner-centered design, we weighed students' feedback against what is known about learning and made design decisions based on a combination of all of these factors.

Rosson and Carroll's (2002) scenario-based design methods and usability case library (http://ucs.ist.psu.edu) helped to guide our design processes. These methods helped us to externalize our thinking as short stories that we could share with stakeholders to ensure that we were understanding problems from their perspectives and designing solutions that met their needs. They also made it possible to make small and large changes to our design ideas prior to building the system. For example, we shared short narratives depicting the type of feedback that we envisioned the system would provide for instructors and then shared these narratives with real instructors. In doing so, we identified additional requirements that the instructors felt would greatly benefit instructors and students. Since we had not built the system yet, we were able to easily update our initial requirements documents and account for this feedback during design.

We also drew on a collection of learning theories and empirical research to guide our design decisions. Theories of group cognition influenced how we defined and perceived of the aims of collaboration and support for improved collaboration (Stahl, 2006). Literature on self-regulation influenced our understanding of the activities required for regulation to occur (Winne & Nesbit, 2009). Research on group process problems during collective sense-making influenced how we operationalized collaborative aims into specific desired patterns of communication (Borge & Carroll, 2014; Kerr & Tindale, 2004; Kozlowski & Ilgen, 2006). Finally, constructionism (Papert & Harel, 1991) guided how we envisioned activities in the system that individuals would access as they worked with their team to understand and improve collaborative activities.

What follows is a description of the final product of our own collaboration—the CREATE environment. Following this description, we provide a detailed account of how and when we used theory to design it.

THE CREATE ENVIRONMENT

We developed CREATE, an online discussion tool, to support the development of socio-metacognitive expertise, or knowledge about and ability to regulate group cognition. It was originally designed to help online undergraduate students improve their collaborative discussion processes. CREATE has three categories of modules: (1) chat modules where groups engage in group discussion, participate in sense-making activities about their discussion, and create plans for improvement; (2) user modules which provide individuals with awareness features to track discussions, discussion assessments, and plans for discussion improvement; and (3) administrative modules where researchers or instructors modify the information and support which students access in the chat modules. However, we will only discuss the chat modules since these are where main collaborative and reflective activities occur.

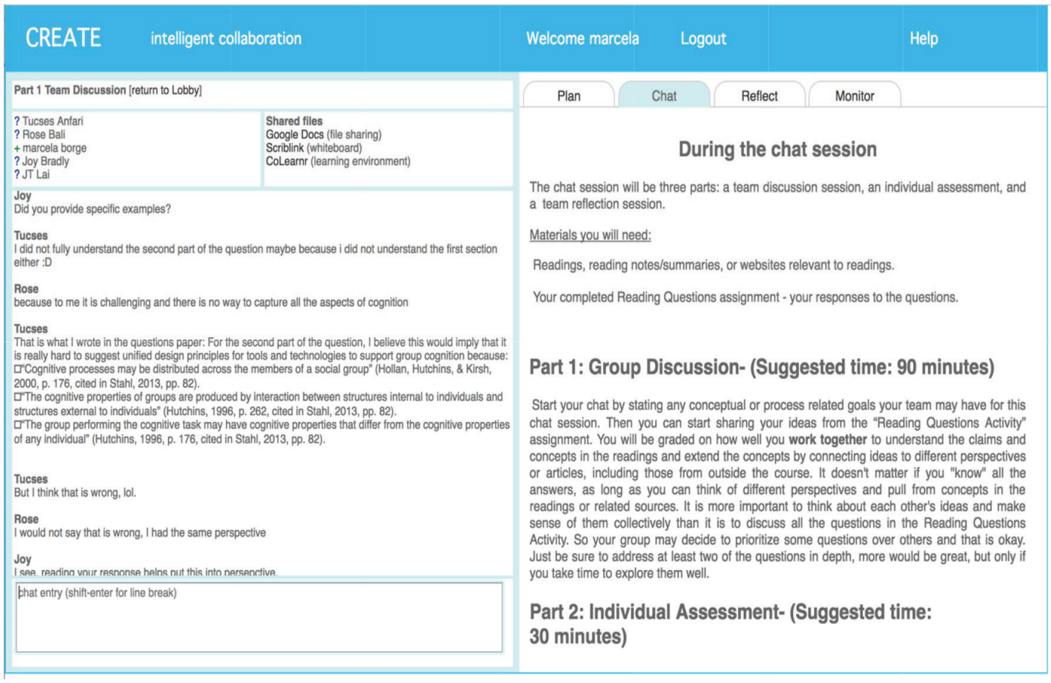

FIGURE 1
Screenshot of the discussion module.

The chat modules consist of a discussion window on the left panel, activity window on the right, and four tabbed workspaces above the activity window: plan, chat, reflect, and monitor (see Figure 1). The discussion window remains open constantly so students can communicate throughout their activity while the tabbed workspaces are opened one at a time to propagate the activity window.

The tabbed workspaces represent the regulatory process that groups will learn to carry out over time as they work to improve their collaborative discussions. Though these processes are usually represented as cycles in most self-regulated learning literature, they are depicted linearly for functionality.

The Plan tab helps teams coordinate a future meeting by entering or changing the meeting subject/name, date, time, and duration. The meeting's objectives (e.g. "Update progress," "Brainstorm design alternatives") can be entered to help the team remember the strategies they plan to use to monitor and regulate discussion activity.

The Chat tab displays discussion instructions, also referred to as the orchestration of individual and collaborative activities in the CSCL literature (Dillenbourg & Hong, 2008; Prieto et al., 2014). Typical orchestration instructions include the topic to be covered, a description of the different required parts and length of the discussion, and when and how to use the Reflect and Monitor tabs. In a typical activity, students are first assigned an individual reading assignment with reflective questions that push students to extend readings, synthesize, and evaluate readings. Then, students meet online with their assigned group, synchronously, to discuss their responses to the reading questions and work to make sense of the readings. After students complete their discussion activity, they move onto the Reflect tab (see Figure 2). The main aim of the Reflect tab is to help translate collaborative learning and group process theory into usable reflective tools that students can use to think about and evaluate their own discussion processes. During reflection, group talk ceases in discussion window.

When students open the Reflect tab, they see an interactive list of desired communication process items informed by a pragmatic model of collaboration that we developed (see top of Figure 2). When students click on an item, the system describes what it is, why it is important, and then instructs students to scroll through the discussion pane to examine the discussion and look for specified patterns. These patterns match rubric scores from 1 to 5 (see bottom of Figure 2 for scores 1–4). Students are also asked to provide evidence from the chat transcripts to justify their scores for each item. Once individuals finish entering what they perceive to be the team's collaborative quality scores and rationale for these scores, they proceed to the Monitor tab and tell the group they are ready to discuss their processes.

The Monitor tab shows the team's average scores for each of the reflection items. The team can use this information to discuss the team's collective sense-making activity in the discussion window and select their biggest strength and weakness in the specific communication processes they evaluated. Based on the weakness a team selects, the system provides suggestions for strategies they can use to improve the quality of their sense-making discourse for their next session. Groups can then decide which strategy or strategies they think would work best for their team from those suggested to them or create their own strategy and enter it into the system (see Figure 3).

