ABSTRACT

Title of Dissertation: RELATIONAL REASONING AND SOCIALLY SHARED REGULATION OF LEARNING IN COLLABORATIVE PROBLEM SOLVING

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The ability to solve complex problems in collaborative settings is considered a critical 21st century competency. Yet, national and international reports have revealed deficiencies in both students' and employees' teamwork and communication skills, which are essential when working collaboratively. These deficits may be underlain by a limited understanding of how cognitive and social processes operate synchronistically as team members work together to solve complex problems. The current study aimed to investigate how two specific processes—relational reasoning (RR) and socially shared regulation of learning (SSRL)—unfold during a collaborative problem-solving (CPS) task. Specifically, the researcher assessed the extent to which different teams exhibited differential proportions of reasoning and regulation; how team activity was distributed across individuals; and, whether frequent sequences of reasoning and regulation could be identified.

To address these aims, four teams of senior undergraduate students (n = 22) were recruited from a capstone design course in mechanical engineering. Over the course of the semester, teams conceptualized and prototyped a design to address a current market need. Each team was video-recorded during the conceptualization process—specifically, as teams evaluated and eliminated ideas from their corpus of designs. Team conversations were transcribed, segmented into utterances, and coded for the presence of RR, SSRL, and task-related and other talk.

Results from chi-square tests of independence, social network analysis, and sequence mining revealed that teams indeed exhibited differential proportions of RR and SSRL, with antinomous reasoning and monitoring and control of consensus emerging as key CPS processes. Further, planning and reflection acted as bookends to CPS, while RR and monitoring processes co-occurred in the interim. Finally, CPS alternated between periods of activity that were shared more and less equally among team members.

This study contributes to the literature on CPS by exploring the dynamic interplay between RR and SSRL and by demonstrating that CPS can be investigated at the micro level, meso level, and macro level. Methodologically, this study demonstrates how leveraging data mining techniques and assembling compelling visualizations can illustrate the recursive and cyclical character of RR and SSRL. Finally, limitations are noted, and implications for research and practice are forwarded.

RELATIONAL REASONING AND SOCIALLY SHARED REGULATION OF LEARNING IN COLLABORATIVE PROBLEM SOLVING

by

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It seems only fitting that a dissertation dealing with regulation would begin with a reflection of some kind. When I entered graduate school fresh out of college, I had little idea of what the next several years would hold in store. Looking back, I can say definitively that the past seven years have been marked by more growth than I would have thought possible. If I have learned anything in my years as a doctoral student, it is that destinations are not nearly as meaningful as the paths that lead you there. In that vein, I would like to pay tribute to just a few of the folks who helped me along the way.

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TABLE OF CONTENTS

List of Tables

List of Figures

CHAPTER I

INTRODUCTION

Statement of the Problem

The ability to solve complex problems in collaborative settings is considered a critical 21st century competency in both the classroom and the workplace (De Dreu, 2007; National Research Council, 2011). This sentiment has been echoed in various national and international reports (Fiore et al., 2017; Griffin & Care, 2014; Organisation for Economic Co-operation and Development [OECD], 2017a, 2017b). These reports also stress that tackling significant social, environmental, and economic concerns requires a combination of cognitive and social skills (Gauvain, 2018). Pertaining to the workforce, the labor market has shifted to a "knowledge economy," in which human capital is emphasized over industrial resources, rendering knowledge the most valuable form of currency (Binkley et al., 2012; Powell & Snellman, 2004). In such an economy, corporations, governments, and other institutions must leverage the knowledge of multiple individuals to solve their most pressing problems. Accordingly, the percentage of jobs demanding high levels of social interaction has grown dramatically over the last several decades (Deming, 2017), and employees and managers alike have reported substantial increases in the amount of time spent on team-related tasks (Cross, Rebele, & Grant, 2016).

Importantly, these team-related tasks often demand collaborative problem solving (CPS), defined as "the capacity of an individual to effectively engage in a process whereby two or more agents attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills, and efforts to reach that solution" (Fiore et al., 2017, p. 2). In essence, CPS involves multiple individuals working interdependently toward a shared goal (Fiore, Rosen, Smith-Jentsch, Salas, Letsky, & Warner, 2010, Fiore, Smith-Jentsch, Salas, Warner, & Letsky, 2010; Wiltshire, Butner, & Fiore, 2018). Further, throughout the problem-solving process, individuals must adapt existing knowledge or generate new knowledge in service of solving a novel, complex, and often ill-defined problem (Wiltshire, Rosch, Fiorella, & Fiore, 2014). It is the novelty of the problem that distinguishes CPS from collaborative work, which typically involves routine tasks with well-established solutions. In addition, the differentiation of roles and the interdependence required among team members differentiate CPS from collaborative decision-making and individual problem solving, respectively. Whereas there is a rich literature in the areas of collaborative learning, judgment, and decision-making, less is known about the processes supporting *complex problem solving* in *collaborative* contexts specifically (Graesser, Fiore, Greiff, Andrews-Todd, Foltz, & Hesse, 2018).

In theory, working with others to solve complex problems may afford certain advantages over individual problem solving, including increases in innovation, efficiency, and effectiveness (Gauvain, 2018; Graesser et al., 2018). Different individuals may have different knowledge bases and experiences to draw on and share with one another, potentially sparking novel solutions (Paletz, Schunn, & Kim, 2013; van Knippenberg, De Dreu, & Homan, 2004). Further, assigning individuals specific responsibilities but then convening as a collective to evaluate progress and make plans can enhance the quality of the solution (Lajoie et al., 2015; Panadero & Jarvela, 2015). By the same token, the social nature of CPS can present certain challenges. The group may struggle to communicate effectively or clearly delineate team member roles, individuals may manifest social loafing behaviors, and conflict, disagreement, and false information may disrupt productive conversation (De Dreu & Weingart, 2003; Jehn, 1997; Paletz, Schunn, & Kim, 2011).

Regardless of the products of collaborative work, it is widely acknowledged that CPS is a core competency in the home, the workplace, and society at large. Thus, students entering the workforce in any field must be well-versed in CPS if they are to excel in their professions. However, a number of reports have revealed deficiencies both in students' and employees' abilities to work collaboratively (National Academy of Sciences, Engineering, & Medicine, 2016; OECD, 2017b). In the workforce, reports have noted shortcomings in teamwork, interpersonal skills, and communication across disciplines (American Management Association, 2012; Hart Research Associates, 2015). Pertaining to students, results from the Programme for International Student Assessment's (PISA) 2015 CPS assessment revealed that only 8% of the more than 500,000 students assessed across 52 countries performed at the highest level of CPS proficiency, while 29% performed at the lowest levels (OECD, 2017b).

It is believed that this global deficit may be due, in part, to a lack of preparation from academic institutions. As a case in point, there are no universally accepted curricula or standards for teaching CPS skills (Scouler & Care, 2018). Concomitantly, there is a dearth of empirical work on complex CPS, making it challenging to identify areas for intervention (Rosen, 2010). Researchers have also noted the difficulty in crafting theoretically and empirically sound measures of CPS (Graesser et al., 2018). In order to develop evidence-based curricula that address society's most pressing problems, work is needed to determine how particular cognitive and social processes come together as individuals work to solve complex problems in social settings. In this regard, empirical studies that examine CPS in naturalistic contexts may prove most informational.

Broadly speaking, CPS is comprised of two components: the cognitive, problem-solving aspect; and the collaborative, communicative, and social aspect (Graesser et al., 2018). Although theoretical frameworks differ in how they propose that the two interact, there is agreement on many of the processes underlying successful CPS. For example, one capacity foundational to problem solving, whether individually or collaboratively, is relational reasoning, or the ability to discern meaningful patterns within streams of information (Alexander & the Disciplined Reading and Learning Research Laboratory [DRLRL], 2012). Relational reasoning is conceptualized as a meta-strategy that entails conscious and effortful processing directed toward identifying underlying associations among concepts, objects, and ideas (Jablansky, Alexander, Dumas, & Compton, 2019). Importantly, these associations may take on different forms depending on the relation identified by the reasoner (Dumas, 2016).

The four forms of relational reasoning featured most prominently in the literature include analogies, or structural similarities; anomalies, characterized as outliers from a set; antinomies, or relations of contradiction or mutual incompatibility; and antitheses, relations of opposition or differing degree (Alexander et al., 2012; Dumas, Alexander, & Grossnickle, 2013). The broader construct relational reasoning has long been regarded as a necessary precondition for higher-order thinking and problem solving (Chase & Simon, 1973; James, 1890; Waltz et al., 1999), as it allows individuals to meaningfully integrate disparate elements into a consolidated mental representation needed for problem solution. Although there is limited research on how relational reasoning operates in CPS contexts, results have indicated that relational reasoning can aid in problem identification (Christensen & Schunn, 2007; Dumas, Alexander, Baker, Jablansky, & Dunbar, 2014), knowledge reconstruction (Echevarria, 2003), and divergent thinking (Chan & Schunn, 2015; Karhu, Ritala, & Viola, 2016).

Pertaining to the more social aspects of CPS, relational reasoning has been linked to uncertainty reduction and team cohesion and coordination (Ball & Christensen, 2009; Paletz et al., 2013). In spite of the knowledge gained from these studies, it is still unclear how relational reasoning unfolds in real time during a CPS task. For example, how is relational reasoning distributed across team members? Are there discernible cycles of relational reasoning that take place during problem solving? More research is needed to answer these critical questions, which may ultimately provide direction on how to train CPS or compose effective teams.

In addition to traditional problem-solving strategies, CPS demands the ability to regulate cognition, emotion, and behavior (Zimmerman, 1989). In collaborative settings, this construct is referred to as socially shared regulation of learning (SSRL; Jarvela, Jarvenoja, Malmberg, & Hadwin, 2013). Specifically, SSRL refers to the processes used by group members to regulate collective activity, such as co-constructing knowledge, aligning task perceptions, setting goals, and monitoring and evaluating progress in service of solving a problem (Panadero & Jarvela, 2015). SSRL is considered a quintessential skill in CPS contexts (Hadwin, Jarvela, & Miller, 2011) in that monitoring and controlling each other's cognitive and metacognitive processes allow groups to jointly construct shared task representations, enhance the socioemotional climate, and adapt performance when necessary.

Compared to constructs such as self-regulated learning (SRL) and co-regulated learning, SSRL has a relatively sparse and homogeneous base of literature (Panadero & Jarvela, 2015). For instance, of the extant empirical studies, many focus on the domain of math (Vauras, Iiskala, Kajamies, Kinnunen, & Lehtinen, 2003; Goos, Galbraith, & Renshaw, 2002), well-structured or highly constrained tasks (Iiskala, Vauras, & Lehtinen, 2004; Rogat & Linnenbrink-Garcia, 2011), and computer-supported collaborative learning (CSCL) environments (Hurme & Jarvela, 2005; Lee, Lajoie, Poitras, Nkangu, & Doleck, 2017). Given that models of self-regulation emphasize the influences of domain, task, and context (Alexander, Dinsmore, Parkinson, &

Winters, 2011; Poitras & Lajoie, 2013), research should focus on the extent to which findings can be generalized beyond these conditions.

Study Rationale

With the increasing complexity of sociotechnical systems in both the workplace and academic institutions, there is a greater need for individuals to pool their knowledge in order to address complex problems. In spite of this shift, stakeholders have identified a global deficit in students' and employees' abilities to work collaboratively (National Research Council, 2011). Although there is a rich literature on individual problem solving and related group constructs such as team learning and decision-making, research on complex collaborative problem solving specifically has been more limited (Graesser et al., 2018). As a consequence, there are no universally accepted curricula for teaching CPS in schools (Scoular & Care, 2018), and assessments of CPS (PISA's Collaborative Problem Solving Assessment; OECD, 2017a, 2017b) are still relatively new. Given the heavily social nature of CPS, it stands to reason that a better understanding of the dynamic, real-time interactions that shape CPS may aid in designing future curricula or trainings.

Two capacities central to problem solving in any arena are relational reasoning and self-regulated learning, both of which demand reflective, evaluative, and strategic processing. Relational reasoning (RR) entails the detection of patterns, the integration of information from multiple sources, and finally the transformation of knowledge (Alexander & DRLRL, 2012). Despite all that is known about this meta-strategy, it has traditionally been studied in individuals (Dumas et al., 2013), with formal measures (e.g., Test of Relational Reasoning [TORR]; Alexander, Dumas, Grossnickle, List, & Firetto, 2016), and in isolated forms (e.g., analogy only). Recently, there have been forays into how RR, in all of its forms, manifests in the discourse of dyads engaged in problem solving in the domain of technology (Jablansky, Alexander, Dumas, & Compton, 2016; 2019), as well as teams of doctors diagnosing patients (Dumas et al., 2014). These studies have begun to unravel how RR unfolds in real-time CPS contexts, but more research is needed to understand how different individuals contribute to the team's overall reasoning, and how the various forms of RR operate in concert with one another. Further, the extant studies have tended to sample teams with a hierarchy, or groups with a designated leader who scaffolds thinking and reasoning (Murphy, Firetto, & Greene, 2017; Sun, Alexander, & Zhao, 2018). Research is needed to determine whether these same findings are true of teams with no appointed leader.

Self-regulated learning (SRL) is highly regarded as an essential skill in any learning or problem-solving context as it refers to the active construction of goals for learning and the subsequent attempt to monitor, regulate, and control cognition, motivation, and behavior, guided and constrained by contextual features in the environment (Pintrich, 2000). SRL is conceptualized as a recursive process in which regulatory processes unfold dynamically and cyclically (Azevedo & Witherspoon, 2009; Winne, 2001; Zimmerman & Schunk, 2001). This implies that SRL processes may fluctuate in frequency over the course of problem solving, based on the phase of learning in which learners are engaged, as well as the capacities (e.g., domain knowledge, self-efficacy) an individual brings to bear on the task. Currently, researchers are devoted to uncovering how and why SRL processes unfold in particular sequences, and what this means about a learner's knowledge and adaptivity, among other things.

At the same time, researchers have also begun to address how SRL manifests in CPS contexts in which multiple individuals must collectively regulate their learning and performance. This construct, termed *socially shared regulation of learning* (SSRL), deals with many of the same processes as SRL, but considers how multiple individuals engaged in a problem-solving task mutually and reciprocally monitor and control each other's actions (Jarvela et al., 2013; Vauras et al., 2003). Given the nascence of this construct, with a recent review reporting on only 13 empirical articles addressing SSRL (Panadero & Jarvela, 2015), researchers interested in facilitating SSRL in service of CPS performance must explore new methodologies, domains, and contexts in which SSRL occurs.

Study Goal and Context

Thus, the present study sought to examine the respective roles of RR and SSRL as they contributed to CPS in the domain of mechanical engineering and, more specifically, a product design task. Engineering design was chosen as the context for this investigation because it principally involves solving complex problems within a group setting. As Dieter and Schmidt write, "Design establishes and defines solutions to and pertinent structures for problems not solved before, or new solutions to problems which have previously been solved in a different way" (Dieter & Schmidt, 2009, p. 1). In this way, effective design demands the formulation of objectives, the application of analysis and synthesis, and the establishment of criteria for evaluation (Diaz-Herrara, 2001). Additionally, because the engineering design process typically takes place within a group, designers must be able to communicate with one another and negotiate the various perspectives and desires of those involved toward a common goal (Bucciarelli, 2002).

Relational reasoning is cast as an essential process in engineering design, with researchers maintaining that "reasoning is at the heart of design activity" (Cramer-Petersen, Christensen, & Ahmed-Kristensen, 2018, p. 39). Analogical reasoning in particular has had a rich history in the domain of design, as it involves accessing and transferring elements from familiar categories and applying it to the construction of a novel idea (Christensen & Schunn, 2007; Visser, 2009). In fact, a number of design methodologies (e.g., Synectics, TRIZ, SAPPhire) explicitly draw on analogical reasoning as a core component of the innovation process (Altshuller & Shulyak, 2002; Gordon, 1961; Sartori, Pal, & Chakrabarti, 2010). Analogies and relational representations more broadly can be especially helpful in framing a problem, and as such, have been linked to the early stages of the design process (Dixon, 2011).

More recently, other forms of relational reasoning, such as anomalous, antinomous, and antithetical reasoning, have been empirically linked to engineering design. For instance, Dumas and Schmidt (2015) found that the relational reasoning abilities of graduate students in mechanical engineering positively and significantly predicted success on an ideation task. Interestingly, analogical and antithetical reasoning significantly predicted the fluency (i.e., quantity) of ideas, while anomalous and antinomous reasoning significantly predicted the originality of ideas (Dumas, Schmidt, & Alexander, 2016).

Engineering design is also fundamentally a social process in which designers work with stakeholders, customers, and other designers to conceptualize and prototype a new product that fills a market need. As with other complex, ill-structured tasks, it becomes paramount for designers to set reasonable goals and adopt intrinsic standards for success in order to solve problems strategically (Lawanto, Febrian, Butlet, & Mina, 2019). However, successful problem solving requires more than the ability to monitor and control one's *own* cognition, emotion, and behavior. Design is a dynamic and socially-mediated process of communicating and coordinating the various knowledge, values, and perspectives of a group of individuals (Atman, Cardella, Turns, & Adams, 2005; Lee & Johnson-Laird, 2013). In this way, the resulting design is best understood not as a summation of participants' products, but as an intersection of them (Dym, Agogino, Eris, Frey, & Leifer, 2015).