What we have just described is the product of our collaborative design inquiry process, one that is still evolving as we move to scale the system. How we generated this initial design is an important narrative that involves a variety of decisions about when and how to use theory, apply design methods, and take design risks. What follows is the story behind this design process as well as reflections on the process and the use of theory to inform design. We left out many human-centered design processes we enacted, i.e., interviewing students and instructors, sharing design scenarios with stakeholders, etc. We also did not focus on detailing how we built the system or evaluated basic usability. Instead, we focused on the role that theory played in each part of the design cycle and the design decisions we made.

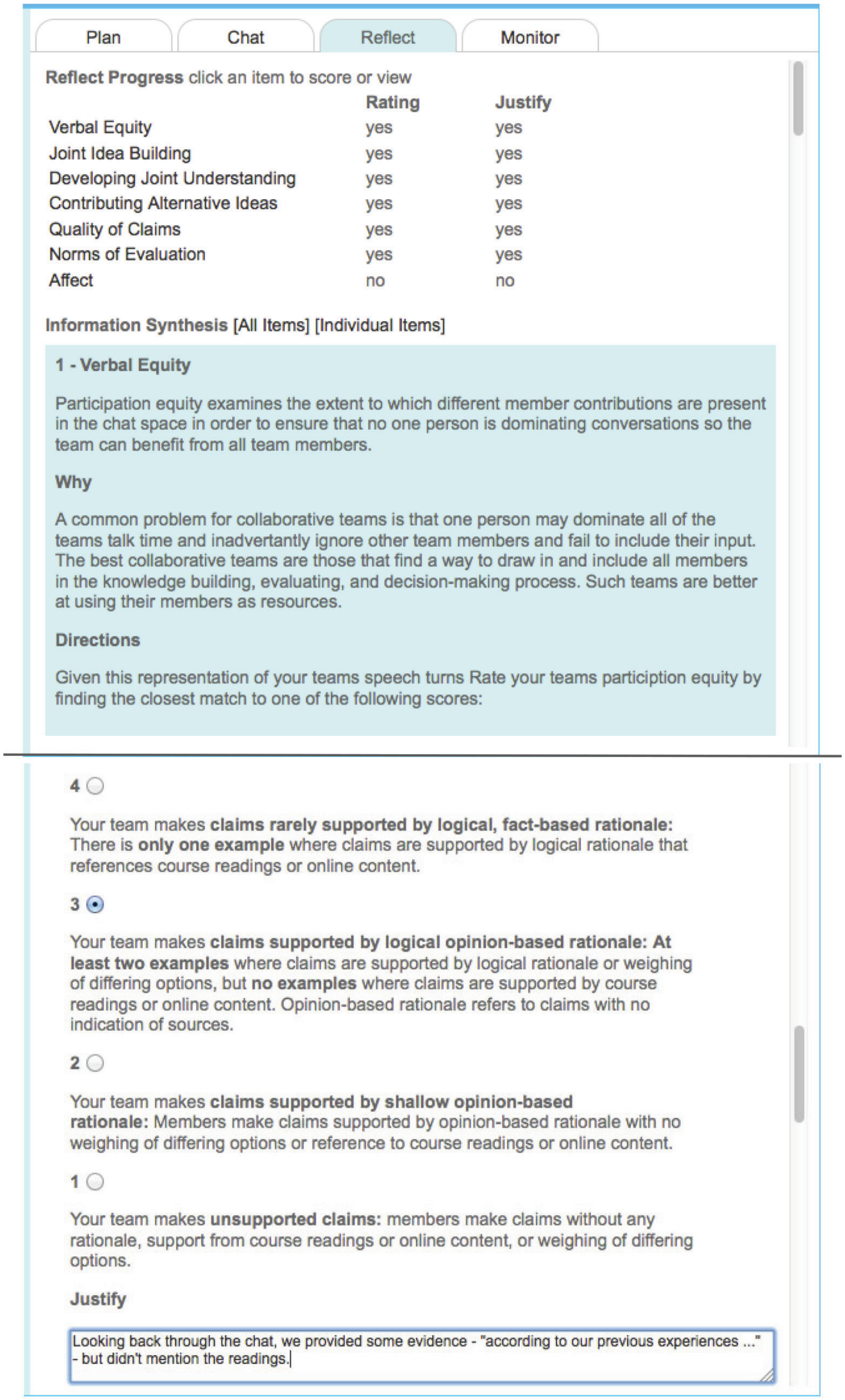

FIGURE 2
Screenshot of the information provided about items in the reflect module (top) and scales provided for each item in the reflect module (bottom); level 5 is not shown.