Thus, the current study sought to examine the roles of relational reasoning and socially shared regulation of learning in an engineering design context. Specifically, four teams of mechanical engineering students were observed as they evaluated a corpus of design ideas and selected one to prototype for their capstone project. This study aimed to add to researchers' understanding of the respective and interactive contributions of individual and socially shared reasoning and regulatory capacities in complex CPS contexts. Unlike prior studies (Iiskala, Vauras, Lehtinen, & Salonen, 2011; Jablansky et al., 2016, 2019), it strove to examine the temporal dynamics of these processes across time. Additionally, this study endeavored to identify commonalities in these patterns across teams, as well as how specific individuals contributed to these patterns in the absence of an appointed leader.

Study Design

This study examined the ways in which RR and SSRL unfolded as teams of mechanical engineering students compared and selected designs for a new product. The study employed a microgenetic methodology to capture real-time changes in the iterations and co-occurrences of these constructs, as well as how different individuals contributed to these patterns. Specifically, teams of engineers were video-recorded during one of their meetings devoted to evaluating and narrowing down their pool of ideas. These meetings were then transcribed, segmented, and coded for RR and SSRL. Using a mixture of quantitative and qualitative techniques, this study sought to provide a rich glimpse into how and potentially why RR and SSRL iterate as they do in CPS tasks.

Research Questions and Hypotheses

Broadly, the goal of this study was to examine iterations of RR and SSRL in a CPS task. Given the need to better understand RR in teams, SSRL in discourse, and real-time interactions among teammates in CPS contexts, the study was partially exploratory in nature. Toward this end, the study posed three central research questions:

Research Question 1: *To what extent do teams express differential proportions of relational reasoning (RR) and socially shared regulation of learning (SSRL) discourse during a collaborative problem-solving task?*

To address the question of whether teams manifest disproportionate proportions of RR and SSRL discourse in the current study, it was necessary to inspect frequencies of each type of speech and evaluate whether distributions of speech were similar or different across teams. Prior to any analyses, team discourse from each meeting was coded for four types of RR (i.e., analogy, anomaly, antinomy, and antithesis) and five types of SSRL (i.e., planning, monitoring/control of understanding, monitoring/control of consensus, monitoring/control of progress, reflection). Then, chi-square tests of independence were run for RR and SSRL, respectively, to determine whether the distributions of each differed significantly across teams. In the case that one of those omnibus tests reached statistical significance, post-hoc testing was carried out to determine where the differences were.

Previous studies have found differences in the proportions of RR and SSRL used by teams in collaborative contexts (Dumas, Alexander, Baker, Jablansky, & Dunbar, 2014; Lajoie, Lee, et al., 2015). However, it is unclear what motivates the usage of particular forms and quantities of each. In other words, it is uncertain whether aspects of the domain, the task, the person, or some combination therein contributes to teams' resultant reasoning and regulatory speech. For instance, one investigation in the domain of medicine found that medical residents drew most heavily on anomalous reasoning when diagnosing patients, while the attending doctor guiding them tended to use proportionally more analogies and antinomies than other forms of reasoning (Dumas et al., 2014). Alternatively, a quasi-experimental study in mechanical engineering found that engineering design students' abilities to reason analogically and antithetically significantly predicted their fluency of idea generation for a classic design problem, whereas their anomalous reasoning predicted the originality of their solutions, and their antinomous reasoning predicted both originality and fluency. Together, these studies suggest that the focal task, as well as one's role on the team (e.g., guiding others' thinking), may foreshadow which forms of reasoning are used most. Further, this research suggests that different forms may address different aspects of problem solving (i.e., number of solutions vs. creativity of solutions).

There has been a similar lack of clarity in which factors best predict the types and amounts of regulatory activity in CPS contexts. For instance, a recent study of doctoral students in pharmacy found that, across the board, few groups engaged in reflection processes when trying to solve a problem about how to reduce medication errors (Lobczowski, Lyons, Greene, & McLaughlin, 2020). Other studies have found that task difficulty is an important determinant of monitoring activity, with higher-difficulty tasks requiring a higher level of coordination and management of individuals' content and task understanding (Lobczowski, Allen, Firetto, Greene, & Murphy, 2020). Still other studies suggest that the types and frequencies of planning, monitoring, and reflection depend on the quality of the group's regulation, with high-quality regulators demonstrating more equivalent proportions of distinct regulatory activities, and low-quality regulators manifesting disproportionate amounts of particular forms of regulation (Rogat & Linnenbrink-Garcia, 2011; Volet, Summers, & Thurman, 2009).

Based on these results, it was hypothesized that there would be disproportionate quantities of RR and SSRL in the current study. In terms of RR, it was predicted that there might be more instances of antinomous and antithetical reasoning since the task necessarily involved differentiating between ideas and comparing their merits and flaws. In terms of SSRL, it was predicted that there might be a disproportionately high amount of monitoring knowledge and understanding, given the difficult nature of the task, and potentially disproportionately low quantities of reflection, as other studies have found that activity to be rare even in doctoral students.

Research Question 2: *How is collective activity within problem-solving episodes shared among team members? Further, to what extent do certain individuals mediate these exchanges?*

Research has demonstrated that successful team problem solving depends not only on the ability to regulate one's own thinking, emotions, and behavior, but also on the capacity to co-construct knowledge, and mutually and reciprocally monitor and control the actions of the collective (Rogat & Linnenbrink-Garcia, 2011, Roschelle & Teasley, 1995). However, the degree to which activities are shared may vary widely within and between teams. For instance, prior research has found that some individuals possess more knowledge and experience with the domain or task than their teammates, leading them to guide the group's thinking and activity (Lobczowski, Lyons, et al., 2020). Collective activity may also be shared more equally among team members (Rogat & Adams-Wiggins, 2014, 2015). Thus, it is important to explore the degree to which different individuals mediate team talk as they problem solve, as well as to examine which team members emerge as "more knowledgeable" or "more regulated" others. Additionally, because shared regulatory processes can change over time (Efklides, 2006), it is important to consider how individuals' contributions change with shifts in time and task.

To address these concerns, one team meeting was segmented into *episodes*, or discernible periods of time in which teams engaged in reasoning and regulatory activities. Episodes have been used in prior research as meaningful units of analysis (Isohätälä et al., 2018; Järvelä et al., 2016; Järvenoja et al., 2017) and are marked by a "continued pattern in content and collaboration, ending with a clear shift in either content or collaboration" (Lobczowski, Lyons, et al., 2020, p.17). Each episode was then coded for the *distribution* of activity within it, which served as an indicator of the degree of sharedness of team activity. Distribution could be characterized as *shared*, denoting activity that was distributed relatively equally among participants, or *guided*, denoting activity that temporarily controlled by one or more individuals. In cases of guided activity, those individuals controlling team activity were noted. Given the complexity of the task before them, and the need to coordinate multiple perspectives and ideas, it was expected that there would be more instances of shared activity than guided activity.

Following the segmentation and coding of activity within episodes, social transition plots were constructed for each episode to illustrate the dyadic interactions among team members. These plots helped visually depict patterns of communication by displaying the types of communication that occurred as well as the frequencies of such communication. For each episode plot, nodes represented speakers and a tie between nodes indicated that one speaker finished talking and the other person responded. Ties were also colored by the type of speech that occurred to distinguish between reasoning, regulation, task-related, and other speech units. After constructing the plots, a series of centrality statistics including weighted degree centrality, flow betweenness, and eigenvector centrality, were calculated in order to identify individuals who were influential in their team's problem solving efforts both when activity was highly distributed and when it was more controlled by particular team members. By considering the distribution of activity in each episode, the types and amounts of speech units produced by team members, and the computed centralities of each individual, overarching patterns in how activity was shared among teammates could be discerned and discussed.

Research Question 3: *What systematic patterns can be uncovered about the ways in which relational reasoning and SSRL discourse emerge in real time?*

A significant challenge in the study of reasoning, regulation, and collaborative problem solving (CPS) is that they are processes that unfold over time. However, traditional statistical paradigms in social science tend to rely on analyses of correlation or group difference that aggregate observations over time, effectively capturing cross-sectional snapshots of phenomena rather than moment-to-moment change (Greene & Azevedo, 2010). If these processes are to be understood more deeply, then the measurement of these constructs must match their conceptualizations. As Greene & Azevedo argue, "Such data must take into account not only what learners do, but when, how often, in what context, in what sequence, and in response to what factors" (p. 208). In the last decade, researchers have begun leveraging data mining techniques to do just that. For instance, using a fuzzy mining algorithm (Günther and van der Aalst 2007; Reimann et al. 2009), Bannert et al. (2014) found that students who scored higher on a transfer task not only exhibited a wider variety of metacognitive activities than students who scored lower, they also looped through metacognitive activities (e.g., planning, monitoring, evaluating) more often and with deeper processing strategies. In another investigation, Kinnebrew and colleagues (2013) used an approach called the Temporal Interestingness of Patterns in Sequences (TIPS) technique to show *when* in the course of a science task middle school students were most likely to engage in activities such as reading, taking notes, monitoring understanding, and explaining ideas. Although there is currently great variability in the techniques researchers use to investigate temporal patterns in processes, this approach holds great promise for uncovering key facets of how reasoning, regulation, and collaborative problem solving emerge.

Thus, the present study sought to create an algorithm to examine patterns in how reasoning and regulation unfolded during the course of a problem-solving task. Additional charts displaying each team's speech units over time made it possible to see not only which sequences of reasoning and regulation occurred most often, but also when and by whom they were voiced. Previous research has revealed that the forms of relational reasoning tend to operate in concert with one another as dyads and teams problem-solve (Dumas et al., 2014; Jablansky et al., 2016, 2019), although these patterns tend to differ as a function of domain, task, and participant characteristics. As a result, it was unclear whether the same patterns would generalize to an engineering design task. The same is true of SSRL in team discourse, which has shown that planning, monitoring, and executing, for instance, serve as introductory activities that then lead in to more reflective phases of monitoring, evaluating, and elaborating (Lajoie, Lee et al., 2015). Thus, it was hypothesized that there would be discernible patterns of utterances of both RR and SSRL, but the exact nature of those patterns was uncertain.

Contributions to the Field

The current study offers several contributions to the literatures of each of the three constructs under examination: relational reasoning (RR), socially shared regulation of learning (SSRL), and collaborative problem solving (CPS). For example, this study will be the first to examine how *all* four forms of relational reasoning iterate in CPS contexts in which the team has no hierarchical structure. Whereas previous research has concentrated on how specific forms of RR are used to scaffold less knowledgeable members' knowledge or guide others' thinking, this study will provide insight into the functions of various forms when all members have generally the same knowledge base. Further, this study will be the first to use data mining techniques to uncover common sequences of relational reasoning employed during CPS. These sequences will help showcase how the forms of RR operate in concert while acknowledging the dynamic, temporal nature of the problem-solving process.

With regard to SSRL, this study will contribute to the sparse database of empirical work examining how this construct unfolds in CPS contexts. Further, in response to the majority of these studies, which have explored SSRL in well-structured tasks in computer-supported collaborative learning environments within the domains of mathematics and medicine, this study will assess the extent to which findings can be generalized to ill-defined tasks in naturalistic environments within the domain of mechanical engineering. This study will also demonstrate how teams vacillate between periods of co-regulation and more equally shared regulatory phases. Finally, sequences of SSRL and RR will help show how the two operate in tandem during collaborative problem solving that goes beyond the documentation of *co-occurrences* of SSRL alone.

Overall, this study endeavors to document the respective and reciprocal roles of two cognitive strategies as they played out in a social and collaborative environment. Given the need to better prepare students to work collaboratively in the workforce, this study has implications for educators, policymakers, and institutions hoping to foster the higher-order reasoning and regulation skills underlying successful CPS.

Definition of Terms

For the purpose of this investigation, the following key terms will be conceptualized as follows:

Collaborative Problem Solving is defined as “the capacity of an individual to effectively engage in a process whereby two or more agents attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills, and efforts to reach that solution” (Fiore et al., 2017, p. 2).

Relational Reasoning is defined as the ability to discern meaningful patterns within streams of information (Alexander & the Disciplined Reading and Learning Research Laboratory [DRLRL], 2012).

Socially Shared Regulation of Learning refers to the processes used by group members to regulate collective activity, such as co-constructing knowledge, aligning task perceptions, setting goals, and monitoring and evaluating progress in service of solving a problem (Panadero & Jarvela, 2015).

Speech units, or *utterances*, roughly constitute one complete thought and may be indicated by a disruption or a pause in speech, often corresponding with independent clauses (Trickett & Trafton, 2007).

Sequence mining is a data mining procedure to identify frequently occurring patterns in a temporal database.

CHAPTER II

REVIEW OF THE LITERATURE

In this chapter, I present the research to date on the roles of relational reasoning (RR) and socially shared regulation of learning (SSRL) in collaborative problem solving (CPS). It begins with an overview of the history of CPS, its theoretical underpinnings, guiding frameworks, and key components. Next, I review the literature on RR, focusing specifically on how RR in its various forms iterates in CPS contexts. I subsequently review the literature on SSRL, exploring its theoretical roots and recent emergence in the literature, as well as its relation to CPS. Finally, I discuss the relation between RR and SSRL as it is depicted in the literature. In each section, findings from the extant bodies of research are synthesized, methodologies are examined, gaps in the literature are identified, and implications for future research are considered. Importantly, the section on CPS presents a more exhaustive review of the literature, whereas the sections that follow are geared more toward understanding how RR and SSRL iterate in CPS contexts. Further, because there is not necessarily one framework that unifies these three constructs *and* models how they interact during real time problem solving, I highlight components of extant theories that I will draw on in the current study.

Collaborative Problem Solving (CPS)

In this chapter, I will first delve into the major frameworks, models, and theories used to understand the nature of CPS. CPS has roots in a variety of disciplines, including but not limited to social psychology, organizational psychology, cognitive science, and education. Although there is overlap between the conceptualizations offered by each field, there are notable differences in how they integrate the social and cognitive components of CPS. These discrepancies reflect the unique goals of each field, the phenomena they seek to understand, the epistemologies undergirding their theoretical frameworks, and the methodologies used to explore their constructs of interest. I will consider each in turn before reviewing the unique roles of relational reasoning and socially shared regulation of learning on CPS.

History of Research on Collaborative Problem Solving

Research on CPS, including both its social and cognitive elements, has roots in the Gestalt psychology movement of the early 1900s. Associated with the Berlin School of Experimental Psychology, the Gestalt psychologists—among them such scholars as Koffka (1922), Wertheimer (1923), and Kohler (1929)—endeavored to understand how humans make meaning from the incalculable and seemingly haphazard stimuli continuously encountered in the world. What the Gestalt psychologists sought to identify, in effect, were laws of perceptual organization that helped to explain how seemingly chaotic displays of stimuli took on structure and meaning. Although the Gestalt approach was primarily concerned with perception and meaning-making in individuals, a number of the ideas explored by Gestalt psychologists have influenced current understandings of problem solving processes and small group behavior. Until recent decades, however, these strands of research largely developed in parallel. Before delving into contemporary theories of CPS, I will briefly explore major developments in the respective research traditions of problem solving and collaboration.

Gestalt influence on problem solving research. The Gestalt influence on problem solving research was apparent in the work of Karl Duncker, a student of Max Wertheimer's and Wolfgang Kohler's. Duncker's work primarily explored the concept of insight, identified as one stage of the preparation-incubation-insight-verification model (Wallas, 1926) of problem solving. Originally, insight was proposed as an alternative to the behaviorist account of successful problem solving by trial and error, in that the "solution" or "truth" of a situation was seemingly intuited (Hartmann, 1931; Kohler, 1929; Tolman, 1928). In effect, insight was said to rest on the detection of the essential interrelations within a problem situation that would then instigate awareness of a plausible solution (Spearman, 1927; Yerkes & Yerkes, 1929). Although this account was popular for some time, it did not find much support in empirical studies (Holyoak, 1990). However, using think-aloud protocols, Duncker (1926) discovered a number of mechanisms by which insight, and problem solving in general, might occur. These mechanisms included, but were not limited to, learning from mistakes, analysis of the end state (i.e., goal), and analogical reasoning.

In an effort to discern more precisely how subjects solve problems, Herb Simon and Allen Newell (Newell, Shaw, & Simon, 1958; Newell & Simon, 1972; Simon & Newell, 1971) formulated a theory of information processing (IP). The IP approach to cognition shared some commonalities with that of Duncker, including the proposition of a set of cognitive operations to solve problems, and the use of verbal protocols to observe problem solving (Ericsson & Simon, 1980, 1987). However, the IP approach was also influenced by the new field of artificial intelligence, and accordingly used computational models to generate hypotheses about problem solving behavior. In essence, the human mind was described as a processing mechanism, not unlike a computer. Problem solving was thus conceptualized as an interaction between an information-processing system (i.e., a problem solver) and a task environment (i.e., a problem), as positioned within a problem space (i.e., a problem-solver’s representation of the problem; Simon & Newell, 1971). Consequently, thinking could be viewed as a progression between knowledge states, punctuated by processing activity that determined the succession from one state to another.

Numerous models of problem solving have emerged since the advent of IP theory—some that emphasize internal processes (e.g., Anderson, 1993; Johnson-Laird, 1980; Laird, Newell, & Rosenblum, 1987), others that prioritize the constraints and affordances of the external environment (e.g., Greeno, 1978; Lave, 1988)— but it is clear that IP theory remains the foundation under which these theories are built.

Gestalt influence on collaboration research. If Gestalt psychology is believed to have influenced problem solving research for individuals, then it was equally impactful for the study of group behavior. It is Gestalt psychologists who are credited with the notion of the whole being other from the sum of its parts, a phrase coined by Aristotle and later explored by Kurt Koffka in his foundational text, *Principles of Gestalt Psychology* (1935). It was with this idea in mind that Ludwig von Bertalanffy founded General Systems Theory (GST) in the late 1930s in an attempt to link the hard and soft sciences. GST was posed as a logico-mathematical field that derived principles applicable to systems across multiple disciplines, where systems were defined as "a set of elements standing in interrelation among themselves and with the environment" (von Bertalanffy, 1971, p. 417). Importantly, GST proffered the notion that social groups might best be understood as systems, and the same principles that applied to systems might help explain the behavior of organisms (i.e., people) within those systems. GST eventually lost favor to frameworks that provided more testable hypotheses (Roberts, Hulin, & Rousseau, 1978), but a number of the principles of systems derived by von Bertalanffy (1950, 1971) and GST co-founder Kenneth Boulding (1956), such as self-organization, adaptation, production of emergent phenomena, and exhibition of nonlinear dynamics, found their way into contemporary theories of group functioning.

Around the time that GST was gaining ground, Gestalt psychologist Kurt Lewin (1939) founded Field Theory (Lewin, 1939), which characterized behavior as a function of a person in his environment, formalized in the equation $B = f(P, E)$. With this equation, Lewin believed he could comprehend the totality and complexity of the "field" in which behavior takes place. Similar to von Bertalanffy (1950, 1971), Lewin (1939) understood groups as wholes based on the *interdependence* of its members or organisms, standing in contrast to many of his contemporaries who defined groups in terms of the *similarity* of group members. Undoubtedly influenced by the social and political climate surrounding World War II, Lewin studied leadership styles, worker motivation, and attitude change (among other subjects) in order to discern how behavior might be altered. Accordingly, Lewin is credited with coining the term "group dynamics."

Although a pioneer in his field, Lewin's work represented only one school of thought on small group behavior. Whereas Lewin and his successors at the University of Michigan viewed groups as vehicles for influencing its members (Cartwright & Zander, 1953; Festinger, 1954, 1957; Seashore, 1954; Thibaut & Kelley, 1959) and focused on the effects of some input factor on some output state, another group coming out of Harvard viewed groups as systems of human interaction, and thus prioritized the classification of patterns of exchange among group members during the course of problem solving (Bales, 1950a, 1950b; Borgatta, 1963; Hare, 1976). Bales's interaction process analysis (IPA) serves as an exemplar of this paradigm, as the technique detailed methods for observing and classifying the behaviors exhibited by group members operating in face-to-face settings.

Yet a third group of researchers from the University of Illinois viewed groups as systems for performing tasks and sought to understand the individual-, group-, and environmental-level factors (e.g., group member knowledge, task complexity, environmental stress) that influenced task performance (e.g., productivity level, decision quality, number of ideas generated; Dashiell, 1930; Carter, Haythorn, & Howell, 1950; Hoffman, 1965). Perhaps the most significant contribution of this school was the input-process-output (IPO) model of group functioning, formalized by McGrath (1964), Steiner (1972), and Hackman (Hackman & Morris, 1975). Of importance in this model, group processes were mediating mechanisms that converted inputs into outputs, and as such, group member interactions acted as the primary determinant of product. Although researchers have since taken issue with many of the implicit assumptions made by the IPO model (e.g., linear progression from input to process to output; static in nature), the IPO model has remained a prevailing influence on groups research.

Interestingly, the Michigan, Harvard, and Illinois Schools of Thought largely developed in isolation until, in the 1960s and 1970s, the social psychological approach to groups research suffered a “system crash” (McGrath, 1997), having reached the limits of what could be achieved by each approach alone. In spite of this crash, groups research continued to thrive. As Levine and Moreland (1990) famously observed, “Groups are alive and well, but living elsewhere” (p. 620). In fact, a review of the literature by Salas and colleagues (2007) found over 130 frameworks or models of team performance and effectiveness published within the last 25 years in the organizational psychology literature alone. Of course, other literatures, such as the cognitive and educational psychology literatures, have studied group functioning too. Ironically, this proliferation of theoretical frameworks may be foretelling of a similar crash to that of the 1960s and 1970s, as “team researchers, and, in fact, whole disciplines fail to communicate” (Salas, Stagl, Burke, & Goodwin, 2007, p. 226). Indeed, the diverse goals, values, paradigms, and assumptions held by researchers may be said to underlie this translational issue. A full review of these frameworks is beyond the scope of this study. However, I will overview a few key frameworks relevant to studying CPS in an educational setting, organized by discipline.

Relevant Frameworks for the Study of Collaborative Problem Solving (CPS)

Frameworks for the study and measurement of CPS in teams come primarily from the organizational and educational psychology literatures. The fields differ in terms of the samples, methods, and variables in which they are invested, but do, for the most part, share similar views of CPS. For instance, the frameworks provided by the organizational and educational psychology literatures tend to agree that CPS involves two or more individuals working interdependently toward a common goal, and that successful CPS demands effective communication among group members, among other cognitive and social capacities. However, the broader contexts in which these frameworks are situated have resulted in differences as well. For example, while organizational research deals more often with experts in hierarchical teams, educational research typically focuses on novices in either a scaffolded environment or non-hierarchical group. On a more fundamental level, organizational research seeks to optimize workplace performance, whereas educational research aims to enhance learning outcomes. As a result, educational frameworks tend to focus on the suite of skills students need for successful CPS, whereas organizational frameworks concentrate more on how these skills come together in real time. In spite of their differences, when taken together, these frameworks offer a comprehensive picture of CPS.

Organizational Frameworks for Collaborative Problem Solving. Within the organizational literature, notable frameworks include Hinsz and colleagues' (1997) groups-as-information-processors model, Cooke and colleagues' (2004) theory of team cognition, Marks and colleagues' (2001) recurring phase model of team processes, and Fiore and colleagues'

(Fiore, Rosen, et al., 2010; Fiore, Smith-Jentsch, et al., 2010) macrocognition in teams model (MITM). I will review each of these in turn, discuss their unique contributions to the study of CPS, and explain their significance to the current study.

Groups-as-information processors approach. One answer to the "system crash" of small group research was the formulation of a *groups-as-information-processors* approach by Hinsz and colleagues (1997). This perspective of groups reflected a scaling up of prototypical information processes (e.g., encoding, storage, and retrieval) from an individual level to a group level (see Figure 1 for generic information processing model), where group-level information processing was defined as "the degree to which information, ideas, or cognitive processes are shared, and are being shared, among the group members and how this sharing of information affects both individual- and group- level outcomes" (Hinsz et al., 1997, p. 53). This metatheoretical approach represented a paradigm shift in the study of small groups, as it found a way to couple individual processes with social cognition.

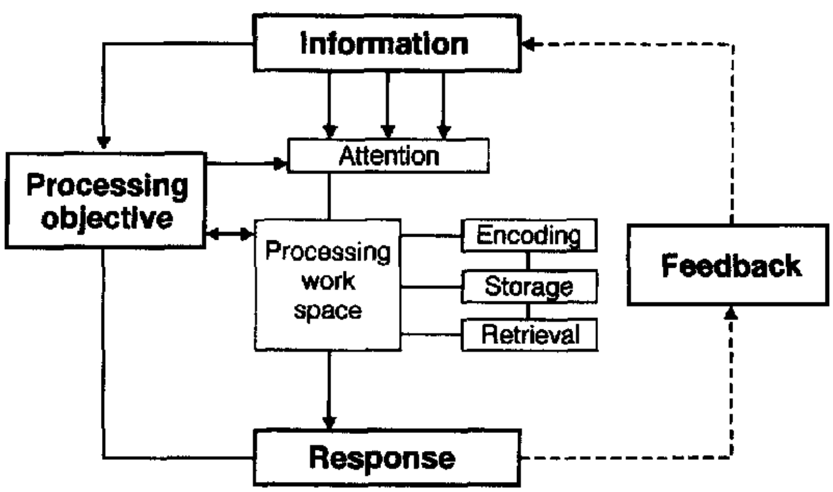

Figure 1. Hinsz and colleagues' (1997) outline of a generic information processing model.

Epistemologically, the groups-as-information-processors approach keeps cognition in individual minds but allows for group-level cognitive structures as well, such as shared mental models (Klimoski & Mohammed, 1994; Kozlowski, Gully, Salas, & Cannon-Bowers, 1996) and transactive memory systems (Wegner, Giuliano, & Hertel, 1985; Wegner, 1995). In this way, the approach acknowledges the interdependencies between individual- and group-level processing, thus skirting atomistic and ecological fallacies in which higher-level phenomena are used to make inferences about lower-level structures and vice versa, respectively (Diez, 2002; Klein & Kozlowski, 2000).

Principally, the information processing approach to groups views the degree of social sharedness as key for understanding group processing (Tindale & Kameda, 2000). In essence, sharing—via communication and interaction—is what makes group processing possible and distinguishes it from individual-level processing. Further, the approach predicts that things that are shared to a greater degree will have a greater impact on team outcomes than things that are shared less. Things that can be shared include but are not limited to: information about the task, characteristics of the group, aspects of group members, patterns of group interaction, and the context within which the task, group, and its members exist (Hinsz et al., 1997).

Although influential for small group research, the groups-as-information-processors approach was not formulated specifically for research on CPS, and mostly involved studies of ad-hoc teams in laboratory settings (Hinsz et al., 1997). Further, although the approach acknowledged a larger environment, it primarily focused on interactions within the bounds of the group (Fiore et al., 2010a). Still, the metaphor of the group as information processor continues to serve as the basis upon which many contemporary theories are built.

Team cognition theory. One line of research that has emerged as an extension of both IPO theory and the groups-as-information-processors approach is that of team cognition. The theory of team cognition characterizes teams as information processing systems and focuses on "how cognitive activity is distributed across two or more interdependent individuals in the context of a complex and dynamic sociotechnical work setting" (Gorman & Cooke, 2011, p. 304). This cognitive activity may comprise learning, planning, reasoning, decision making, problem solving, remembering, and designing. Put differently, team cognition provides a way of describing how thinking and knowledge building occur within and between individuals. Moreover, it is concerned with the organization, representation, and distribution of knowledge among teammates (DeChurch & Mesmer-Magnus, 2010).

This framework views change in team knowledge and performance as arising from team processes, or interactions between and among team members, task, and environment. Accordingly, team cognition researchers use an IPO framework to explain the antecedents and outcomes of team interactions. In this way, the effects of inputs, such as shared knowledge, on outputs, such as team effectiveness, are mediated by processes like communication and coordination (Gorman & Cooke, 2011). Importantly, team cognition is viewed as an emergent process occurring during team interaction (Cooke, Gorman, Duran, & Taylor, 2007) in that lower-level phenomena, such as an individual's knowledge, reasoning, and regulatory strategies, interact dynamically with those of other individuals, ultimately manifesting as a collective, higher-level phenomenon (Kozlowski, Chao, Grand, Braun, & Kuljanin, 2013).

Recurring phase model of team processes. Although team cognition regards teams as complex and dynamic systems that change and adapt over time, the majority of team effectiveness models have taken a rather static approach to the study of team process (Marks, Mathieu, & Zaccaro, 2001; McGrath & Hollingshead, 1993). For instance, studies examining the functioning of teams over a series of tasks may aggregate process data so as to look at overall relations between team process and team outcomes. In doing so, critical sources of variance over time are collapsed into a single indicator that cannot capture the dynamism and emergence of team process.

Marks and colleagues (2001) developed the recurring phase model of team processes to address how temporal factors of team processes may affect team functioning. The model theorizes that teams perform in temporal cycles of goal-directed activity called *episodes*, defined as "distinguishable periods of time over which performance accrues and feedback is available" (Marks et al., 2001, p. 359). These episodes consist of identifiable periods of *action* and *transition* between action. Whereas action reflects engagement in acts that directly contribute to goal accomplishment (e.g., coordination, monitoring processes), transition refers to the reflection, evaluation, and planning that typically punctuate taskwork. Further, cycles of IPO episodes are nested in these periods of action and transition, such that outputs from a transition period may serve as inputs for the subsequent action period. These IPO cycles then continue to play out within periods of action and transition. The length and frequency of these periods will necessarily differ as a function of team objectives, expertise, norms, leadership, and the larger environment in which the team is operating. The nature and complexity of the task, as well as the tools teams have at their disposal, will also have an impact on the duration of these periods. Importantly, this framework suggests that it is not only *what* but *when* particular processes occur that is critical for understanding ultimate team performance. To illustrate, Marks and colleagues (2001) display four potential rhythms with which teams may pursue task accomplishment (see Figure 2), demonstrating the importance of using real-time measures (e.g., communication transcripts, video records of behavior) to model dynamic team processes, thus taking a more microgenetic approach to the study of team performance.

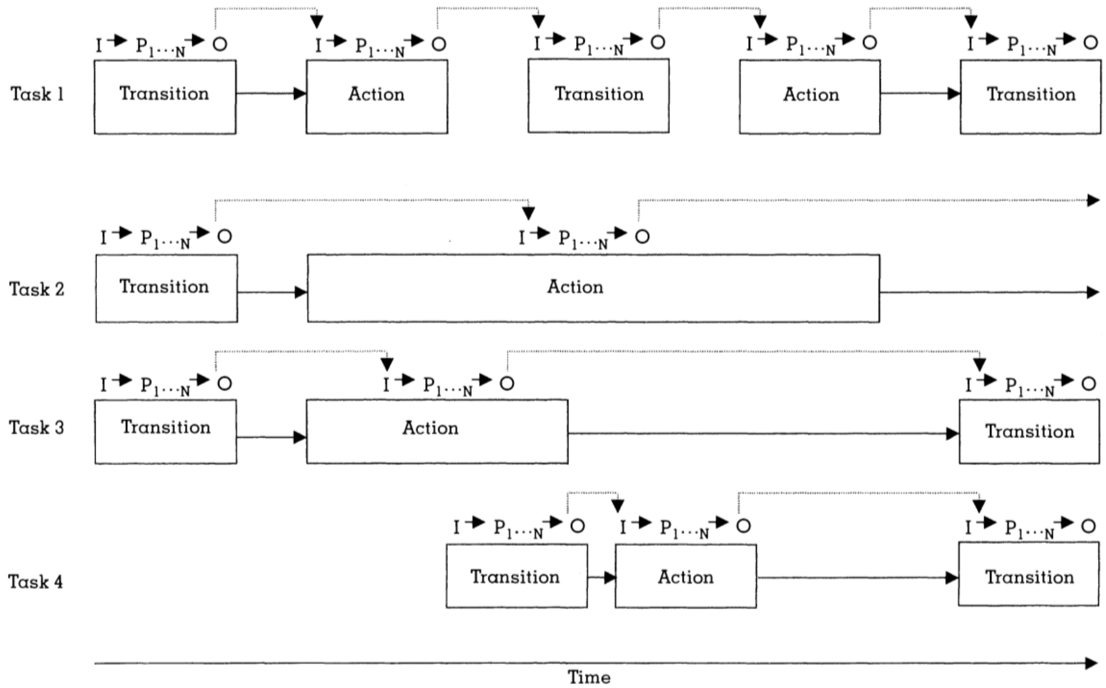

Figure 2. Possible rhythms of team task accomplishment illustrated by Marks et al. (2001) within the recurring phase model of team processes.

Macrocognition-in-teams-model (MITM). The frameworks advanced by team cognition and the recurring phase model of team processes undoubtedly contributed to a more nuanced understanding of team performance as well as the development of more sensitive measures of team process. However, these frameworks have primarily been used to explain routine procedures or performance in relatively stable environments. But many teams—especially those in engineering design—routinely operate in situations that are highly novel and variable (Fiore, Rosen, et al., 2010). Additionally, these frameworks are more general in their focus on teamwork, rather than CPS, per se.

The MITM (see Figures 3 and 4) was developed as an extension of rule-based (i.e., routine) team cognition to explain knowledge-based complex, collaborative cognition (Fiore, Rosen, et al., 2010; Fiore, Smith-Jentsch, et al., 2010). Macrocognition is defined as "the process of transforming internalized knowledge into externalized team knowledge through individual and team knowledge-building processes" (Fiore, Rosen, et al., 2010, pp. 204-205). In this way, the MITM is not simply concerned with the degree of overlap or interaction among team members' knowledge, but also with the team's generation of new knowledge during periods of adaptation. In addition to its influence from team cognition and the recurring phase model of team process, the MITM is informed by theories of externalized cognition, group communication theory, group problem solving, and collaborative learning and adaptation (Fiore, Rosen, et al., 2010). With these theoretical foundations, MITM explains change in team functioning and performance as arising from a series of iterative processes focused on team knowledge-building within a collaborative, novel problem-solving context (Fiore, Rosen, et al., 2010).

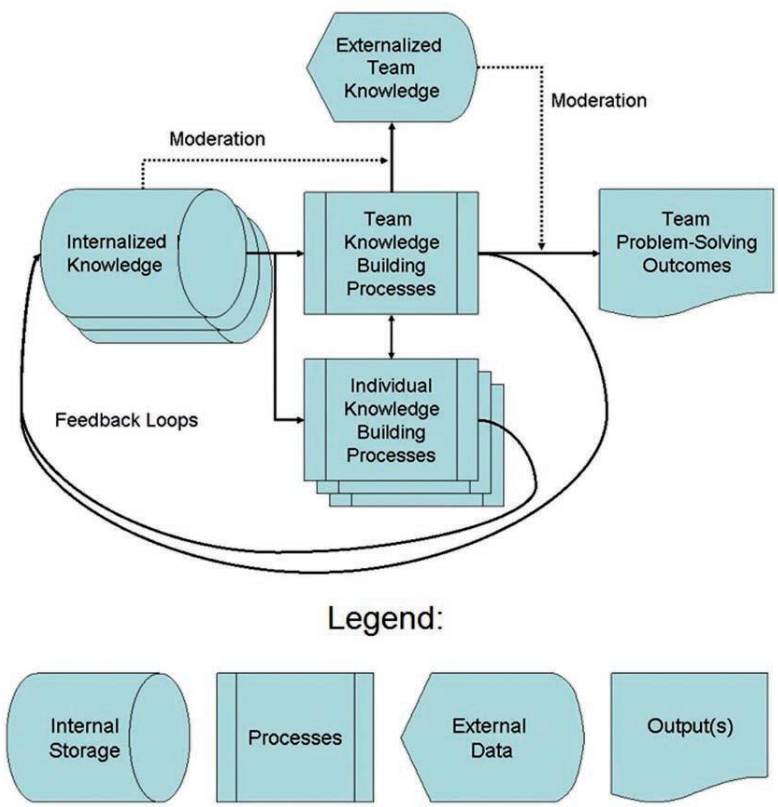

Figure 3. Macrocognition-in-teams-model forwarded by Fiore and colleagues (2010a, 2010b).