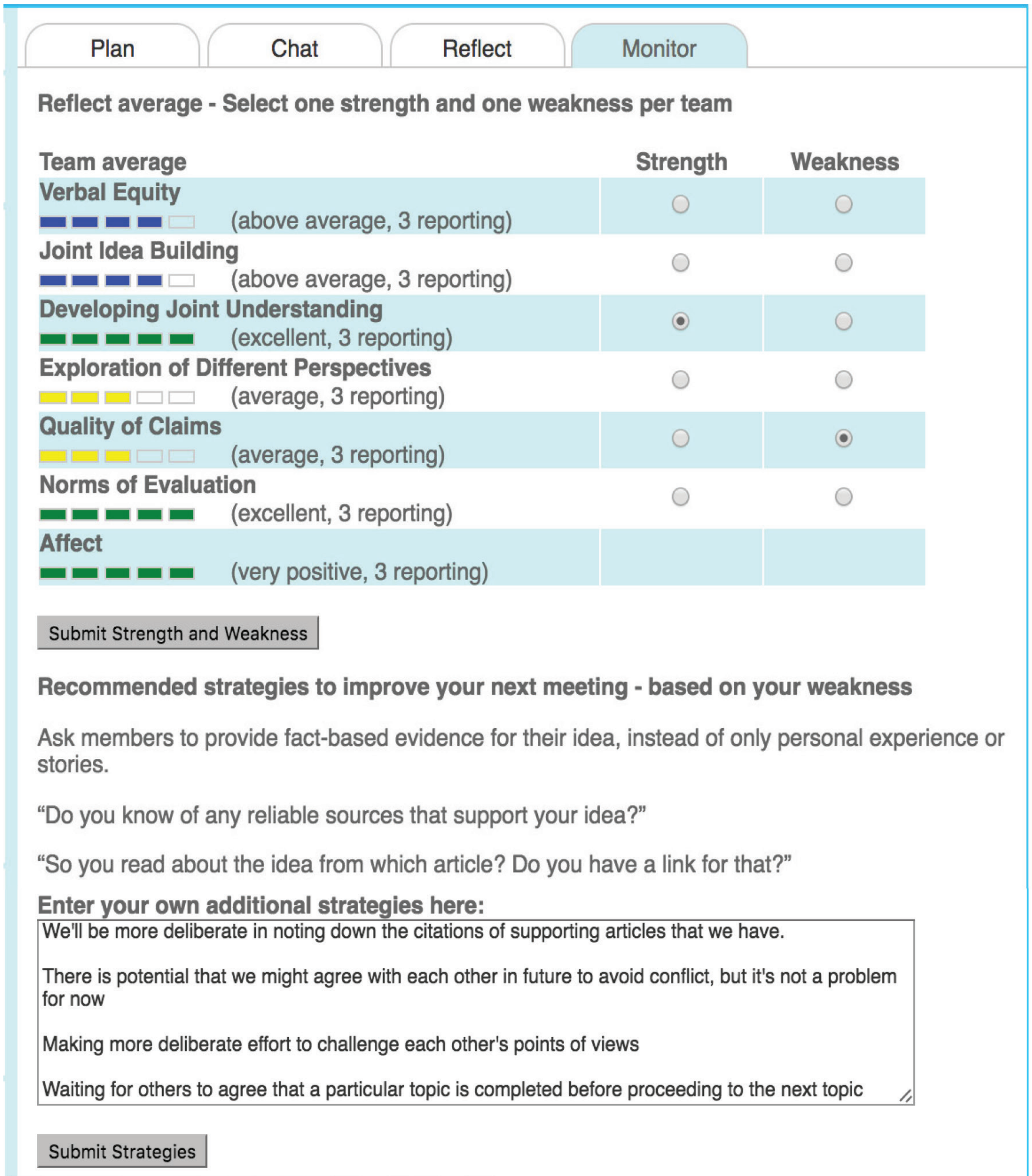

FIGURE 3
Screenshot of the monitor tab.

THE CREATE ENVIRONMENT DESIGN NARRATIVE

Our design process consisted of three phases. In our first phase, we gathered requirements for qualities a system would need to help students develop knowledge about collaboration and help them learn to monitor and regulate collaborative processes over time. A large part of this phase focused on developing conceptual models to guide our future design. In the second phase, we built on these models to design the system by using technology to reorganize individual and team activity. After making several design decisions, we moved to the third phase, where we tested our models and alternative design options to develop the initial prototype.

Phase 1- Developing a Theory of Socio-Metacognitive Expertise to Inform Design

We began our design process by drawing from Human Computer Interaction (HCI) methods (Rosson & Carroll, 2002) to formulate a root concept for our system. The initial concept for the CREATE environment was to build a computer-supported, collective-regulation system that would improve the quality of collaborative discourse processes. Our rationale for building such a system was the growing recognition that students struggle to monitor and regulate important discourse and socio-emotional processes during collaborative activities (Barron, 2003; Borge & White, 2016; Järvelä & Hadwin, 2013; Järvelä et al., 2016).

We assumed designing this system would be a challenge due to the nature of the tasks we would be supporting and were uncertain about the extent that theory could guide us. We also knew it would be difficult to help students regulate collaborative discourse since the field of CSCL had such diverse ways of defining and evaluating collaboration (Jeong, Hmelo-Silver, & Yu, 2014). So, we recognized that at some point we would have to fill gaps between theory and practical design options.

Given these challenges, we had to ensure that the entire design team understood the main purpose of the system, including the primary task, collaboration, and the secondary tasks, regulation, that we would be supporting. We wanted to ensure that the entire design team understood how other researchers conceptualize the task of collaboration and regulation, what we envision as optimal task performance, and how to measure changes in primary task performance in order to evaluate the system. Through this process, we were developing our version of a theory of socio-metacognitive expertise by determining what students would need to learn to develop expert knowledge and skill to regulate collaborative activities.

Socio-metacognitive expertise requires the development of both knowledge about collaborative processes and skills to manage collaborative interactions (Borge & White, 2016; Borge, Ong Shiou, & Rosé, 2018). Socio-metacognitive knowledge includes an understanding of optimal collaborative activity and a form of pattern recognition to be able to identify different types of communication patterns associated with more and less sophisticated collaborative activity (Borge &

White, 2016; Borge et al., 2018). Socio-metacognitive skills include the ability to use knowledge about collaborative activity to compare existing patterns of communication to desired patterns of communication and to correct problems by strategically modifying future collaborative activity to achieve desired outcomes (Borge et al., 2018).

Once we knew what we wanted students to learn, we had to determine how best to support this type of learning in a computer system. Following the example of Palincsar and Brown (1984), we used research literature to develop three conceptual models that would guide much of the activity and information design in the system: a conceptual model of collaborative competence, an assessment model for collaboration, and a conceptual model of the process of regulation to guide how we would organize and support regulation in the system.

A conceptual model of collaborative competence

In previous work, collaborative activity was unpacked into four core processes: (1) planning, (2) information synthesis, (3) knowledge negotiation, and (4) productivity (Borge & White, 2016). However, in considering what sets collaborative activity apart from other forms of group activity (i.e., cooperation) we found interdependent sense-making processes that occur during information synthesis and knowledge negotiation to be important (Stahl, 2006). Therefore, we determined that the four processes listed above were defining aspects of effective collaborative teams, involving both project management (planning and productivity) and collaborative activity (information synthesis and knowledge negotiation).

The realization that there was a distinction between a productive collaborative team and collaboration led us to define collaborative activity more narrowly. Building on theories of group cognition (Stahl, 2006), we defined collaboration as an interactive process where individuals (1) externalize ideas for the purpose of synthesizing available information into a collective whole, and (2) collectively negotiate what is known to make sense of shared information and develop new knowledge that did not exist within the group prior to collaboration. From this perspective, collaborative competence entails the ability to carry out these two processes well in authentic contexts. As such, we chose to focus on supporting only two of the four core competencies of effective collaborative teams as identified by Borge and White (2016), the two that were critical to synthesizing and negotiating collective information.

We unpacked information synthesis and knowledge negotiation into definitions with concrete examples that students could understand and that we could provide to students as part of reflective features in the system (see Table 1 from Borge et al., 2018).

TABLE 1
Pragmatic model of collaborative discourse competence

	Communication Aims	Definition	Positive Examples	Negative Examples
Information Synthesis	Distribution of Verbal Contributions	The extent to which all members are contributing to the discussion process.	Team verbal contributions are almost perfectly equitable.	One member contributes most turns of speech and at least one member is barely contributing.
	Developing Joint Understanding	The extent to which teams ensure ideas are understood as intended by speakers by rewording, rephrasing, or asking for clarification.	Team takes time to reword another member's idea to check for understanding or ask another member to explain an idea by elaborating further, and also synthesize major decisions or multiple ideas of members.	The team does not show any instances where a member tries to reword, summarize, or confirm another member's idea or decision, or a possible team action.
	Joint Idea Building	The extent to which team elaborates/adds to other contributions to ensure ideas are not ignored or accepted without discussion.	Team members add to another's idea over a large number of turns AND do not show instances of ignoring others or adding unrelated ideas.	Members either ignore others and pose different suggestions that do not connect to the original idea, or simply accept the idea and move on.
Knowledge Negotiation	Exploring Alternative Perspectives	The extent to which teams present and discuss alternative opinions/claims/ideas.	Team members point out problems or come up with alternative perspectives for an idea or claim and discuss these in depth over many turns of speech.	There are no instances where members point out problems or alternative perspectives.
	High Quality Claims	The extent to which teams provide sophisticated, fact-based rationale.	Claims are supported by course readings or online content AND include sophisticated, logical rationale or weighing of differing options.	When members make claims they do not include any rationale, evidence, or weighing of options.
	Constructive Discourse	The extent to which teams adhere to social norms during evaluation that show that members' and their ideas are respected and valued.	Responses are professional and respectful with at least 1 instance where person acknowledges the reasonableness of an opinion or claim before pointing out flaws or counter arguments. No examples members attack a member's intelligence or character, make disrespectful comments about the idea, or use inappropriate or offensive language.	Members may repeatedly engage in extremely inappropriate or offensive language (i.e., blatant profanity, vulgarity, racism, sexism, etc.), or there are examples where a member attacks another member's intelligence or character (e.g. " you don't know what you're talking about"), or make disrespectful comments about member's ideas (e.g. "that is stupid").

Information synthesis

Within this model, information synthesis consists of three categories of communication patterns: distribution of verbal contributions, development of joint understanding, and joint idea building.

Distribution of verbal contributions

Distribution of verbal contributions is a pattern of information sharing that focuses on the proportion of information contributed by each member relative to the team's total available information. It specifically targets problems associated with verbal dominance that negatively impact a group's potential to effectively solve problems (Barron, 2003; Borge & Carroll, 2014; Hogan, 1999b; West, 2007; Woolley, Chabris, Pentland, Hashmi, & Malone, 2010). If a turn of speech is conceived as a piece of information, then persistent patterns of inequity over time would indicate that the team is not making adequate use of all members as cognitive resources.

Developing joint understanding

This category of communication pattern is related to patterns of collective discourse comprehension. Focusing on problems associated with collective miscommunications (Kozlowski & Ilgen, 2006), it examines the extent to which teams make an effort to ensure that members comprehend shared information by taking time to reword, rephrase, or ask for further clarification of shared information. This type of behavior is similar to how individuals check their own comprehension when reading or watching videos (Brown & Smiley, 1977; Palincsar & Brown, 1984), but it focuses on comprehension at the level of the group.

Joint idea building

This category focuses on the extent to which team members elaborate on another member's contribution in order to expand ideas jointly and ensure that information introduced by any member is not ignored or accepted without discussion. As such, joint idea building shares some similarity to transactivity, which is the extent to which learners refer to and extend the ideas of their fellow collaborators (Teasley, 1997; Weinberger, Stegmann, & Fischer, 2007). However, we narrow the definition by only including discourse acts that agree with and expand an idea and eliminate argumentation acts aimed at opposing an idea or providing alternative perspectives. We classify those communication acts as knowledge negotiation.

Knowledge negotiation

Knowledge negotiation consists of three additional categories of communication patterns: exploring alternative ideas, quality of claims, and norms of evaluation (Borge et al., 2018). Each of these communication patterns impacts the quality and diversity of information available to teams as they work to negotiate their collective understanding of shared information and make decisions related to their respective positions to create new knowledge.

Exploring alternative ideas

Exploring alternative ideas focuses on the extent to which teams present and explore alternative perspectives, claims, or suggestions. This category aims to reduce problems associated with unique information, a known tendency for groups to ignore information known only to a minority of group members (Stasser & Titus, 2003). Pushing all members to seek and share unique information reduces the social risk associated with contributing information that no one else is familiar with (Edmondson, 1999) and creates a system that values diverse inputs. This category also aims to reduce early consensus quality and satisficing tendencies where a team simply adopts the first viable idea (Atman et al., 2007; Ball, Evans, & Dennis, 1994) by ensuring that groups spend time considering viewpoints other than those favored by the group or presented in course content.

Quality of claims

This category focuses on evaluating the extent to which teams provide logical, fact-based evidence and rationales, and weigh options when making claims. This category aims to reduce problems associated with group tendencies to provide low quality evidence and argumentation (Duschl & Osborn, 2002; Noroozi, Weinberger, Biemans, Mulder, & Chizari, 2013; Weinberger & Fischer, 2006). We chose not to promote a formal argumentation script that requires arguments to have specified parts such as claims with qualifiers, data to support the claim, and warrants to an argument, i.e., Toulmin's model of an argument (Toulmin, 1958). Instead, we chose to focus on whether groups display logic behind their arguments and whether they refer to external sources or rely solely on personal opinions and experiences.

Constructive discourse

The final category of communication patterns is constructive discourse. This category focuses on addressing problems associated with interpersonal risk-taking by promoting the development of psychological safety, an important factor in group learning, failure management, and innovation (Edmondson, 1999;

McGrath, 1999; Van der Panne, van Beers, & Kleinknect, 2003). The aim of constructive discourse is to push groups to behave in a professional and respectful manner that helps members feel that their ideas are valued, that errors are valuable learning opportunities, and that it is safe to take cognitive and social risks.

An assessment model for collaboration

Once we separated communication processes into categories, we had to develop a way to help students evaluate their existing communication patterns. This was done by turning each category into a reflection item. This aspect of our work was challenging because it required us to provide students with recognizable discourse markers of a range of activities in each category. For example, our model of competence indicated that proposing and exploring alternative perspectives was an important aspect of knowledge negotiation, but we had to help students compare their existing state of exploration of alternative perspectives to a desired one.

Our solution was to provide students with a range of less to more sophisticated examples of communication patterns for each assessment category to serve as assessment markers. We created a rubric for each category that included a range of dysfunctional to highly functional patterns and students had to read through their discussion transcript to try to match the patterns they saw to the range of patterns listed. For example, if students could not find an example where members provided additional information or evidence to support or extend another member's idea or claim, this indicated their team had a dysfunctional communication pattern for the Joint Idea Building category. A functional pattern in the Joint Idea Building category would require students to identify multiple examples within their discussion where members extended or elaborated on the ideas of others that lasted multiple turns of speech (see Table 2 for example of the assessment scaffold for Joint Idea Building). We followed this strategy for each of the six communication patterns. However, it is important to note that there were important trade-offs in devising concrete markers for discourse assessment. We managed to simplify a complex activity into specific patterns students could recognize and use to evaluate their activity, but this came at the potential cost of realism. In other words, these examples may not always match how markers of collaborative competence would be assessed in the real world.

In order to simplify evaluation and ensure reliability, we had to make decisions about a variety of practical things, i.e., what counts as sufficient idea building turns and how we make it concrete for students. For example, in Table 2, we indicated that a sufficient number of turns of idea building is three or more turns. This is a pragmatic cut-off to help students focus more intently on their processes and understand the bigger picture, but it may also be an invalid representation of col-

TABLE 2
Example of One of the Six Assessment Items from the Discourse Quality Assessment

	Joint Idea Building
What does this mean?	This item focuses on examining the extent to which team members extend and explore other member's contributions in order to ensure that ideas introduced by members are not ignored or accepted without discussion. This does not mean that when someone poses a question others answer it. Nor does it mean that when someone shares an opinion/fact others agree with it. It means that when someone responds to a question/ request others extend/elaborate on that response and when someone shares an opinion/fact others extend, elaborate, or provide evidence/support for that opinion or fact.
Why is this important?	Teams often fail to use collective brainpower to develop more sophisticated ideas. The best collaborative teams engage in the joint idea building where they take each other's ideas and develop them together. In this way, the development of ideas can benefit from the group's diverse backgrounds or areas of expertise. (See research references)

Direction: **When team members share ideas or make claims, what happens afterwards?** Pick a score that most closely describes your team's processes.