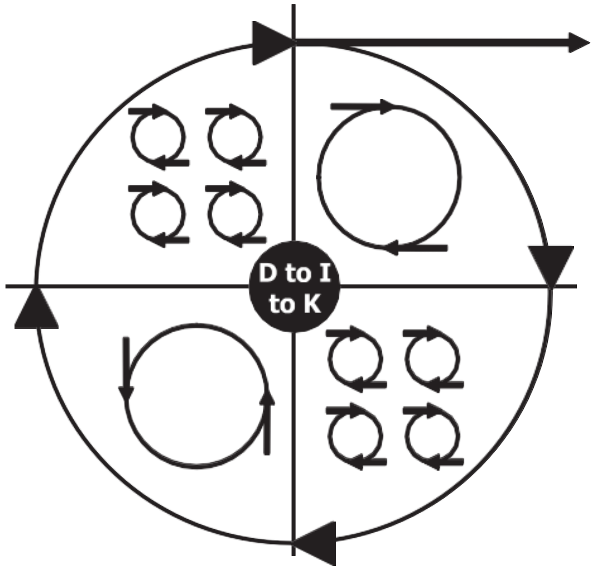

Figure 4. Qualitative representation of macrocognitive processes occurring across individuals and the team within a particular stage of problem solving (Fiore et al., 2010b).

Specifically, Fiore and colleagues (Fiore, Rosen, et al., 2010; Fiore, Smith-Jentsch, et al., 2010) suggest four phases of collaborative problem-solving and an accompanying five macrocognitive processes, each of which are said to arise during each phase. Collaboration phases include knowledge construction, problem model development, team consensus, and outcome revision and evaluation. As such, the framework implies the importance of both higher-order (i.e., relational) reasoning processes and regulatory behaviors in guiding activity during these phases.

During knowledge construction, team members identify relevant domain information, form individual and team-level mental models of the problem, develop individual and team-level knowledge, and set up the communication environment. Team members then integrate their knowledge and understanding in the problem model development phase into a unified conception of the problem, proposing goals and feasible solutions. Team consensus then involves reaching agreement on the specific goals the team will pursue and the solution the team will seek. Finally, the team analyzes, tests, and validates this solution in reference to the agreed upon goals in outcome revision and evaluation. If the team decides that their solution or goals are not viable, then they may return to any of the previous stages. Like the recurring phase model of team processes, MITM stresses the iterative nature of collaborative problem solving, and accordingly the importance of examining process over time.

Within each phase of collaboration there are several macrocognitive processes at work, including individual knowledge-building processes, team knowledge-building processes, internalized team knowledge, externalized team knowledge, and team problem-solving outcomes. Whereas individual knowledge-building involves the individual gathering relevant information about the domain and gaining knowledge from interacting with elements of the sociotechnical context, team knowledge-building involves the dissemination and sharing of knowledge among teammates. Internalized team knowledge refers to the distributed knowledge of each team member regarding both taskwork and teamwork needs.

Because the MITM was developed for teams operating in novel situations in which team members have distributed knowledge and limited or no experience working with one another, the process of internalized team knowledge provides a way of describing how individual knowledge about one's own area of expertise becomes increasingly integrated (i.e., coordinated) with other individuals' expertise and knowledge about the task. As internalized team knowledge is verbalized and communicated, it is transformed into externalized team knowledge. Unlike the other processes described, which predominantly pertain to the level at which knowledge is being built or communicated, team problem-solving outcomes refers to the relative effectiveness of problem solutions formulated at each of the phases. Again, each of these processes is said to have some influence during each collaboration phase.

As an extension, or, special case of, team cognition, the MITM provides researchers insights into team functioning during complex, collaborative problem solving. As such, it lends itself well to engineering design, in which individuals must work interdependently, coordinate their knowledge and actions, and solve ill-structured problems over the course of weeks or months. Further, engineering design demands both innovation and efficiency (Dumas & Schmidt, 2015), which necessitates a constant negotiation of task constraints with problems that need solving. Thus, the ability of a team to adapt its problem model, proposed solutions, and criteria for evaluating effectiveness is critical to effective team performance (McComb, Cagan, & Kotovsky, 2015). Taken together with the groups-as-information-processors approach, team cognition theory, and the recurring phase model of team processes, it is clear that successful CPS demands a complex interaction of social and cognitive capacities at both the individual- and team-level.

Key components of organizational frameworks of collaborative problem solving. Although the theoretical frames presented above represent multifarious research traditions, each offers key components that I will draw on in the current study. For instance, the groups-as-information-processors approach stresses the importance of social sharedness in CPS environments. That is, while cognition exists in individual minds, CPS performance is determined, in large part, by whether and how individual cognitions, motivations, emotions, and behaviors are shared with others. Put differently, there may be a relation between individual capacities assessed in isolation (e.g., relational reasoning) and those assessed in a collaborative setting to the extent that these capacities are invoked in team discourse or interaction.

Building on this notion, team cognition theory proposes that individual processes interact *dynamically* with those of others to produce higher-level team structures that are not mere aggregations or linear combinations of their individual parts. This suggests the importance of examining how contributions are distributed across individuals as well as how overall patterns of the team manifest. In this vein, the recurring phase model of team processes suggests that here are discernible episodes of teamwork and taskwork, and that examining patterns in a microgenetic framework may illuminate the natural ebbs and flows of a given team's CPS. Finally, all of the aforementioned ideas are integrated in the MITM, which identifies critical cognitive and social processes in CPS—higher-order reasoning and socially shared regulation, among them—that can be expected to play out in iterative cycles and in reference to ill-defined problems.

Educational Frameworks for Collaborative Problem Solving. Whereas organizational models describe how CPS iterates in reference to workplace performance, educational frameworks reflect concern with CPS as it pertains to learning outcomes. Thus, while there is overlap in many of the social and cognitive components of CPS detailed in the organizational and educational psychology literatures, the way in which the respective fields bring these elements come together do tend to differ. As a case in point, educational frameworks tend to focus more on assessment of an *individual's* collaborative behavior, rather than the collaborative behavior of the *team* as a whole.

Within the educational realm, key frameworks include Roschelle and Teasley's (1995) Theory of the Construction of Shared Knowledge in Collaborative Problem Solving, the teamwork process model adopted by the United States Centre for Research on Evaluation, Standards, and Student Testing (CRESST), and the CPS models formulated by the Assessment and Teaching of 21st Century Skills project (ATC21S; Griffin, McGaw, & Care, 2012) and PISA (OECD, 2013, 2017a, 2017b).

Theory of the construction of shared knowledge in collaborative problem solving. In order to address how learning occurs in a computer-supported, collaborative learning environment, Roschelle and Teasley (1995) formulated the theory of shared knowledge construction in CPS. Like many of the organizational theories presented, Roschelle and Teasley's conceptualization of CPS is underlain by a groups-as-information-processors approach, such that individual-level cognitive abilities are recognized as well as team-level social interactions and emergent processes. More specifically, the authors characterize CPS as a process of maintaining a joint problem space (JPS), a shared knowledge structure much like the SMMs described by organizational researchers (Roschelle & Teasley 1995). A JPS is said to support CPS by integrating taskwork goals, planning behaviors, knowledge of the problem, and awareness of available problem-solving actions. Importantly, once knowledge is introduced and accepted into the JPS, team members must continuously monitor ongoing activity and work to rectify any conflicts, disagreements, and misunderstandings that may hamper progress.

Similar to the recurring phase model of team processes, Roschelle and Teasley (1995) advocate a microanalysis of teamwork in order to fully capture how CPS occurs. Although they do not advance their own model of how team process emerges, they note that successful CPS involves cycles that alternate between lower and higher intensity periods.

CRESST teamwork process model. Another theory originally intended for CPS in a computer-supported learning environment was the teamwork process model detailed by CRESST (Chung, O'Neil, & Herl, 1999; O'Neil, Chung, & Brown, 1995; see Figure 5). In contrast to Roschelle and Teasley's focus on *how* team processes come together during CPS, the CRESST model addresses in more depth *what* processes are needed for successful CPS. Adapted from the teamwork model developed by Salas and colleagues (Morgan, Salas, & Glickman, 1993; Salas, Dickinson, Converse, & Tannenbaum, 1992), the CRESST model divides CPS into respective categories for collaboration and problem solving, each of which is associated with its own suite of subskills. For instance, collaboration is a function of six dimensions including adaptability, coordination, decision making, interpersonal skill, leadership, and communication. *Adaptability* demands an awareness of team activities, constraints inherent in the task environment, and an ability to monitor the source and nature of problems that arise (O'Neil, Chuang, & Chung, 2003). Next, *coordination* involves the synchronization of team activities and resources in order to complete the task in a timely fashion. Third, *decision making* requires the integration of information, identification of possible alternatives, selection of the best solution, and evaluation of the consequences. Team members also need *leadership*, which involves being able to direct activity and establish a positive atmosphere, and *interpersonal skill*, in which that positive atmosphere is maintained through cooperative behavior and resolution of dissent. Finally, *communication* is needed for any of the former to be possible, characterized by a clear and accurate exchange of information, acknowledge of receipt, and proper use of technology to do so.

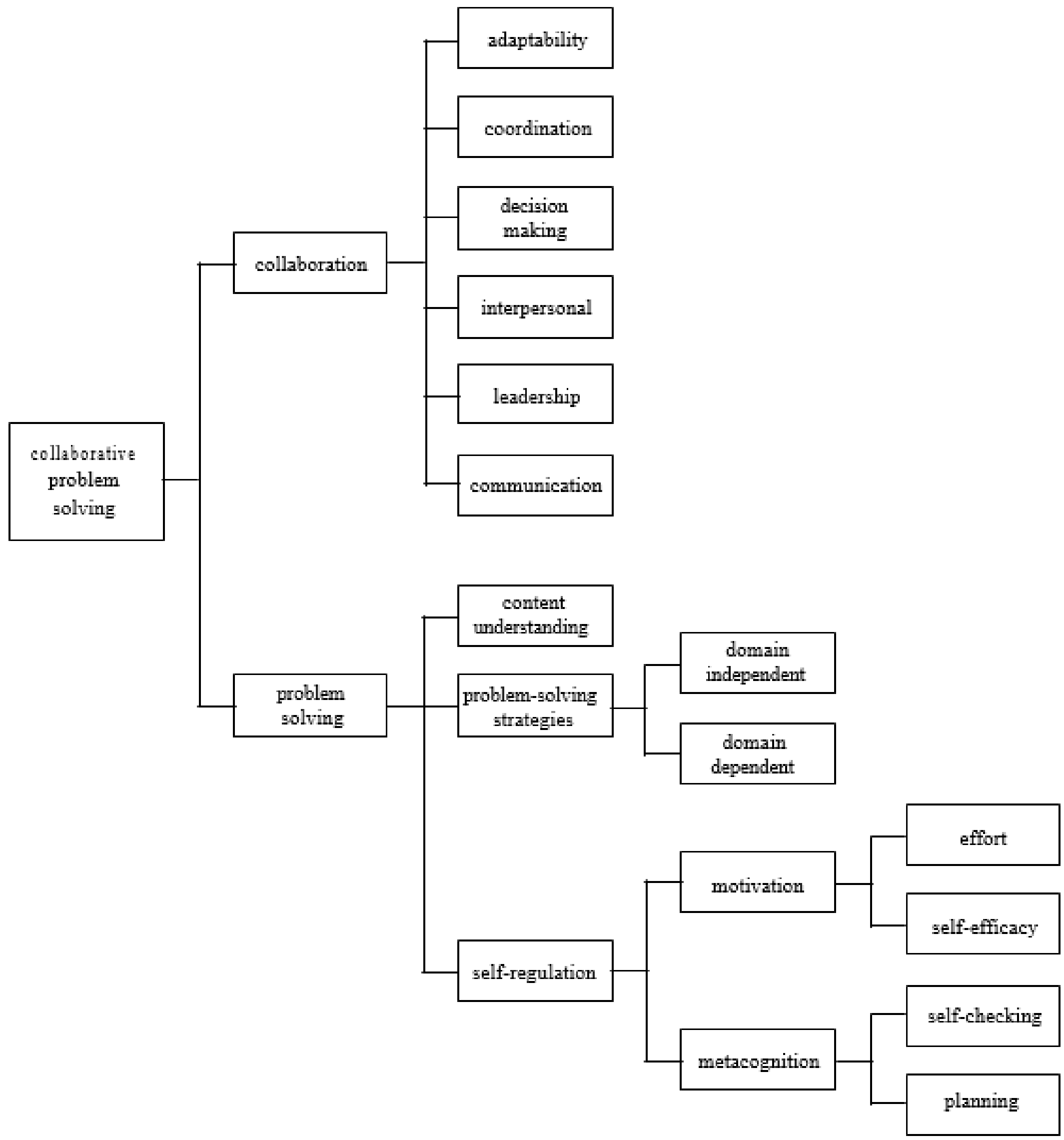

Figure 5. Collaborative problem solving components described by the Center for Research on Evaluation, Standards, and Student Testing (CRESST) model (Chung, O'Neil, & Herl, 1999; O'Neil, Chung, & Brown, 1995).

The counterpart of collaboration, problem solving, is then comprised of *content understanding*, *problem solving strategies*, and *self-regulation*. A good problem solver, according to the model, must possess a sufficient knowledge of the content with which he or she is engaging. Further, the problem solver needs a collection of domain-general (e.g., relational reasoning) and domain-specific problem-solving strategies. Finally, the problem solver must exhibit self-regulation, consisting of motivation and metacognition, operationalized as effort and self-efficacy and self-checking and planning behaviors, respectively.

With its investment in the observation and measurement of CPS in learning environments, the CRESST model has served as the paradigm for two large-scale initiatives for assessing and improving CPS in 21st century students, ATC21S (Griffin et al., 2012) and PISA (OECD, 2013, 2017a, 2017b).

***ATC21S framework of collaborative problem solving*.** The ATC21S framework of CPS came to fruition through the efforts of stakeholders and educators interested in defining and developing pedagogies and assessing 21st century skills in students entering the workforce (Care, Scoular, & Griffin, 2016). Specifically, the project was undertaken as a step in formulating standardized measures of CPS in human-to-human interactions. Headquartered at the University of Melbourne, the ATC21S project was sponsored by Microsoft, Intel, and Cisco, and supported by the governments of Australia, Singapore, Finland, United States, Netherlands, and Costa Rica. The ATC21S framework casts CPS as a composite skill arising from the links between critical thinking, problem solving, decision making, and collaboration (Fiore et al., 2017; Scoular, Care, & Hesse, 2017). It further divides CPS into social and cognitive dimensions, where the social is comprised of participation, perspective taking, and social regulation, and the cognitive of task regulation and learning and knowledge building.

Within the social dimension, p*articipation* refers to an individual's engagement both with teammates and the task (Hesse, Care, Buder, Sassenberg, & Griffin, 2012). An individual rated high in participation would demonstrate a willingness to engage with the task, to initiate and promote interaction with others, and to persevere in the face of difficulty. In this way, the act of participation is reflective of an underlying social constructivist epistemology wherein an individual becomes a member of a community of practice by transitioning from a more peripheral role in problem solving to a more central role.

Perspective taking refers to the quality of interactions with teammates and consists of subcomponents of *adaptive responsiveness* and *audience awareness* (Care et al., 2016). Perspective taking is regarded as a multidimensional construct consisting of affective, socio-developmental, and linguistic elements. An individual high in perspective taking would therefore be one who is aware of teammates' knowledge and can tailor responses to them in appropriate affective, socio-developmental, and linguistic ways. Finally, the *social regulation* category stems from the observation that team members bring different knowledge, experience, opinions, and strategies to a given task, and success depends partially on the ability of the group to harness those differences. Social regulation, then, hinges on recognizing one's own strengths and weaknesses (i.e., metamemory) as well as those of teammates' (i.e., transactive memory). Additionally, individuals must exhibit initiative to take on and complete the task, and negotiation skills for resolving conflict or achieving resolution.

Within the cognitive strand of CPS, *task regulation* refers to the competencies involved in completing taskwork, such as analyzing the problem, setting goals, managing resources, and collecting information (Care et al., 2016). In doing so, individuals must be systematic in their search for a solution and continuously monitor progress, but still remain flexible in approach and tolerant of ambiguity. *Knowledge building* reflects the ability to integrate and synthesize contributions from other team members and further refine these problem representations, plans, and monitoring activities. *Learning* is then indicated by progress within a hierarchy of problem-solving phases. First, problem solvers must identify patterns (i.e., reason relationally) between and among pieces of knowledge. In the next phase, problem-solving strategies are invoked and the consequences of those strategies are considered. In the final phase, hypotheses are generated through a process of reflection and monitoring. As new knowledge is gained, problem solvers reconstruct their understandings of the problem and adapt their strategies for solving the problem. Importantly, whereas task regulation captures the scoping of the problem space and collection of information, knowledge building and learning involves the use of that information.

***PISA framework of collaborative problem solving*.** Although the ATC21S framework represented the first effort to identify critical aspects of CPS and generate a method of assessing and teaching CPS, the framework has not been widely adopted in schools. However, one initiative that draws heavily on the ATC21S framework and has been implemented in over fifty countries is OECD's Program for International Student Assessment (PISA), which released its first assessment of CPS in 2015. One primary difference between the frameworks provided by ATC212S and PISA is in the way they define CPS (Scoular et al., 2017). The ATC21S framework characterizes CPS as a complex, coordinated activity between two or more *individuals*, whereas PISA defines CPS in terms of *agents*. This reflects PISA's use of computer-mediated communication between individuals and computer agents, versus ATC21S's observation of human-to-human interactions. Beyond the difference in definition, their purposes are slightly different. Namely, ATC21S was created to identify the steps and subskills needed for CPS for the benefit of students and educators, while PISA was meant to serve as a summative assessment to inform larger systems of education. For the most part, however, the two frameworks are similar in emphasizing the respective cognitive and social components of CPS (Scoular et al., 2017).

Specifically, PISA's CPS framework incorporates three collaborative competencies and four problem-solving processes (Fiore et al., 2017; Scoular et al., 2017). The first collaborative competency, *establishing and maintaining shared understanding*, comprises the identification of shared knowledge, acknowledgement of perspectives of other agents in the collaboration, establishment of a shared representation of the problem, and continuous monitoring and renegotiation of shared understanding throughout the process. Like the perspective taking component of the ATC21S framework, this first collaborative competency may involve responding to requests for information, verifying what others know, and resolving conflicts or misunderstandings. The next competency, *taking appropriate action to solve the problem*, involves identifying which strategies are needed to tackle the problem and then enacting those strategies and evaluating their success. Finally, *establishing and maintaining team organization* necessitates a consideration of each agent's talents, resources, and assets, an understanding of each agent's role, and the continual adaptation of strategies and reflection on team progress (Fiore et al., 2017; Scoular et al., 2017).

The four problem-solving processes were adapted from PISA's 2012 assessment of individual problem solving. The first, *exploring and understanding*, involves interpreting initial information about the problem through exploration and interaction with it. In the next process, *representing and formulating*, agents connect their prior knowledge to what they know about the current problem. This may be done by communicating with others or through the use of external objects such as graphs, tables, or symbols. Then, during *planning and executing*, agents determine goals, create plans to attain these goals, and finally enact the plans. Last is *monitoring and reflecting*, in which agents track progress while executing plans, reflect on the quality of solutions, and revise plans when necessary.

Importantly, the PISA framework crosses the three teamwork (i.e., social) competencies with the four taskwork (i.e., cognitive) processes to yield 12 resultant skills on which to base CPS assessment; OECD, 2017a, 2017b). Although not included in the framework itself, PISA's report on CPS does acknowledge differences in CPS performance on the basis of particular task characteristics (e.g., well-defined versus ill-defined tasks, static versus dynamic tasks), problem scenarios (e.g., consensus versus negotiation tasks), team composition (e.g., hierarchical versus non-hierarchical), and team member characteristics (e.g., prior knowledge, motivation, cognitive aptitudes; Graesser et al., 2018).

Key components of educational frameworks of collaborative problem solving. As with the organizational theories, there is not one unifying framework within the educational realm that captures exactly how relational reasoning and socially shared regulation of learning might iterate in CPS. However, there are aspects of each of the aforementioned frameworks that have relevance for the current study. For instance, the CRESST model delineates separate collaborative and problem-solving components of CPS and implies how relational reasoning and socially shared regulation of learning play a role in both. Within the problem-solving component, there are specific designations for problem solving strategies (e.g., relational reasoning) and self-regulatory activity. Although less obvious than its counterpart, the collaboration component involves integrating information, identifying alternatives, and evaluating consequences, all of which presumably demand the ability to see patterns and compare ideas on the basis of similarities and differences. Even more importantly, collaboration can be achieved only if team members are continuously monitoring and evaluating task progress, making plans, maintaining a positive socioemotional climate.

Building on the subset of skills needed for CPS, the theory of shared construction of knowledge helps elucidate how problem solving and collaboration come together, noting the possibility of higher and lower intensity periods of taskwork and teamwork, and thus, the importance of applying a microanalytic framework to the study of CPS. The ATC21S and PISA frameworks offer additional value by providing guidelines for the identification and measurement of both the social and cognitive components of CPS at various stages of the CPS process.

Review of Collaborative Problem-Solving Frameworks

Despite their varying foundations, purposes, and samples, the frameworks provided by the organizational and educational psychology fields similarly support the notion that CPS is a dynamic, emergent process that involves two or more individuals working interdependently toward a shared goal. More specifically, the frameworks characterize CPS as a process of transforming internalized knowledge into externalized knowledge through linguistic and behavioral communication and interaction. Further, many of the frameworks reviewed advance the proposition that CPS is an iterative process that may vacillate between discernible periods of higher and lower intensity.

Pertaining to the key facets of CPS, all of the frameworks emphasize a cognitive, problem-solving component and a social, collaborative component. With regard to the cognitive component, teams must demonstrate an ability to analyze a problem, develop a coherent representation of the problem, collect information, identify patterns and interrelations between pieces of information, and integrate and synthesize that information. In this way, the ability to reason relationally—that is, to discern meaningful patterns between and among seemingly disparate elements—becomes critical for CPS. Further, understanding not only what makes certain objects, concepts, or situations *similar*, but also what *differentiates* them, is a key component of RR and similarly crucial in CPS. In reference to the social, collaborative component, teams must demonstrate an ability to regulate collective activity, including the cognitions, emotions, and behaviors of the group. As such, socially shared regulation of learning (SSRL), in which team members co-construct knowledge, align task perceptions, set goals, and monitor and evaluate progress, also serves as a cornerstone of effective CPS. The respective roles of RR and SSRL in CPS, along with the ways in which they have been defined and studied, will be explored after reviewing gaps in the CPS literature.

Gaps in the Collaborative Problem-Solving Literature

In spite of the recognition that students across the globe lack critical CPS skills needed to be productive in the workforce, there is still no universally accepted curricula for teaching or training CPS in schools (Scoular & Care, 2018). This may be due, in part, to the fact that our understanding of CPS has largely been shaped by findings for slightly different constructs, including group work, decision-making, memory, and learning (Graesser et al., 2018). Although CPS shares some commonalities with these constructs, it is unclear whether studies of these constructs would be generalizable to CPS contexts.

Extant frameworks of CPS specifically emphasize that successful CPS is marked by a combination of cognitive and social capacities enacted during taskwork and teamwork. Further, these theories highlight how CPS may involve cycles of lower and higher intensity activity (Marks et al., 2001; Roschelle & Teasley, 1995), suggesting that CPS may look different depending on the rhythm with which a particular team engages with a particular task. Because CPS may instantiate differently by team, it is crucial that researchers find more valid and reliable methods of capturing and quantifying real-time interactions between team members, as well as identifying critical periods of activity during taskwork that contribute to CPS. Put differently, the measurement of CPS must be commensurate with its hypothesized operationalization. Thus, if CPS is said to unfold dynamically over the course of several hours or days, then researchers cannot reliably rely on retrospective questionnaires or static survey instruments that aggregate responses over time.

Relational Reasoning and Collaborative Problem Solving

In order to address open questions about CPS, this dissertation will focus in part on relational reasoning (RR), which acts as a key component of problem solving. Indeed, the ability to detect patterns has long been thought to lie at the heart of learning and problem-solving. In his seminal work *The Principles of Psychology,* William James (1890) highlighted a unique ability for humans to discriminate and draw associations. When speaking about discerning similarities and differences, he asserted that, "It is obvious that the advance of our knowledge *must* consist of both operations" (p. 550). This idea was echoed by Charles Spearman who, in writing *The Abilities of Man* (1927), defined intelligence in terms of the ability to construct relations, or perceive connections between things. Intelligence tests that followed further emphasized the centrality of patterning in solving novel problems (Cattell, 1943; Raven, 1941).

Traditionally, relational reasoning has been studied as a unitary construct, operationalized as analogical reasoning, which entails the discernment of similarities between and among objects, ideas, or events. However, analogies constitute just one type of relational reasoning (Alexander et al., 2016). Alexander and colleagues (Alexander & DRLRL, 2012, p. 272) formally define relational reasoning as a family of cognitive procedures "purposefully applied to recognizing or deriving meaningful relations or patterns between and among pieces of information that would otherwise appear unrelated." This ability is effortful and requires deep processing of problem elements, facilitating transfer of knowledge from one situation to another. In addition to analogies, relational reasoning encompasses anomalies, antinomies, and antitheses (Alexander & DRLRL, 2012). All of these forms involve mapping lower-level relations to higher-level relations; the difference is the quality or character of the linkage. Definitions for each form will be provided below, as well as ways in which the form has been studied in relation to CPS.

Forms of Relational Reasoning and Associations with Problem Solving

Analogical reasoning. Although scholars have investigated this foundational cognitive ability (Hofstadter, 2001; James, 1890; Spearman, 1927), Sternberg (1977, 1979) is credited with developing the componential model of analogical reasoning. In this model, the process of solving analogy problems is represented by a series of cognitive processes undertaken in a logical sequence: encoding, inferring, mapping, and applying. Specifically, the reasoner begins by encoding, or recognizing and comprehending, relevant features of the problem. Then, the reasoner must infer the relation between the lower-order elements of the problem, map the lower-order relations into a higher-order pattern, and finally apply this relation to produce a response.

Studies of analogical reasoning in groups have been carried out with students and professionals, in both traditional laboratory settings (i.e., *in vitro*) and in naturalistic settings (i.e., *in vivo*). These studies have converged on several findings, both related to the teamwork and taskwork inherent in CPS. For instance, pertaining to cognitive outcomes, the ability to comprehend and generate analogies can promote domain learning. Mason and Sorzio (1996) demonstrated that elementary student groups that constructed their own analogies scored higher on a graphic task depicting heat and water flow, produced higher-quality written reports, and performed better on a transfer task than those who had been given an analogy by a teacher or those with no analogy at all. Further, those positive benefits persisted even after 20 days had elapsed, suggesting that analogical reasoning can be a mechanism by which knowledge is organized or restructured. This finding has been replicated with undergraduates as well, such that learning in an array of STEM fields (e.g., chemistry, engineering) was bolstered when groups of students reasoned analogically together (e.g., Bellochi & Ritchie, 2011; Emig, Mcdonald, Zembal-Saul, & Strauss, 2014; Yerrick, Doster, Nugent, Parke, & Crawley, 2013).

In groups of professionals, analogical reasoning has been utilized as a tool for cognitive re-focusing. In one case, an attending neurologist interspersed analogies into a discussion of patient symptoms when reasoning with his team of medical residents about possible patient diagnoses (Dumas & Dunbar, 2014), using the analogies to bring to mind previous cases that were relevant to the discussion. Other *in vivo* studies have found analogies particularly useful in identifying, explaining, and solving problems (e.g., Chan, Paletz, & Schunn, 2012). For example, Christensen and Schunn (2007) found that engineering teams engaged in new product development used *within-domain* analogies—or those in which the source and target of the analogy come from the same domain—to identify problems, *between-domain* analogies—those in which the source and target come from disparate domains—to explain concepts, and a mixture of within- and between-domain analogies to solve problems. Similarly, Trickett and Trafton (2007) found that scientific experts tended to use analogies during data analysis. Beyond identifying and explaining problems, analogies can contribute to CPS by boosting creativity and promoting the generation of novel ideas (Chan & Schunn, 2015; Karhu, Ritala, & Viola, 2016).

Analogical reasoning also appears to impact the social side of CPS. To illustrate, Casakin and colleagues (2015) found that within-domain analogies promoted cohesion among team members by encouraging active communication. This communication then facilitated a greater shared understanding of the task. These findings are supported by other research which suggests that analogies can help to resolve uncertainty (Ball & Christensen, 2009). However, analogies may not always have a positive impact on the group's social atmosphere. Paletz et al. (2013) uncovered a pattern of within-domain analogies leading to conflict among team members, particularly as it pertained to interpretations of data and coordination of the team. It was reasoned that analogies might bring to light differences in underlying assumptions, thus sparking conflict. Analogies may also be used differently depending on *who* populates the team. Saner and Schunn (1997) found that within-domain analogies were more prevalent in lab meetings with individuals of similar backgrounds, whereas between-domain analogies were more likely to be used when talking with an audience of individuals with a wide range of expertise. In this way, the type and function of analogies appears to be shaped, in part, by the composition (e.g., background, knowledge) of the group.

Altogether, analogies seem to serve an important role in the collaborative and cognitive aspects of CPS. This role applies both in school and in the workplace, with children and adults. However, research is needed to uncover more about how analogical reasoning changes over the course of problem solving, how it is distributed across team members, and more specifically how it interacts with other cognitive (e.g., anomalous reasoning) and social capacities (e.g., socially shared regulation).

Anomalous reasoning. Although research on relational reasoning has typically privileged analogical reasoning above the others, the ability to reason anomalously is similarly important for higher order thinking and problem-solving skills. An *anomaly* represents a relation of dissimilarity in the form of a deviation from an expected pattern, or an outlier within a set

(Alexander et al., 2015; Chinn & Brewer, 1993). In this way, detection of an anomaly demands first an understanding of the pattern governing the set, and then a realization that the elements of a member of that set are atypical in one or more ways. Because of the cognitive conflict it can cause in an individual's understanding of a phenomenon, anomalous reasoning is highly regarded as a means of promoting conceptual change and the restructuring of knowledge (Chinn & Brewer, 1998; Kuhn, 1962; Kuhn, Amsel, O'Loughlin, Schauble, Leadbeater, & Yotive, 1988). Fittingly, this form of reasoning has been studied predominantly in STEM fields (Darden & Cook, 1995; Dumas, Alexander, Baker, Jablansky, & Dunbar, 2014; Dumas, 2017; Klahr & Dunbar, 1988).

As with analogical reasoning, empirical research has linked anomalous reasoning to CPS performance. For samples of students (i.e., middle school students, undergraduates), these studies suggest a reciprocal relation between anomalous reasoning and domain knowledge, such that deeper disciplinary knowledge increases a group's ability to deal with anomalous patterns, and dealing with anomalies provides nuanced knowledge for the group to draw on during problem solving (Echevarria, 2003; Trickett, Trafton, & Schunn, 2009).

Groups of professionals' responses to anomalies have also been implicated in problem-solving performance in a variety of domains. For instance, one study found that groups of wildland firefighters were better able to manage fires when they could identify and interpret discrepancies they were seeing (Barton, Sutcliffe, Vogus, & DeWitt, 2015). Specifically, the detection of discrepancies helped leaders make better sense of the situation and increased communication among team members. In this way, anomalous reasoning served to enhance both the team's shared understanding of the problem and the coordination with which to enact a response (Watts-Perotti & Woods, 2007).

In a similar vein, anomalous reasoning has been cited as instrumental in helping to diagnose patients in medical settings (Dumas et al., 2014). In fact, the discernment of discrepancies was found to serve as the first part of the diagnostic process, such that identifying abnormalities in patient presentation facilitated the generation of viable hypotheses about the patient's condition. Thus, anomalies may serve a similar function for professional teams as they do for student teams (e.g., Echevarria, 2003).

One caveat to the ability to reason anomalously during CPS pertains to the group members' experience with and knowledge of the focal domain. For instance, Echevarria's (2003) study of middle school students' scientific reasoning in genetic biology revealed a tendency for students to focus only on the most salient anomalies and to spend more time understanding rather than resolving those deviations. Thus, although anomalies may serve as catalysts for knowledge reconstruction, individuals with less disciplinary experience or familiarity may have limited attention to devote to actually problem solving. Thus, when analyzing the CPS performance of a given team, researchers must consider the background of each group member and the constraints or affordances imposed by such characteristics. In spite of these potential limitations, the relation between anomalous reasoning and the social and cognitive aspects of CPS is uncontestable.

Antinomous reasoning. A third form of relational reasoning, *antinomy*, denotes a relation of mutual exclusivity or a paradoxical relation. It demands the understanding that there is a true incompatibility between objects, ideas, or situations across sets, and thus often involves categorizing what something *is* by describing what it is *not* (Alexander & DRLRL, 2012). Whereas anomalies deal with members of a set that are aberrant, antinomies refer to objects or ideas that cannot be part of a set. Antinomous reasoning has also been associated with conceptual change (Slotta, Chi, & Joram, 1995), as well as originality in engineering design (Dumas & Schmidt, 2015) and medical decision-making (Dumas et al., 2014).

Unfortunately, there are few, if any studies, that have examined antinomous reasoning in groups and its relation to CPS performance. One study investigated the interrelations among the four forms of relational reasoning in medical discourse and diagnosis (Dumas et al., 2014). Dumas and colleagues discovered that an attending neurologist used proportionally more antinomies than expected in guiding discussion among his residents, suggesting that antinomies may be important in classifying and organizing elements of a problem. Further, the disparity between the attending doctor and the residents may indicate that certain individuals—as determined, perhaps, by knowledge within a domain or position within a hierarchy—are more likely than others to reason by antinomy, and accordingly, to scaffold this reasoning for other group members. More generally, these findings suggest that reasoning not only about similarities, but about differences, may be critical for problem solving. Additionally, this study found that the doctors reasoned with all four forms of relations, providing evidence that the forms of relational reasoning do not necessarily occur in isolation. Rather, the forms may operate in concert, building on one another and promoting problem-solving success. As an example, an individual might find a relational similarity between two situations but follow up this observation with an antinomy to distinguish important dissimilarities between the scenarios. This insight represents a promising avenue for future research.