SCORE	Definition
5	**Multiple examples** where the team provides additional information or evidence to support or extend an original claim/suggestion as part of an in-depth conversation that includes at least **three turns of speech by the different team members.**
4	There **is only one example** where the team provides additional information or evidence to support or extend an original claim/suggestion as part of an in-depth conversation that includes **at least three turns of speech by the different team members.**
3	There **at least two examples** where the team provides additional information or evidence to support or extend an original claim/suggestion as part a short exchange **over one or two turns of speech (posts).**
2	There **is only one** example where the team provides additional information or evidence to support or extend an original claim/suggestion as part a short exchange **over one or two turns of speech (posts).**
1	The team provides a collection of claims/suggestions related to the problem or question at hand, but show **NO instances** where members provide additional information/evidence to support or extend an original claim/suggestion. Members either ignore other and pose different suggestions or simply accept the idea and move on.

laborative competence. Selecting pragmatic definitions of the levels of sophistication for the six communication patterns was one of the more controversial design decisions we made. In the end, we decided it was more important to help students be precise in evaluating collaborative processes that contribute to group cognition than it was to ensure that each ordinal example we provided was accurately mapping real-world activity. We could not help students learn to regulate activity without an assessment model they could follow, and we knew we could improve the assessment model over time to make it more valid.

We then worked with graduate students to develop the different items. Expert coders were trained first to do micro-analysis of communication acts. They separated students' online chat posts into utterances and then categorized each utterance into different acts using an existing framework (e.g., judgement acts, requests for elaboration, summary acts; for details see Rosé & Borge in press). Once students developed substantial inter-rater reliability (Landis & Koch, 1977) using this micro coding framework (Kappa = 0.78), they moved on to using the macro-framework, the six assessment items for discourse quality. We tested the reliability of our macro-assessment among two expert coders on 20 percent of the total data for a study, and found a high level of inter-rater reliability for correlation of scores, $r = .86$; $p < .001$, as well as substantial categorical agreement: Kappa = .64; $p < .001$ (see Borge et al., 2018).

Developing a conceptual model of regulation

Regulation is the secondary task in the CREATE system. It is deemed secondary because it is a meta task; it is used to improve performance on the primary task. Regulation is no less important than the primary task, collaboration.

In order to reduce problems that prevent students from regulating activity, we had to identify common problems associated with regulation. Building on ideas proposed by Winne and Nesbit (2009) we created a production model of all the possible points where regulation could go wrong. We identified six areas in need of support (see Figure 4). These areas include (1) attention, (2) awareness of processes, (3) recognition of a problematic state, (4) problem appraisal, (5) ability and desire to apply a strategy, and (6) the cognitive capacity to exert effort.

People are limited by the number of things they can pay attention to at one time (Koch & Tsuchiya, 2007; Lamme, 2003). When faced with time pressure, people also have a tendency to focus on completing tasks at the expense of the quality of the processes they use when completing those tasks (Kerr & Tindale, 2004). Students are no exception to this tendency. In collaborative contexts, students tend to focus on completing work tasks, while ignoring their collaborative processes (Barron, 2003; Hogan, 1999a). If students do not pay attention to collaborative processes, how can they be aware of problems associated with these processes?

Our model suggests that to help students improve collaborative skills, they must pay attention to collaborative processes. Attention is the gate-keeper to regulation (Koch & Tsuchiya, 2007; Lamme, 2003). Without awareness of problems, they are unable to "see" what happened and reflect accurately on what occurred.

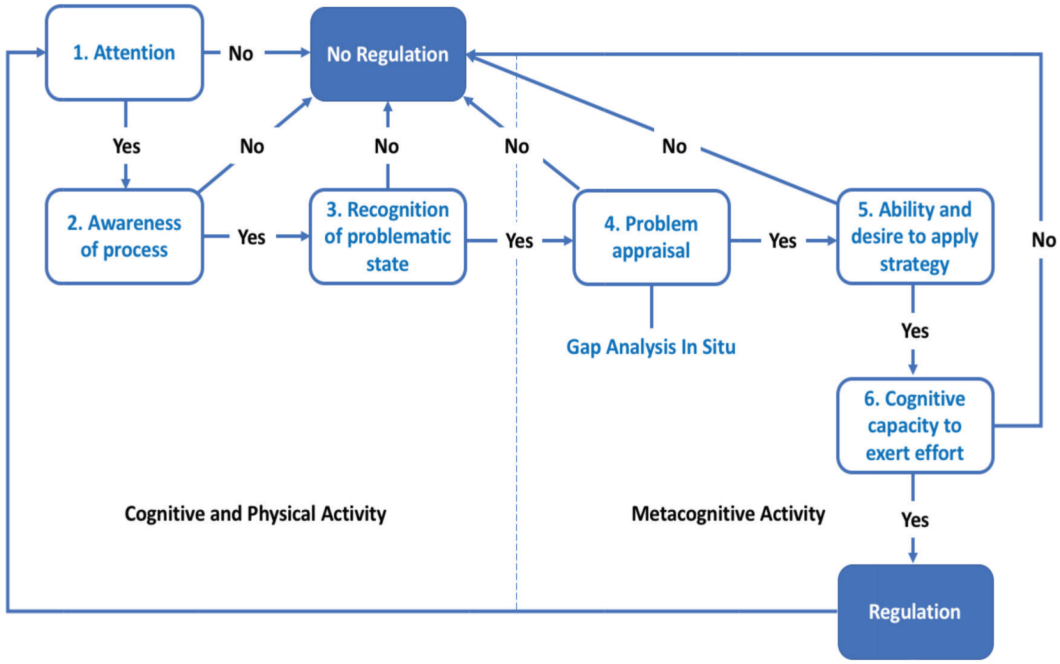

FIGURE 4
From Borge et al., 2018, A conceptual model of the process of regulation "in the wild", as informed by theoretical and empirical work.

Reflection for the purpose of regulation is central to learning (Kolb, 2014; Schank, 1999; Schön, 1987; White & Frederiksen, 1998). This form of reflection is often referred to as gap analysis in business and industrial and organizational psychology literature (Nesbit, 2012; Weick, Sutcliffe, & Obstfeld, 2005). Gap analysis is a process of comparing the current state of the problem to the desired state of the problem, where the desired state is some model of competent activity (Nesbit, 2012). This form of reflection is complex, which is why few do it well, but without it future regulation cannot occur (Winne & Nesbit, 2009; Nesbit, 2012).

We concluded that a system designed to support the development of collaborative competence should aim to support (a) collective understanding about collaborative processes and collective gap analysis during reflection, (b) guidance for strategy selection and future goal formation, and (c) feedback from others to calibrate gap analysis.