Antithetical reasoning. An *antithesis* is a relation of difference in degree. Like antinomy, antithesis represents conflict between objects, ideas, or events. However, while there may be opposition, the differences do not rise to the level of exclusion. For example, if the descriptors hot versus cold are applied to an object, what is being represented is a difference in temperature, rather than the presence or absence of heat (which would be classified as antinomous). Antithetical reasoning is considered central to persuasion and argumentation to the extent that it promotes understanding of both sides of an issue (Chinn & Anderson 1998; Kuhn & Udell, 2007). For instance, it has been suggested that to argue effectively, individuals must know how to strengthen their position while weakening the opposing position. Antithetical relations are also regarded as fundamental in the organization of human language and thought (Marková, 1987).

As with antinomous reasoning, few if any studies have devoted attention to how antithetical reasoning manifests in CPS contexts. The study carried out by Dumas and colleagues (2014) demonstrated that antitheses were a present but infrequent part of the diagnostic process. When antitheses were voiced, it was usually used by the attending neurologist toward the end of a meeting as a way to point out oppositional points of view. However, the authors reasoned that the general lack of antithetical reasoning may have been reflective of the domain, the task, or the degree of conflict within the group. In the current study, I seek to determine the extent to which Dumas et al.'s findings generalize to engineering design teams composed of students. Given that a critical part of the engineering design process entails comparing design ideas and subsequently ranking "better" and "worse" on a predefined set of criteria, it is possible that individuals engaged in this process would verbalize more antitheses.

Measurement of Relational Reasoning Within Groups

Historically, RR has been assessed through various visuospatial measures designed to tap only analogical reasoning, such as Raven's Progressive Matrices (Raven, 1941). More recently, Alexander and the DRLRL (2012, 2014, 2015) have developed a series of measures that target all four forms of RR in both visuospatial and linguistic manner. The Test of Relational

Reasoning (TORR; Alexander & DRLRL, 2012), for example, contains four scales of eight selected response items. Each item contains novel figural items designed to assess participants' abilities to identify relations of analogy, anomaly, antinomy, and antithesis. Importantly, the TORR aims to tap participants' fluid rather than crystallized abilities, and accordingly does not require any prior knowledge.

In spite of advances in measuring RR as a multidimensional construct, current instruments almost exclusively assess RR in individuals. Consequently, other methods must be developed to assess RR in collaborative settings. Expanding on the coding scheme used by Dumas et al. (2014), Jablansky and colleagues (2016) developed a comprehensive coding scheme for identifying relational and non-relational statements in discourse. Although this coding scheme has been used in studies of dyads and classrooms featuring teachers and students (Jablansky et al., 2016, 2019; Sun, Zhao, & Alexander, 2017), no research to date has assessed RR in the discourse of teams of individuals engaged in a CPS task.

Gaps in the Relational Reasoning Literature

As mentioned, one gap in the literature is the lack of research on RR in the discourse of teams engaged in CPS. Given that schools and stakeholders alike are invested in promoting CPS skills in students entering the workforce, it is important to assess these skills in a context that mirrors those that students are likely to face in the workforce. Therefore, research should examine RR as it occurs in the real-time problem-solving efforts of individuals with a common goal. Doing so will address another gap in the literature, which pertains to the focus on individuals' RR, rather than the emergent RR of a team. Specifically, although much is known about the RR capacities of adolescents and adults, less is known about the types and quantities of RR these individuals would verbalize during a collaborative task. In this way, determining the strength of the link between individuals' propensities for RR and the RR they express in a social context will help to advance research. Finally, little is known about how RR unfolds in real time. Although research suggests that the forms of RR may operate in concert with one another (Dumas et al., 2014; Jablansky et al., 2016; Sun et al., 2017), it is unknown whether certain forms are more likely to co-occur, or whether certain larger patterns of relational reasoning might be expected given the nature of the domain, the task, or the group.

Socially Shared Regulation of Learning and Collaborative Problem Solving

Decades of research support the notion that successful learners *self-regulate* their learning (Bandura, 1977, 1986; Boekaerts, Pintrich, & Zeidner, 2000; Flavell, 1979; Zimmerman & Schunk, 2001). That is, learners employ a suite of cognitive, behavioral, motivational, and emotional strategies to monitor and control their learning (Zimmerman & Schunk, 2008). For instance, a learner might invoke prior knowledge (i.e., cognition) in order to solve a focal problem, or keep track of time (i.e., behavior) to make sure she is making sufficient progress toward her goal (Alexander, Dinsmore, Parkinson, & Winters, 2011). Models of SRL have varied conceptual roots, ranging from more individual constructivist perspectives (e.g., information processing; Winne & Hadwin, 1998) to more social constructivist perspectives (e.g., social cognitive model; Zimmerman & Schunk, 2001). However, most of these theories agree that learning is goal directed, that learners actively construct knowledge in service of goal achievement, and that self-regulation of learning is constrained to some degree by contextual and environmental factors (e.g., Winne & Hadwin, 1998).

Although much SRL research focuses on individual performance, strategies, goals, beliefs, and evaluation, there is acknowledgment among research that the social environment is implicated in SRL (Hadwin & Oshige, 2011). As a case in point, Zimmerman and colleagues

(Zimmerman & Cleary, 2009; Zimmerman & Kitsantas, 1997; Zimmerman & Paulsen, 1995) note that opportunities for observation, imitation, and feedback of others can facilitate an individual's ability to self-regulate learning. Further, the social cognitive account of SRL emphasizes the reciprocal nature of influences between person, behavior, and environment (Bandura, 1986; Zimmerman, 1989). However, a consideration of how a group of individuals with a shared goal mutually and reciprocally regulate their emotions, cognitions, motivations, and behaviors appears to be out of the scope of this model and others. Given the regularity with which students are tasked with working collaboratively, and the concurrent need for collaborative skills in the workforce, it would seem prudent to consider how SRL iterates in a highly social, interdependent problem-solving context.

In service of this goal, researchers have begun investigating a construct termed *socially shared regulation of learning* (SSRL), broadly conceptualized as the process by which a group of individuals collectively regulate their learning and problem solving (Jarvela & Hadwin, 2013; Jarvela et al., 2015). More formally, SSRL "involves interdependent or collectively shared regulatory processes, beliefs, and knowledge (e.g., strategies, monitoring, evaluation, goal setting, motivation, metacognitive decision making) orchestrated in service of a co-constructed or shared outcome" (Panadero & Jarvela, 2015, p. 4). That is, group members work to co-construct goals and standards and then mutually regulate activity as they problem solve. Unlike SRL, which may focus on an individual's cognition in the presence of others, SSRL refers to collaboration cognition that emerges as individuals work toward a shared goal (Hadwin & Oshige, 2011). Further, this socially shared regulation necessitates an awareness of one's own metacognitive experiences as well as that of one's teammates (Lajoie & Lu, 2012).

Conceptual Frameworks of Socially Shared Regulation of Learning

Since the advent of the term SSRL, two frameworks have been featured most prominently in the literature. These models include Volet and colleagues' (Volet, Summers, & Thurman, 2009) theoretical framework for socially-regulated learning and Hadwin and colleagues' (Hadwin, Jarvela, & Miller, 2011; Jarvela & Hadwin, 2013) model of socially shared regulated learning.

Volet and colleagues' theoretical framework for socially-regulated learning. Volet and colleagues (2009) take a situative approach to understanding self-regulated learning (SRL) in collaborative settings, inspired by Barron (2003), Greeno (2006), and Nolen and Ward (2008). This approach emphasizes the notion of "learning in activity," which refers to cognitions and understandings as they are constructed during learning activities. Fittingly, this approach advocates the investigation of socially-regulated learning by examining real-time interactions between team members and the way that they engage with a focal task or problem. Far from assuming that collaboration and co-regulation are inherent in any social exchange, Volet et al.'s framework presents a matrix that can be used to categorize the nature of any social collaboration across two dimensions: level of social regulation and sophistication of content processing (see Figure 6).

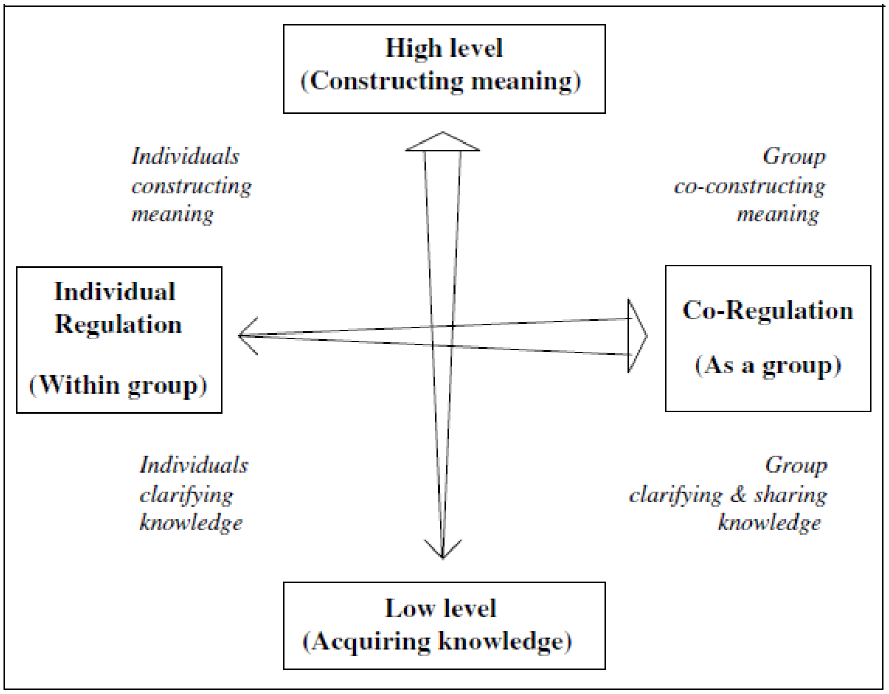

Figure 6. Volet et al.'s (2009) theoretical framework for socially-regulated learning, which consists of a matrix that can be used to categorize the nature of any social collaboration along the dimensions of level of social regulation and sophistication of content processing.

Along the first dimension, social regulation ranges from individual regulation within a group to co-regulation as a group. Here, regulation is considered a recursive process that may vacillate between periods of higher or lower co-regulation (Volet et al., 2009). In times of lower co-regulation, a given individual might be engaged in clarifying knowledge or monitoring their own understanding of the problem. By contrast, higher co-regulation might involve all group members participating in constructing and maintaining a shared conception of the problem.

Along the second dimension, content processing represents the mental or cognitive activities (i.e., information processes) used by team members to process content knowledge and similarly ranges from low to high. Whereas high-level content processing may include elaborating, speculating, drawing relations, and asking thought-provoking questions, low-level content processing may include sharing information, exchanging ideas, clarifying understandings, or providing definitions. What makes the former exchanges *high-level* is the assumption that these activities lead to co-construction of knowledge, while in the latter, *low-level* exchanges, there is no attempt to transform or integrate knowledge with one's own mental representations (Volet et al., 2009).

Hadwin and colleagues' model of socially shared regulated learning. Although different in its visual depiction of the construct (see Figure 7), the model of socially shared regulated learning forwarded by Hadwin and colleagues (2011) is similarly built on information processing and situated learning perspectives. The model focuses on cognitive activity that occurs within and between individuals but emphasizes the importance of situational affordances that enable SSRL to emerge (e.g., information and communication technology). However, beyond cognitive activity, the model also includes designations for metacognitive, motivational, emotional, and behavioral actions. Another critical difference between the models pertains to the measurement of regulatory activity. Whereas Volet et al. (2009) place regulation on a continuum, Hadwin and colleagues (2011) describe discrete categories of regulation in a group: self-regulated learning (SRL), co-regulated learning (CoRL), and shared regulation of learning (SSRL).

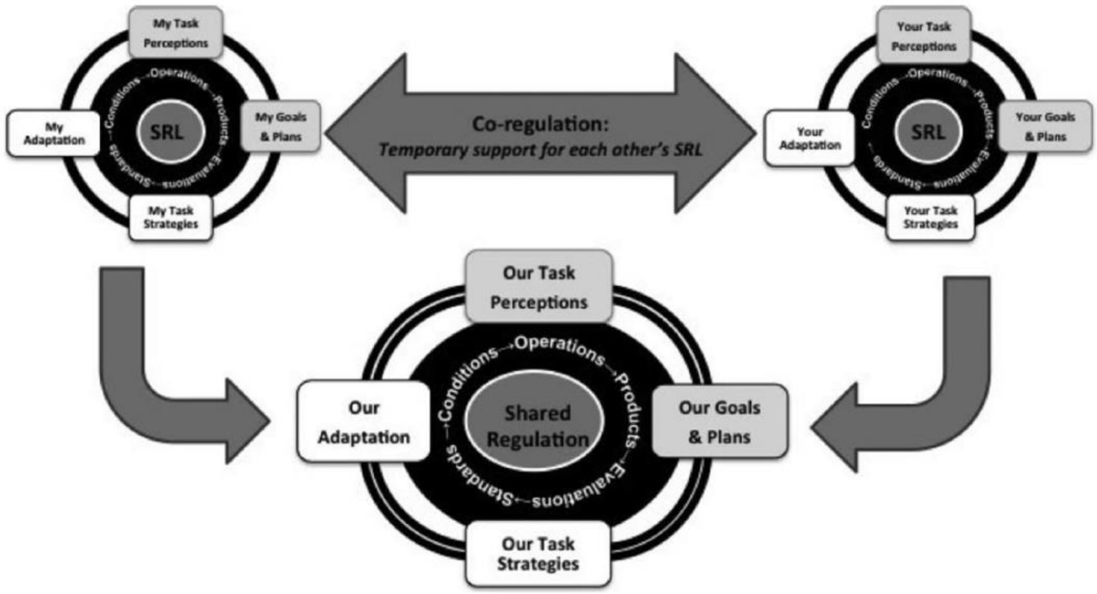

FIGURE 12 | Socially shared regulated learning model 1. Adapted from Järvelä and Hadwin (2013).

Figure 7. Hadwin and colleagues' (Jarvela & Hadwin, 2013) model of socially shared regulated learning.

Hadwin et al.'s (2011) framework for SSRL originated in the COPES model of SRL advanced by Winne and Hadwin (1998) two decades earlier. The COPES model posits that learning occurs in four phases, each accompanied by five processes (Winne & Hadwin, 1998). The phases include *task definition*, in which the learner forms a perception of the goal for the task*; goal setting and planning*, in which the goal from the previous stage is updated or reframed and a plan for approaching the task is subsequently formed; *enacting tactics and strategies*, in which the learner applies operations to achieve the tasks and monitors the performance of these tactics; and *adaptations to metacognition*, in which the learner evaluates the success of the tactics from the previous stage and makes modifications as necessary.

Each of these phases is impacted by conditions, operations, products, evaluations, and standards. *Conditions* refer to internal and external affordances and constraints affecting learners. Internal, *cognitive conditions* include domain knowledge, motivation, beliefs, and awareness of strategies, while external, *task conditions* include time, resources, and local context. *Operations* refer to the actual information processes invoked during learning, such as searching, monitoring, assembling, rehearsing, and translating, otherwise known as SMART processes (Winne, 2001). These operations results in *products*, an example of which might be a definition of the task, as in the first phase of SRL, or the ability to recall information for a test, as in the third phase (Greene & Azevedo, 2007). Products are then *evaluated* as they compare to *standards*, criteria the learner believes to be the optimal end state of the phase in which they are engaging. If there is poor fit between products and standards, the learner may exert control and revise the operations, re-formulate products or revise standards. Importantly, Winne and Hadwin (1998) stipulate that SRL unfolds in *loosely* sequential and recursive phases, referring to the notion that there is no typical cycle, and that learning and problem solving generally require recycling through the phases until a satisficing end point has been reached.

As mentioned, Hadwin and colleagues' (2011) model of SSRL draws on the COPES model of SRL. As such, it includes provisions for the four phases and five processes involved in SRL and posits a similarly recursive and recycling progression through the phases. In extrapolating to a collaborative environment, however, it includes three distinct modes of regulation: self-, co-, and shared regulation, which broadly characterize the extent to which group members are mutually and reciprocally monitoring and regulating learning and problem solving.

The first mode, self-regulation, intuitively refers to the regulatory actions taken by an individual to adapt to interactions with other group members. For example, an individual might imitate the actions of another group member or may strive to regulate her own emotion and motivation during problem solving. One step further, co-regulation usually applies to dyadic exchanges in which regulatory activity is guided or scaffolded by one individual. This may occur when one individual is more knowledgeable than others in the group or when a particular individual takes control of group activity. Finally, shared regulation describes the joint regulation of group activity and implies a greater balance of sharedness than in co-regulation.

As is true of the COPES model, Hadwin et al.'s (2011) model of SSRL assumes that regulation may vacillate between periods of self-, co-, and shared regulation. In differentiating between the latter two modes of regulation, Volet and Mansfield (2006) suggest that different goals may lead to co- versus shared regulation. They note that in their study, co-regulation was triggered by individual and control goals, whereas shared regulation was triggered by collaborative goals. Thus, it appears that groups may adapt their regulation strategies in order to be compatible with goal pursuit.

Essential components of socially shared regulation of learning for the current study. Because there are many components to group regulation, the current study will focus on a few key aspects common to both of the models discussed. The first pertains to different levels or categories of regulation. Both Volet et al. (2009) and Hadwin et al. (2011) note that in group settings, regulation can occur within or between individuals. Further, this regulation can be initiated by a more knowledgeable other or jointly and more equitably by all team members. The second component considered in this study is the proposed cyclical, recursive nature of social regulation. Specifically, this study will aim to identify different phases within the regulatory process as well as the extent to which they repeat over time. The final component relates to the content of the regulation being done. As mentioned, Volet et al. (2009) note that regulation may involve asking high-level questions, drawing relations, providing definitions, or sharing information. Consequently, it seemed that not only identifying cycles of regulation, but examining their content, would provide key insights into social regulation.