Phase 2- Building on Theory to Imagine Different Design Paths

We began planning our system by brainstorming big ideas about the general structure of the system. We used principles of constructionism (Papert & Harel, 1991) to help us determine the types of information and activities that individuals would need to construct socio-metacognitive expertise. Building on previous

TABLE 3
Matrix depicting system envisionment guided by two learning theories

Socio-metacognitive Development Theory	Constructionist Principles for Educational Technology			
	Learner Control	**Scaffolded Advice Tools**	**Individual Differences**	**Tasks and Projects**
Collaborative Capacities	Students decide how to use, apply, and explore theoretically grounded models of competence and features in system.	System houses collection of capacity goals, problems, and strategies and features to support capacity development.	Instructors can modify discussion instructions to better meet student needs. Students can be task oriented, process oriented, or both.	Students will make sense of course content through collaborative discussion and then figure out how to improve the quality of these sessions over time.
Cycles of Learning	Students can decide how to organize discussions and select types of tools they feel are best for a task.	Students are given context specific advice for completing tasks or problem solving.	Students have multiple ways of getting advice and feedback.	Students complete discussion activities, reflect on the quality, and plan future activity for multiple sessions.
Socio-metacognitive Activity	Students have anytime access to feedback and assessment items and previous discussions for sense-making activity	Theoretically grounded process assessments are provided to help students engage in targeted reflection and planning.	Students can decide what communication patterns to improve and what strategies to select to modify future discussions.	Teams' strategy selections and perceived success can be archived and accessed as a means to reflect on their ongoing team processes.

work (Shimoda, White, Borge, & Frederiksen, 2013; White & Frederiksen, 1998), we created a matrix of key aspects of socio-metacognitive development organized by these constructionist principles to help us envision the system (see Table 3). This matrix also served as a tool to help us reflect on the design decisions that were made during development in order to ensure that we satisfied our original theoretical design principles.

The key aspects we chose to emphasize from socio-metacognitive development were developing understanding of core collaborative capacities (i.e., information synthesis and knowledge negotiation), providing cycles of socio-metacognitive learning, and supporting socio-metacognitive activity. For each of these we had to envision features and activity in the system that would provide learner control, scaffolded advice tools, accommodation for individual differences, and meaningful tasks and projects.

After initial brainstorming, we moved on to sketching out different design options. We used the conceptual models developed in Phase 1 to guide the design process. For example, in order to determine specific features in the system, we had to examine the conceptual model of regulation "in the wild" that we created in Phase 1 and think about how we could use technological features to increase the likelihood of regulation.

One of the most important decisions we made was when to provide support for process awareness. We decided to provide awareness support after collaboration rather than during collaboration. We speculated that providing support during collaboration had too many potential costs. Students could become dependent on technological support and fail to learn how to become more aware of processes for themselves (Collins, 1996). Additional stimulus could also negatively impact an already complex activity. So, we decided to find a way to support awareness as part of reflection. This approach required us to manipulate how the process of regulation happened in the system to create a new activity design model, a set of organized activities intended to support group regulation.

The work of previous scholars helped us generate ideas for what types of activities could exist in the system to better support regulation of group cognition. For example, the system could archive all discussions, making it possible for students to relive previous activity. White and Frederiksen's (1998) reflective assessments modeled how to reorganize the process of regulation by beginning the reflective process with problem evaluation. After discussions, students could use archives to compare their existing communication processes to examples described in the system and repeat this process for each reflection item. Our model of competence provided the information and examples that guided this activity for students, enhancing their knowledge base in ways similar to how White and Frederiksen (1998) enhanced inquiry science processes for young learners.

These new set of activities supported in the system reorganized the regulatory processes and moved us from our conceptual model of "regulatory activity in the wild" to our envisioned activity model, regulatory activity in the system (see Figure 5 for activity model). This new activity model could support desirable processes and mitigate known problems associated with regulation. By archiving the discussion and making it accessible to teams after collaborative activity, we provided them with a second chance to examine their processes as part of guided reflection. During reflection, we could provide scaffolds to help students compare

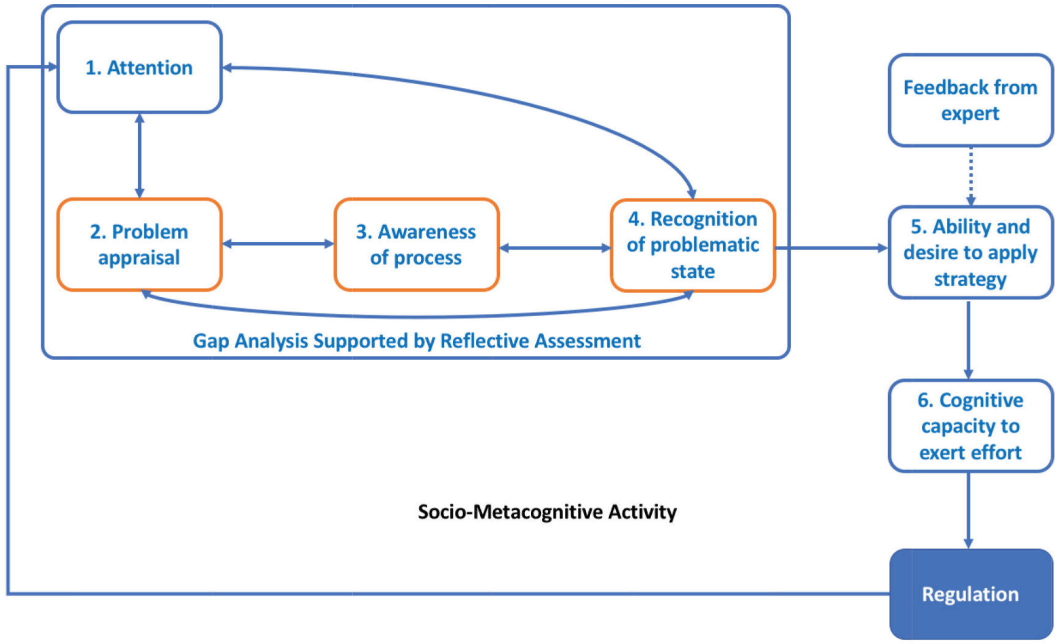

FIGURE 5
An activity model from Borge et al. (2018), depicting how the use of technology could modify the process of regulation (modifications highlighted) to mitigate problems and enhance regulatory activity.

different states of collaborative activity and reduce problems associated with group regulation by directing their attention towards relevant communication patterns in their archives. We believed this type of activity design could increase the likelihood of awareness and correct appraisal of collaborative problem states, thereby increasing the likelihood of regulation during future collaborative activity.

The more we envisioned specific features in the system, the more difficult design decisions became. For example, making decisions about how to script reflection was a challenge. Theory was not helpful as a means to inform design decisions at this fine-grained level. Though we know reflection is important and can improve learning outcomes, the effects of different scripted methods of reflecting on learning outcomes are unclear (Nesbit, 2012). We are still in need of more robust theories of scripting (Fischer, Kollar, Stegmann, & Wecker, 2013). As a result, we were unable to decide on a reflection script to use.

We considered two scripting options. Both options required students to examine their discussion by going through each reflection item and matching their existing communication patterns to a listed pattern, but we did not know how to guide attention during this evaluation process. One option supported future thinking by pushing students to pay attention to a list of provided strategies to select one that they thought would improve future discussions. The other option supported targeted evaluation by pushing students to provide evidence from the discussion archive to support their evaluation of discourse quality. This option pushed students to pay closer attention to specific discourse processes. To determine which design path to take, we decided to test our general activity design model and different scripting options as part of prototype testing.

Phase 3- Testing Theories in Action

Theoretical testing

We conducted a user study to (a) test the utility of our activity design model as a means to support the improvement of the quality of collaborative discussion processes over time, and (b) determine which of the two reflective scripts better facilitated socio-metacognitive learning.

To accomplish these aims, we examined learning at a group level, conceptualizing it as a change in the understanding of what high quality collaboration entails and as a change over time in the ability to apply this knowledge to create high quality discourse. To measure this type of learning we developed a reliable, macro-coding framework based on our model of competence that used combinations of speech acts as a means to identify discursive patterns that coincided with range of low to high quality collective cognitive processes (Borge, Ong, & Rosé, 2015). Our research team used these communication analysis tools to determine the quality of online discussions and tested how different information and activity design paths affected the quality of collaborative processes over time.

Thirty-seven students from an online information sciences and technology course were assigned to one of thirteen teams of two to three people. These teams were placed into one of the two individual reflective-assessment conditions: Future Thinking, and Evidence-Based. The Future Thinking condition included scripts to push students to pay attention to a list of provided strategies in order to select one they thought would improve future discussions. The Evidence-Based condition used scripts to push students to provide evidence from the discussion archive to support their evaluation of discourse quality.

When assigning groups to a condition, we were careful to ensure that the populations of both conditions were as similar as possible, especially for known variables that impact collaboration like number of women on a team or number of work hours per week. As part of normal class work, teams were required to carry out an activity that built on our theory of socio-metacognitive expertise development in a computer-based collaborative environment over five discussion sessions, spanning ten weeks of their semester.

To test the ideas behind our system, we emulated system activity without building the actual system. We did this by placing students in a chat-based environment and providing paper-based reflective activities and feedback to emulate envisioned features in the system. The procedures for the activity were as follows: (1) students completed a required weekly reading and individual assignment that asked higher-order questions about the readings; (2) students submitted the individual assignment to a drop box; (3) groups met in an online chat environment to discuss and make sense of the reading questions for 60 minutes; (4) after discussion, the chat ceased, and individuals could fill out paper-based assessments of the six communication patterns following one of the two scripts; (5) the group discussed how each of them assessed the team, identified its strengths and weaknesses, and could suggest strategies from guides they could use to improve.

In session one, teams received full credit for the discussion regardless of the discussion quality. After the first session, we gave students our initial assessments of their discussion quality and told them that the subsequent discussions would be graded based on discussion quality. A trained research assistant measured collaborative discussion quality at five time points over the ten weeks. All teams followed the activity design model created in the design planning phase, but we tested two different design options for structuring reflective activity in the system.

When examining the discourse data, we found the activities succeeded in getting students to think about their existing processes and identify concrete changes they could make to improve their discussions. For example, in the excerpt below, students completed their first discussion on the topic of databases and then paused chatting so individuals could complete the guided reflection activity. Afterwards, the students discussed their assessments and collectively recognized that they needed to provide better evidence and take more time to reason through ideas:

Tay	Okay and as for knowledge negotiation, out of 15 what did you give us?
Kim	A 7 out of 15.
Tay	And why did you give us that score?
Kim	Well, no additional resources such as citing from the internet was used to help in explaining our topics
Tay	I gave us a 10/15 because, yes, we did not cite or reference outside material but we did incorporate outside examples in a couple of our questions to help better explain our reasoning. But, yes, we did lack referencing the book or websites.
Kim	Do you think we went into detail with the pros and cons of the database?
Tay	We did not really, which actually was one of my questions, ha, ha. So, that is something we definitely did miss and ran out of time for.
Kim	Yes, for our first discussion, we definitely missed a few key details.
Tay	Well it’s good that we went over what we missed in this discussion so we can do better on the next! Overall, I do think our discussion was a success. We will have our next meeting Monday at our usual time unless either of us needs to reschedule for another day.

Though it was not required, some teams decided to assign roles managing parts of the conversations associated to the reflection items.

José	So, I think we need to figure out how to avoid fragmenting our discussions.
Xu	Yes, I will be hyper critical of myself and say that after reading the chat I felt that I was dropping packets, meaning that I was asked questions that I saw while [evaluating] the chat, that I did not see while the chat was going on ...
Cal	Too bad we don't have a talking stick.
José	A talking stick??
Cal	One person talk at a time when you have the talking stick.
Xu	I think we need a moderator ...
José	yes, we should just agree at the beginning of every discussion who will be the moderator.
José	We can take turns
Xu	Yes. I felt that I could have done a better job. Sorry, guys!
Xu	But overall, I was not displeased and I think we did better than last time even though I felt last time we were better organized cause José was acting as a moderator then.
José	Oh, yeah much better
Xu	So, can we summarize to-do for next time?
José	1. Agree on a moderator
José	2. Moderator can also serve as the instigator if everyone is too agreeable.

Other teams realized the importance of thinking deeply about the material to have more interesting discussions:

Chris	We really didn't challenge each other this session.
Mina	Yeah, I think we need to challenge a little bit more although me and Linda did for a little bit.
Chris	It was a difficult reading.
Linda	It seriously was. I'm pretty sure if we all had a stronger grasp of what the article was trying to say we would have been able to challenge a bit more.
Chris	It was hard to challenge facts we didn't understand.
Linda	Yeah...it's hard to disagree when we can only talk about definitions.
Chris	Well I think then for next time we need to challenge more.
Mina	We just need to better focus on understanding first before we start the question process. That may assist in the direction that our questions go and rather sets the mood for the entire discussion as a whole.
Chris	Agreed.

At the end of the semester, Linda discussed how she changed her whole approach to the readings by forcing herself to go out to the web to look for examples to help her understand the readings and to counter ideas presented in them. Other students reported doing the same.

Results of an ANOVA test indicated significant improvement on the quality of team discussion quality over time and found teams in the Evidence-Based condition had significantly higher quality discussions at each time point and supported their assessments with evidence from the chat transcript more than Future Thinking condition (For more details see Borge et al., 2018). These findings indicated that students were modifying activity over time and improving the quality of collaborative discourse, something that direct instruction and repeated practice with awareness tools alone had not been able to show (Hogan, 1999a; Järvelä & Hadwin, 2013). Findings also suggested that the structure and flow of reflective activities could impact the quality of discussions. We used the findings from this study to finalize our reflective scripts and conceptual models of the system.

User experience testing

After developing our first functional prototype system, we had twelve undergraduate students from an information science and technology course test the system as part of a simulated task and provide suggestions for improvement. The students were assigned teams and instructed to conduct a general usability testing of the CREATE system. After summarizing user feedback and analyzing different options, we made additional modifications to our requirements and to the system.