Measurement of Socially Shared Regulation of Learning in Groups

Although Panadero and Jarvela (2015), in their review of the construct, found only 17 studies addressing SSRL—13 of which presented empirical data—there are several commonalities in how it has been studied and linked to problem solving. For instance, studies of the SSRL have tended to examine primary school or higher education students working to solve relatively well-defined problems. Further, most of these studies have investigated SSRL in the domain of mathematics (e.g., Hurme, Merenluoto, & Jarvela, 2009), with comparatively fewer studies in the social sciences and humanities (e.g., Janssen, Erkens, Kirschner, & Kanselaar, 2012).

In order to capture groups' emergent SSRL, researchers have relied on video recordings of verbal and non-verbal interactions among team members. Thus, analyses of data have been predominantly qualitative or mixed-methods in nature, featuring discourse or content analyses (e.g., Iiskala et al., 2011; Lobczowski, Allen, et al., 2020; Lobczowski, Lyons, et al., 2020). Panadero and Jarvela (2015) note that there have been no experimental or quasi-experimental studies of SSRL yet, with researchers instead leveraging SSRL in naturalistic tasks or computer-supported collaborative learning environments. They add that most groups have ranged in size from two to four members, with only one study examining SSRL in a six-person group.

Although evidence is limited, several studies (Grau & Whitebread, 2012; Janssen et al., 2012; Jarvela et al., 2013; Volet et al., 2009) have demonstrated that shared regulation has a positive association with learning and problem-solving outcomes. For instance, Janssen and colleagues (2012) found that engagement in regulatory activities (i.e., planning, monitoring task progress) predicted the performance of groups of secondary students working on a historical inquiry task. Further, Jarvela, Malmberg, and Koivuniemi (2016) uncovered positive relations between socially shared planning and motivation with learning outcomes in an analysis and synthesis task. It is hypothesized that when regulatory activity is shared to a greater degree, group members talk more about relevant knowledge, which in turn promotes problem-solving (Grau & Whitebread, 2012). Further, the greater balance of power during shared regulation may enhance the socioemotional climate of the group, prompting individuals to share more, leading to more monitoring and feedback from others (Rogat & Linnenbrink-Garcia, 2011).

Gaps in the Socially Shared Regulation of Learning Literature

In spite of all that has been learned, Panadero and Jarvela (2015) conclude that SSRL research is still in its infancy, and that several gaps must be filled before designing and implementing interventions. For one, the range of groups and tasks included in extant studies remains narrow. As mentioned, most studies of SSRL examined groups composed of two to four individuals. It is unclear whether group size has any relation to SSRL, or how SSRL might emerge if activity were distributed across more than five or more individuals. Concomitantly, it is unknown whether findings from these groups would generalize to tasks of varying difficulties or objectives. As noted by Panadero and Jarvela (2015), most researchers did not justify their selection of task, nor did they clarify whether the task was sufficiently difficult that it necessarily demanded collaboration, which is key for the emergence of SSRL (Iiskala et al., 2011). Relatedly, the extant literature has primarily examined SSRL in the domain of mathematics. Thus, it is unclear if the same findings might be observed in collaborations in other domains, such as the sciences or humanities.

Another key gap in SSRL research is that studies have seldom considered the resources individual team members bring into a CPS context (e.g., higher-order reasoning skills) or, more generally, how different individuals contribute to or drive regulatory activity during problem solving (Winne, Hadwin, & Gress, 2010). For instance, individuals perceived as leaders might contribute to more or different aspects of SSRL than other group members. Alternatively, if one individual is driving regulatory activity, then other team members might not be as motivated to contribute. In this way, understanding how SSRL unfolds during real time is critical.

Relational Reasoning and Socially Shared Regulation of Learning

In addition to examining the respective relations between RR and SSRL with CPS, it is important to consider how the former constructs are associated in the literature. In point of fact, RR and SSRL have rarely, if ever, been examined in tandem. That is, there are no studies focusing on how the four forms of RR interact with individuals' regulatory behaviors during a team problem solving task. There is a robust literature on learners' regulatory behaviors during reasoning tasks; however, the reasoning is typically assumed because of the nature of the task and is not systematically measured or assessed. As a case in point, Zheng, Li, and Lajoie (2019) investigated the joint roles of achievement goals and SRL on clinical reasoning performance. Although both reasoning and regulation constructs were implicated in the study, clinical reasoning referred to the task. Therefore, what was assessed was task performance (i.e., accuracy in diagnosing correct medical condition), rather than the nature of the reasoning completed.

Another issue pertaining to the study of RR and SSRL, as evidenced in Zheng and colleagues' (2019) study, is that the type of reasoning examined is often described as *clinical* or *scientific*, which is distinct in definition and operationalization from *relational* reasoning. For example, Taub and colleagues (2018) endeavored to assess how learners used metacognitive processes and scientific reasoning processes in a game-based learning environment. In this study, scientific reasoning was operationalized as hypothesis testing, and these hypothesis tests were subsequently coded as being relevant, partially-relevant, or irrelevant. While the thinking that gives rise to a hypothesis may certainly be relational (e.g., analogical), this is generally not examined.

A complement to the issue of performance being used as an operationalization of reasoning is the use of reasoning as an operationalization of regulatory activity. In one study, researchers coded metacognitive activity in a problem-based learning environment of medical students (Lajoie et al., 2015). When providing examples for each of their coded categories, they considered analogies one manifestation of *evaluation*, as well as detecting differences (i.e., anomalies) and discrepancies (i.e., antinomies) as manifestations of *monitoring*. This is representative of a pattern in which researchers conflate RR and SSRL, making it difficult to understand their respective and potentially complementary roles in CPS.

In spite of the lack of empirical data on how RR and SSRL iterate with respect to one another, it seems conceivable that the two might co-occur in a variety of ways. For instance, noticing conflicting task objectives might lead team members to reformulate their plan from a prior phase of SSRL. By the same token, applying prior knowledge from similar tasks might help the team identify important information as they begin completing the focal task. Alternatively, it is possible that engaging in SSRL might stimulate RR. For example, when selecting a strategy to enact to solve a problem, teams might explicitly choose to draw inspiration from similar problems. In the same vein, teams may recognize a need to distinguish different concepts or ideas and then engage in antinomous or antithetical thinking. Given the sparse empirical work on which to draw, one aim of the current study is to develop distinctive codes for RR and SSRL and discern patterns in how they iterate in a CPS task.

General Summary

From the few studies available, it appears that both the ability to reason about higher-order relations as well as to monitor, control, and regulate learning as a collective are tied to collaborative problem-solving outcomes. However, future research must tackle key issues pertaining to how these capacities unfold during problem solving and whether any patterns of occurrence can be determined as they relate to the types and quantities of RR and SSRL verbalized, as well as the people who verbalize them. In this way, the current study aims to contribute to the literature on CPS by employing real-time measures of teamwork and taskwork.

Specifically, this study will focus on two constructs key for CPS performance—RR and SSRL. Guided by the frameworks reviewed above, this study will use a combination of non-parametric analyses, social network analyses, and data mining to identify patterns in the ways that RR and SSRL iterate during problem solving, as well as how teammates interact with one another and contribute to the team's problem-solving efforts. By exploring CPS microgenetically in a number of teams over the course of several problem-solving episodes, this study can provide support for what is already known about the construct, as well as clarity about the lesser studied mechanisms by which cognitive and social capacities come together during problem solving. Further, this study can demonstrate alternative approaches to the measurement and analysis of CPS, a pressing need within the empirical literature. Consequently, the results may inform educators, policymakers, and stakeholders endeavoring to improve the CPS of students and professionals alike.

CHAPTER III

METHODOLOGY

Participants

The participants in this study were four teams of senior undergraduate students (n = 22) enrolled in the University of Maryland's mechanical engineering capstone design course, Integrated Product and Processes Development (ENME472). Senior undergraduate students majoring in mechanical engineering were chosen as the target population for this study for several reasons. First, the abilities of senior engineering students should be roughly equivalent to that of new entrants into a professional designer career. Second, the university setting afforded a semi-structured environment in which teams engaged in solving different problems could be more easily compared than college teams operating outside of a class structure or professional teams residing in different firms or companies, for whom expectations, operations, and processes may differ widely. The course ENME472 was chosen because it aims to expose students to all aspects of the design process such as problematization, idea generation, conceptualization, and prototyping. Students are taught engineering-specific methodologies used to evaluate and select designs that they are expected to use in their own projects. Although projects differ among teams, all teams must fulfill similar task requirements (e.g., generate ten unique design ideas per person), making it possible to compare teams more easily.

The first team, Team 1, included six males with a mean age of 21 (SD = 0.63), five of whom were native English speakers. Five of these students identified as White or Caucasian and one identified as Asian or Pacific Islander. Team 2 was composed of three males and two females with a mean age of 22 (SD = 0.55), all of whom were native English speakers. Three of the individuals identified as Caucasian or White, one identified as African American or Black, and one identified as Asian or Pacific Islander. Team 3 included six males with a mean age of 22 (*SD* = 2.25), five of whom were native English speakers. Four of the individuals identified as Caucasian or White, and two identified as Asian or Pacific Islander. Finally, Team 4 was composed of four males and one female with a mean age of 22 (*SD* = 1.64), four of whom were native English speakers. Four of the students identified as Caucasian or White and one student identified as Asian or Pacific Islander.

Design

The study was naturalistic in nature, as there was no manipulation involved in either the composition of teams or the manner in which teams approached the generation and selection of ideas. The study may also be considered microgenetic in design, as it aimed to capture moment-to-moment changes in the reasoning and regulation used by team members as they solved problems collaboratively.

Procedure

To recruit teams, an email was sent to ENME472 course instructors explaining the goals of the study and asking that any teams interested in participating contact the researcher. The email also noted that for a team to be eligible, all members had to consent to participate. Each individual was offered $50 in Amazon or Visa gift cards for their participation at the end of the study. In accordance with course procedure, students were permitted to choose their teammates. Data were collected from three teams in the Fall semester of 2016 and from a fourth team in Fall of 2018. After consenting to participate, teams notified the researcher of when and where they would be meeting, and the researcher attended and video-recorded these meetings. Teams generally met in person once per week to complete assignments related to their project. The duration of the meetings was left to the discretion of the group.

Course Context

In ENME472, teams must identify a problem with an existing product and design a new product to solve that problem. During the first month of the semester, teams focus on conceptualizing and evaluating design ideas in several discrete tasks. After deciding on the problem they will address, team members must individually generate a set of ten unique ideas for a new product design. Following a presentation of those ideas, each team must select ten to evaluate in more depth. Over their next few meetings, teams narrow down this pool of ideas to five, and finally to one. Of note, all teams use the same methodology (i.e., Quality Function Deployment; Akao, 1972, 1990) to evaluate their ideas. This includes generating a list of customer requirements for the product (i.e., priority features the customer expects) and translating that list into a set of engineering characteristics (i.e., physical features, variables, or performance metrics) needed to fulfill those requirements. For instance, in the case of designing a new laptop, a customer requirement might be that the laptop is portable, while its associated engineering characteristics might be weight and overall dimensions. This methodology also demands a weighting of each criterion based on its importance to the design. Finally, design ideas are evaluated on the criteria identified, both against a benchmark design (i.e., the most comparable product currently on the market) as well as the designs generated by the team.

For the purposes of this study, team meetings centered around the comparison and selection of design ideas were observed, based on the hypothesis that more reasoning and regulation would occur in these initial phases of the project. Teams notified the researcher when they were engaged in this phase of the task so that the researcher could attend and video-record the meeting. Team meetings were not constrained or guided in any way and could run for as long as the team deemed necessary.

Each of the four teams in the current study focused on a different problem. Specifically, Team 1 (Team Kayak) aimed to lower incidence rates of capsizing accidents in kayaks. Most of their ideas focused on features they could add to the structure of the kayak or ways of increasing the buoyancy of its paddles. Team 2 (Team Baby) by contrast, was interested in creating a more efficient method of measuring babies right after birth that would minimize miscalculations caused by the baby squirming. Their ideas ranged from infrared scanning solutions to stretchy caps that could be used to measure the baby’s head circumference. Team 3 (Team Toilet) was interested in older and differently-abled populations and conceptualized modifications to toilet seats to help individuals rise from them more easily. Finally, Team 4 (Team Ambulance) strove to design a medical robot that could be installed in an ambulance in order to provide more immediate and precise treatment for critical conditions such as cardiac arrest or hemorrhage.

Data Collection, Preparation, and Coding

Data collection and preparation. Team meetings were filmed by the researcher with a Canon EOS Rebel T3i DSLR camera. Several research assistants then created written transcripts of each meeting from the video recordings. Throughout this process, the researcher watched random selections of each video and compared it with the written transcripts to make sure audio was captured and recorded accurately.

Transcripts from each meeting were then broken up into speech units that would later be assigned a code (see Figure 8 for flowchart of data collection, preparation, and coding process). A speech unit roughly constitutes one complete thought and may be indicated by a disruption or a pause in speech, often corresponding with independent clauses (Trickett & Trafton, 2007). In this paradigm, it is possible for one word to count as a unit if that word has a substantive meaning. For instance, if a student answered “Yeah” to a question, the word could count as its own unit. If, however, the “Yeah” acted as a colloquialism or filler word designed to precede a statement or connect to a longer substantive statement, it would not be regarded as its own unit. A single sentence could contain multiple utterances if more than one thought was communicated. In such cases, conjunctions such as “and,” “because,” “but,” and “so” often indicated where to segment units. For instance, the sentence “That’s true, but should we choose this idea?” would be segmented as follows: That’s true,/ but should we choose this idea?/. It is common in group discussions for several individuals to be speaking at once or to be speaking over one another. If a thought was interrupted by another person and continued after that person finished speaking, the thought was broken up into separate units.

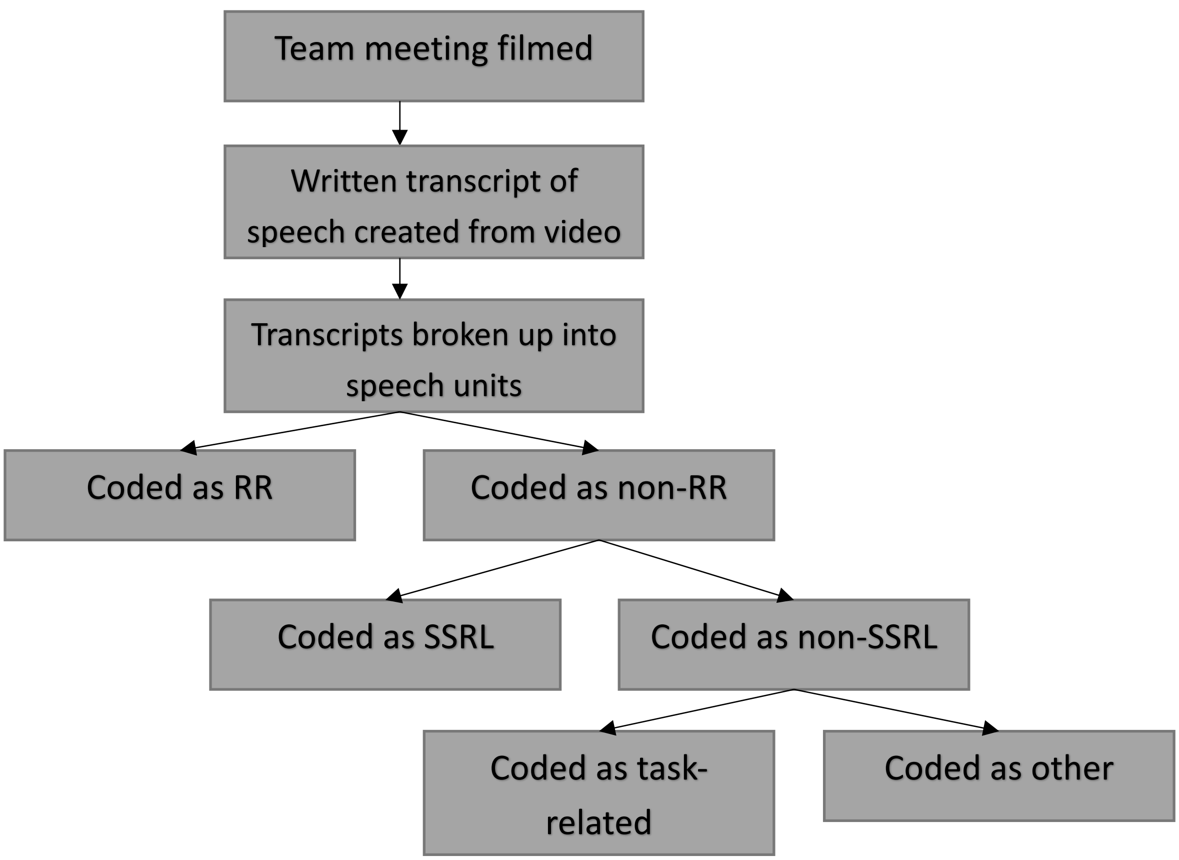

Figure 8. Flowchart of data collection, preparation, and coding.

Data coding of utterances. After utterances were segmented, one code was assigned to each utterance. There were three general categories of codes, including (a) relational reasoning (RR); (b) socially shared regulation of learning (SSRL); and (c) task-related or other. Codes for RR, task-related, and other talk were adapted from the coding scheme originally developed by Dumas and colleagues (2014) and expanded by Jablansky and colleagues (2016, 2019) specifically for teams engaged in problem solving. Codes for SSRL were adapted from Lobczowski, Lyons, and colleagues' (2020) social regulation of learning (SoRL) coding scheme. See Table 1 for definitions of possible speech unit codes and Table 2 for an example of a coded excerpt.