Once the system met most of the users' basic needs, we implemented CREATE in another iteration of the information sciences course and received feedback from thirty students. The system still had bugs, but the majority of students (69%) felt CREATE provided meaningful learning experiences and argued for the need to make the activities a required part of the course.

Those who recommended keeping the CREATE activities did so even though these activities took three times longer to complete than the alternative individual activity. These students discussed how much richer and more meaningful the learning experiences were as a result of the CREATE sessions. Of particular note was feedback associated with students' perceptions of our model of assessment, because as we stated it was one of our more controversial design decisions:

> "I believe in keeping the CREATE environment and the rubric that comes along with it, because it helps users to work efficiently in a team setting.

> With the guided rubric, we were able to better facilitate our time and focus on core concepts instead of just being all over the place. Once we all became comfortable in our roles in the group and how to better communicate, the format of the CREATE discussion was the unspoken basis for how we worked together outside of the discussions…. The CREATE discussions helped each of us find our strengths and weaknesses and we've had a much better team dynamic because of it."

Students who valued the activity also stated that the activity created a sense of connectedness and the importance of engaging in deeper sense-making:

> "I am for keeping these discussion activities. It allows us to come together as a group and almost forces us to think deeper and understand the concepts more. It is hard as an online student to make relationships with other students to discuss concepts and what we don't understand so these discussions allow for that to happen. Also, it taught me how to have quality discussions. I didn't realize that I was adding no additional benefit by just agreeing to everything my team said until these assignments. I now have more meaningful discussion with all of the groups I am involved in."

Seventeen percent of students were ambivalent about the system and activities. They saw value in the activities, but had negative experiences with teammates. Fourteen percent of students did not feel the system was worth using or should be required. Those students all stated that it required too much effort and preferred an easier option:

> "I would remove the CREATE environment discussion sessions. They are too time consuming and I'm basically engaging in a structured discussion session discussing course or online content. Multiple choice quizzes are significantly easier. I have to read the weekly course readings and lectures, so a weekly quiz would take me 15 minutes to complete versus 90 minutes to complete a tedious discussion session."

DISCUSSION: REFLECTING ON THE ENTIRE NARRATIVE

Socio-metacognitive development is at the heart of developing solid collaborative skills. CREATE was designed to help students collaboratively construct knowledge and collaborative skills, both as groups and individuals, through a series of tasks. The system provides "spaces" for students to evaluate, monitor, and review their own development around these skills. Our findings from the testing phase suggested the design was successful in achieving these goals from a learning theory and constructionist approach.

Though we were careful to build on theory, we had to make decisions throughout our design process that either pitted certain theoretical principles against each other or came at the cost of another important educational consideration. For example, we had to decide between supporting the whole task or component sub-skills (Collins, 1996): prioritizing the whole task of collaboration with all its complexity or prioritizing the development of simplified set of core skills for the process of socio-metacognitive regulation.

We decided to prioritize supporting component sub-skills, while attempting to support as much of the whole task as we could. We envisioned collaboration as the opportunity to practice the whole task and then used individual gap analysis and collective planning as a means to support the component skills students needed to develop to improve at the task. Thus, we decided to script collaborative reflection rather than collaborative activity and then designed specific scripts to do so.

We also decided to leave the decision-making processes around how and when to regulate collaboration up to students, while providing structured guidance for evaluating and planning collaborative activity. This meant that students would have to struggle through collaborative activity and put forth effort to improve collaboration on their own. This decision came with a cost: not all teams may improve if some individuals decide they do not want to put forth the effort to improve. Though this level of student control poses some risks, we believed this approach is more conducive to development of the conditional knowledge necessary to regulate collaborative activity without computer support. For this reason, we tried to give students as much control over their collaboration as possible as they completed real tasks, while providing theoretically-grounded process structure and guidance. Nonetheless, theory and research were not sufficient to guide design.

As we went back and forth between theory and practical implementation, we found that theory could only take us so far in the design process. Practical implementation requires the operationalization of theoretical constructs, that is, to concretely define abstract ideas into measurable observations.

One of the realizations that came out of our design is the existence of a divide between theory and implementation. Concrete definitions of critical collaborative processes in educational literature are lacking, which makes implementing theory-based interventions difficult. The works of Palincsar and Brown (1984) and White and Frederiksen (1998) were crucial to helping us bridge this divide. Palincsar and Brown (1984) helped us to organize our understanding of the problem space, whereas White and Frederiksen (1998) provided concrete examples of how complex process can be broken down and operationalized.

Building on the examples provided by Palincsar and Brown (1984) and White and Frederiksen (1998), we created assessments that were both theory-based and pragmatic. The general communication categories that made up the six reflective assessment items were well established by research and theory, but the range of collaborative states that we described within each category was not. We had to operationally define different states, from less to more sophisticated collaborative activities to help constrain and guide attention during gap analysis towards critical communication patterns. Student feedback and analysis of findings from our testing phase suggested that this approach succeeded in guiding attention and increasing awareness of problematic collaborative states, but this accomplishment may come at the cost of generalizability of the model of collaborative competence. Thus, it is necessary to examine the impacts of modifying reflection items on collaborative processes in the future. We will also need to continue to make iterative improvements to the model of collaborative competence as we increase our understanding of what constitutes high quality collaborative discourse.

CONCLUSION

Learning tool design is very different from other forms of technology design, because there are a variety of educational design trade-offs that need to be considered alongside theory and HCI methods (Collins, 1996; Quintana et al., 2006). One of the main contributions of this paper is to concretely document how learning theories and the analysis of design trade-offs can be synthesized as part of an HCI design cycle when designing learning technologies.

Overall, we feel our design decisions satisfied most of the constructionist principles we set out to follow by providing students with opportunities to practice understanding, evaluating, and regulating collaborative capacities over multiple cycles of learning so as to develop socio-metacognitive expertise. Nonetheless, as Carroll and Kellogg (1989) point out, there will always be a tension between theory and the implementation of that theory.

As technology design and education become increasingly interwoven, our community needs to become better at applying theory and resolving tensions and to design technologically enhanced learning tools that go beyond supporting knowledge comprehension towards extending how to think and learn with technology. We believe CREATE is a step in this direction.

The development of socio-metacognition, the ability to understand, monitor, and regulate collective thought processes, is becoming increasingly important. Technology is continually making access to information cheap, thereby increasing the burden on collaborative analysis and sense-making activity. Whether we learn to engage in collective information analysis for the purpose of developing new knowledge can have real-world consequences for our society. A lack of collaborative competencies can prevent us from solving complex societal problems (Kozlowski & Ilgen, 2006).

Yet, we currently have no accepted instructional models to guide how we support complex collective sense-making activity in educational settings. Our narrative demonstrates how theory and design can be synthesized in an attempt to help address this problem. However, more research and design narratives are needed on the development of theoretically-informed, technologically-enhanced systems to support collective thinking processes. In this way, we can begin to bridge the gap between theory and implementation.

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