Importantly, the coding scheme was monothetic in nature, meaning that only one code could be applied to each utterance. That is, an utterance could be coded as RR, SSRL, task-related, *or* other. Further, each utterance could only receive one code from within a category. A monothetic scheme can present challenges for coding, as some instances of RR could appear to be indicative of regulatory activity. For example, a student might ask whether a feature of one design serves a similar purpose as that in another design. This could be seen as an attempt to draw an analogy between the ideas as well as monitoring one's understanding of the content. Thus, a decision rule was made that in cases of possible overlap, RR codes would be prioritized over SSRL. This was done to separate more clearly the two for the purpose of understanding how RR iterates alone as well as how it co-occurs with SSRL.

Table 1

Definitions and Examples of Speech Unit Codes for Relational Reasoning (RR), Socially Shared Regulation of Learning (SSRL), Task Related (TR) and Other (O)

UNIT	CODE	DEFINITION	EXAMPLE
RR			
	Analogy (AG)	Identifying relation of structural similarity among two objects, ideas, or situations.	"That would be almost similar to, has some similarities to Ciara's cap."
	Anomaly (AM)	Identifying relation of non-conformity or aberration from larger pattern.	"But [this design] can lift all your weight whereas all these other ones can't."
	Antinomy (AN)	Identifying relation of incompatibility or mutual exclusivity between two objects, ideas, or situations.	"Yeah so it's like the hat… you only have discrete values, and I think measuring band you can have continuous values."
	Antithesis (AT)	Identifying relation of contrast, opposition, or difference in degree along continuum.	"Boat dams would probably weigh your boat down more [than doggy paddle]."
SSRL			
	Planning (PL)	Setting goals or creating plans related to task understanding, content understanding, or task performance.	"Okay so, um, do we want to skim through the concepts again?"
	Monitoring/Control of Understanding (MCU)	Tracking the understanding of task or content, including monitoring one's own understanding or taking control to actively seek out information or explanation.	"Okay, so this… walk me through this. How is the shaft attached to the plate?"
	Monitoring/Control of Consensus (MCC)	Directly soliciting feedback from teammates about opinions and evaluations for the purpose of establishing consensus and making decisions.	"Ling, Grady, what are you thinking?"
	Monitoring/Control of Progress (MCP)	Tracking progress by monitoring or controlling completion of task, goals, or subgoals, or references to time	"Alright, what else do we want to do in an hour tonight?"
	Reflection (RE)	Processes related to the evaluation, appraisal, or reviewing of task understanding, content understanding, task progress, task difficulty, or task performance	"Well we've decided on our three concepts."
TR and OTHER			
	Task-related (TR)	Statements or questions about the task at hand that are not relational or regulatory in nature.	"So we have cost, measurement accuracy, force on infant, total procedure time… those are our highest weighted engineering criteria."
	Off-task (OT)	Statements or questions outside the scope of the task.	"I had somebody call me at four am…"
	Unelaborated (UN)	Brief statements that express confirmation, disconfirmation, or ambiguity.	"Okay."
	Inaudible (IN)	Statements that could not be heard and transcribed.	"Like (inaudible) pounds."

Table 2

Application of Coding Scheme to Discourse of Team Baby

SPEAKER*	TURN
Sarita	So then what was the other one?/ TR
Springer	Like measuring glasses/ TR
Sarita	Okay/ UN
Springer	They're not glasses/ AN
	but it like sits on the infant like glasses so,/ AG
	and holds tape in the same spot./ AG
	That's pretty much the ones that I would share from this./ TR
Ciara	I think my like only one that really did the circumference was just similar to the onesie and cap./ AG
	And then something that was like similar— yeah I think it was just the “onesie” and “cap” that had anything to do with circumference./ TR
Sarita	Okay./ UN
	Was it different enough to write--/ MCU
Ciara	Uh uh/ UN
Sarita	--or do anything?/ MCU
	No?/ TR
	Okay./ UN
	I think this goes along with my with my concepts as well. Umm./ TR
Ciara	Yeah I think mine was like the most (inaudible)/ IN
Sarita	Oh wait,/ TR
	I did the sensors,/ TR
	like kind of what you did Corey, with using sensors for the length/ AG
	but using sensors for circumference./ AN
	I guess we could do that./ TR
	Sensors, and... (talking to herself)/ TR
	(writing on blackboard) Okay./ UN
	So does anyone want to suggest something to go from here?/ MCC

Note. *All names are pseudonyms. / indicates a break between speech units. AG = analogy; AN = antinomy; IN = inaudible; MCC = monitoring/control of consensus; MCU = monitoring/control of understanding; TR = task-related; UN = unelaborated.

Relational reasoning codes. RR utterances included analogies (AG), anomalies (AM), antinomies (AN), and antitheses (AT). AGs were coded when a speaker identified a higher-order relation of similarity among two objects, ideas, or situations. For example, when comparing two design ideas one student said, "I do see the support band and glasses having a lot in common, as in the principle behind them." Here, the student discerned a structural similarity among the ideas—namely, that the support band and glasses were formulated with the same purpose in mind.

AMs were coded if a speaker identified a relation of nonconformity or aberration. For instance, one student noticed that "all of [the ideas] are fairly similar except for the motorized one." In doing so, the student recognized that the idea involving a motor was inconsistent with the larger pattern governing the rest of the ideas.

ANs were coded if a speaker noted a relation of mutual exclusivity or the delineation of a *categorical* boundary between two conditions. As with the other RR and SSRL codes, ANs could be verbalized not just as statements, but also as questions. As a case in point, one student asked, "What distinguishes [the variable size cap idea] from the measuring band?" Even though the student was asking for clarification, the phrasing of this question indicates that the student was thinking about the categorical boundaries between these two ideas. The answer she received was also antinomous in nature because it identified the feature where they diverged in a mutually exclusive manner: "[With] the hat… you only have discrete values, um, and I think [with] measuring band you can have continuous values."

Finally, ATs were coded for statements or questions about relations of opposition or difference in degree. Although they may seem to be similar to ANs, antitheses are relations of objects, ideas, or concepts that exist on the *same* continuum, whereas antinomous things cannot co-exist. For instance, an antithesis was coded when a student argued that "the dimensions of this [design] are better than for the [baseline design]," as the designs were considered divergent on the continuum of the feasibility of their dimensions.

Socially shared regulation of learning codes. Socially shared regulation of learning (SSRL) utterances could receive one of five codes related to planning, monitoring and control, and reflection. These codes were adapted from Lobczowski and colleagues' (2020) coding scheme for social regulation of learning (SoRL) in teams. A code of planning (PL) was marked by setting goals or creating plans related to task understanding, content understanding, or task performance. PL could include establishing goals or subgoals, deciding on an order of steps, or discussing actions the group would take later in the meeting or outside of the meeting. In one instance, PL was coded when a student suggested, "So let's do this again but with everything being compared to [this idea]." Additionally, PL could incorporate talk about hypothetical plans (e.g., "We could do X") or questions about plans (e.g., "Should we do X tomorrow?").

Utterances related to monitoring and control could receive one of three codes. Of note, monitoring and control were kept together as these processes work conjointly and are often inseparable within speech units. Monitoring/Control of content or task understanding (MCU) referred to tracking the understanding of task or content, including monitoring one's own understanding or actively seeking out information or explanation from others. This generally involved asking teammates for information when there was a gap in knowledge to be filled, whether conceptual (e.g., "Well how else could you power something other than hydraulics?") or task-related in nature (e.g., "I thought we were trying to get [our ideas] down to three."). It could also involve simply observing one's own lack of understanding, as one student noted, "Okay, I don't know the complete design."

Students could also monitor and control the more social process of building agreement of task, understanding, or plans, which was called monitoring/control of consensus (MCC). The core of this code involved directly soliciting feedback from teammates for the purpose of establishing some degree of consensus. This was evident in one exchange in which a team member asked, “Is this fine with everyone?” MCC could also occur during design comparison, such as when one student posed the question, “What do we think about [this design]?” Importantly, there could be instances in which feedback was solicited about plans for proceeding. In these cases, the decision rule was to code PL in order to differentiate the consensus demanded by establishing plans from that of monitoring and controlling *current* performance.

Additionally, students could monitor and control their progress (MCP). This entailed tracking movement toward goal completion by discussing how much was left to do or referencing the amount of time left to do it. For example, after eliminating one design from the corpus of design ideas, one student said, “Okay, six to go,” providing information both about how much had been accomplished as well as how much there was left to do. MCP could also include questions about progress (e.g., “Oh, are we done?”) or comments about the speed with which the team was moving (e.g., “We’re crankin’ through these!”).

The last code centered on processes related to the reflection, evaluation, or review of task understanding, content understanding, task progress, task difficulty, or task performance, labeled RE. This could involve determining whether consensus was met, content was understood, or a goal was achieved. Importantly, RE could involve statements about *what* was done (e.g., So we have our top three [ideas.]”) as well as judgments about *how* it was done (“It’s hard when you [rank ideas] as a team.”).

Task-related code. Utterances that did not fit into the RR or SSRL categories were assigned a code of *task-related* or *other*. Task-related talk, coded TR, referred to any utterances made about the task at hand that were not relational or regulatory in nature.

Other codes. Any remaining utterances were assigned a code of unelaborated, off-task, or inaudible. Unelaborated statements (UN) denoted statements that were extremely brief and stood alone as single utterances. For this reason, statements such as “Yes,” “No,” “Okay”, “Alright,” I don’t know,” or “I guess,” were coded UN. Off-task talk (OT) demanded the mention or discussion of thoughts or ideas peripheral to the task at hand. This tended to include talk about plans outside of class, jokes, or other distractions. Examples include comments such as “There’s a lot more people on campus this year” and “Gonna have some M&Ms.” In the case that a word or sentence could not be transcribed, a code of inaudible (IN) was given. Both OT and IN units were subsequently excluded from analyses.

Episode segmentation and coding. A subset of the data that were collected (i.e., one team meeting) were segmented into episodes to more closely analyze the degree to which activity was distributed among team members. Here, an episode was defined as a collection of student talk turns in which students engaged in regulatory processes or higher-order reasoning discourse. An episode would begin with a statement by a group member that would subsequently guide the ensuing discussion; when the topic of discussion could no longer be tied to that initial statement, that episode ended and a new episode began. Of note, episodes could be of any length, ranging from a few lines of talk to hundreds of lines of talk, provided that the conversation could be tied back to that initial statement. However, episodes that did not involve any regulation or reasoning, or contained predominantly off-task talk, were discarded from further analysis.

After segmenting team conversation into episodes, each episode received a code of shared or guided, corresponding to the extent to which activity was distributed among team members. A designation of *guided* signified that one or more individuals were temporarily directing or controlling the activity of the group or acting as a more knowledgeable other. For example, one episode that was coded as *guided* featured a student telling his teammates what needed to be accomplished in their meeting and taking control to formulate plans to achieve it. In another, one student used his expertise with the subject matter to guide his teammates' ratings of a particular design idea. Importantly, for *guided* distribution of activity episodes, the speaker or speakers doing the guiding were documented. A designation of *shared* activity was given to episodes in which students contributed roughly equally toward shared reasoning and regulatory activity, helping to co-construct knowledge and move toward shared understanding. This was evident in one episode in which team members all weighed in on the criteria they would use to compare designs, with no one person consistently directing the activity of the group or demonstrating more knowledge or understanding of the task than others. Because of the time-intensive nature of this coding, only one team meeting was segmented into episodes and coded for its degree of sharedness.

Interrater reliability. Interrater reliability was established between the author and a second coder in several phases including: idea unit (i.e., utterance) segmentation; coding of RR; coding of SSRL; coding of task-related and other talk; segmentation of episodes; and coding of episodes. Prior to each phase, the second coder completed several training sessions in order to get acquainted with the coding scheme.

In preparation of the first phase, a random 20% of each team's transcript was selected for analysis. The decision to code a portion of each transcript, rather than one full transcript (~25%

of the data), was made to ensure that the coding scheme was appropriately applied to each team, acknowledging that different teams might manifest different patterns of speech and interaction. After training and refining the rules for segmentation, each coder segmented units for each team independently, then met to resolve any discrepancies. Here, disagreement was operationalized as a difference in the number of overall utterances as well as placement of unit breaks. Agreement for the four transcripts was high, averaging 91.7%.

In the next phase, the same selection of each team's transcript was coded for RR. Coders independently evaluated whether the utterances were relational or non-relational in nature, and then proceeded to code relational utterances for the specific form of RR represented. Disagreements were discussed and resolved following the completion of each transcript. Reliability was then evaluated for each transcript in terms of (1) the percentage agreement on whether a unit was relational or non-relational and (2) a Cohen's Kappa to denote agreement on the particular relational category (i.e., analogy, anomaly, antinomy, or antithesis). Agreement on relational/non-relational designation averaged 94.5% and Cohen's Kappas among the transcripts averaged $\kappa = 0.85$.

In a similar process, coders independently examined the remaining utterances in each transcript for SSRL. In this phase, agreement averaged 94% on whether units were SSRL or non-SSRL and Cohen's Kappas for the type of SSRL averaged $\kappa = 0.86$. Next, the coders evaluated the rest of the transcripts for task-related and other talk (i.e., off-task, unelaborated, and inaudible). Cohen's Kappas at this stage averaged $\kappa = 0.93$.

In the final phase, the coders delineated and coded episodes for Team Kayak's transcript only. Because this segmentation involved determining starting and ending places for particular threads or topics that would then dictate the beginning of the next episode, the coders met and collaboratively segmented the transcript into episodes, discussing any disagreements as they arose. Then, the coders independently determined what code the episode should receive (i.e., SRL, Guided, SSRL, or no code for non-regulatory/reasoning episodes). Agreement between the raters was 85% and $\kappa = 0.74$. For episodes that were coded Guided, the person or people guiding the discussion were noted.

Data Analytic Plan

Research Question 1: *To what extent do teams express differential proportions of relational reasoning (RR) and socially shared regulation of learning (SSRL) discourse during a collaborative problem-solving task?*

To address this question, it was necessary to begin by inspecting frequencies of each type of speech unit by individual as well as by team overall. Then, a chi-square analysis was used to determine whether the distributions of RR and SSRL units differed across teams. Specifically, chi-square tests of independence compared the observed team frequencies of RR and SSRL units, respectively, with a null condition in which all teams voiced equal proportions of each type of unit. If the omnibus chi-square tests proved statistically significant, post-hoc analyses were carried out to locate the source of the differences.

Research Question 2: *How is collective activity within problem-solving episodes shared among team members? Further, to what extent do certain individuals mediate these exchanges?*

To examine in more depth the degree to which problem solving was shared among team members, one team meeting was segmented into episodes. Each episode was then coded in terms of how distributed activity was among participants, which served as an indicator of the degree of sharedness of the group problem solving. The number of episodes, as well as the frequency of each type of episode, was counted. In cases where a code of *guided* was given, the individuals guiding the conversation were documented.

For a subset of the episodes, social transition plots were constructed to illustrate the dyadic interactions among team members. In this analysis, nodes represented speakers and ties between nodes indicated that one speaker finished talking and the next person responded. These networks explored patterns in how overall talk was distributed among teammates as well as the extent to which certain individuals led or mediated discussions. Because ties between nodes represented dyadic interactions, this analysis could not model the continuous sequence of speech throughout the meeting. However, the segmentation and examination of discrete episodes within the meeting provided a series of snapshots into how activity was distributed at particular points in time. To provide further insight, the ties between nodes were weighted according to how often that tie occurred and colored to indicate the type of speech unit verbalized.

To aid in understanding how activity was distributed among teammates, a number of centrality statistics were computed for each team member, or node, within the social transition plots. Broadly, node centrality refers to how important a given actor is in a network (Freeman, 1978). Centrality has, in fact, been studied in the context of group problem solving since the late 1940s (e.g., Leavitt, 1951) with evidence suggesting that group communication patterns can explain variation in team performance, organization, satisfaction, and leadership. However, there exist a multitude of centrality measures in social network analysis and each operationalizes centrality slightly differently. For instance, while some statistics characterize centrality in terms of the number of connections nodes possess (e.g., degree), others view centrality in terms of being an intermediary between nodes (e.g., betweenness). Still others measure centrality as a combination of the two (e.g., eigenvector centrality; Bonacich, 1987). In the current study, centrality was evaluated in three ways by considering degree centrality, flow betweenness, and eigenvector centrality. These centrality statistics were considered in tandem with the episode's code to see how individuals' centrality corresponded with the degree of sharedness documented in the episode coding. One question of interest was whether those individuals identified as the leader within episodes of a *guided* distribution of activity would also manifest higher centrality scores, given by their attempts to control or mediate team discussion. However, this analysis also sought to move beyond the identification of central individuals by taking into account the types of verbalizations (i.e., reasoning and regulation) made by individuals in each episode. General patterns in episodes' distribution of sharedness, individuals' centralities, and individuals' substantive contributions are discussed, with exemplar transition plots presented as illustrations.

Research Question 3: *What systematic patterns can be uncovered about the ways in which relational reasoning and SSRL discourse emerge in real time?*

A sequence mining tool was constructed to discover meaningful and systematic patterns of RR and SSRL talk as they occurred in engineers' problem-solving discussions. In order to prepare the data for sequence mining, speech units for each team meeting were assembled in order from the first unit of the meeting to the last. Then, an algorithm was written in Excel's Visual Basic for Applications (VBA) to search for patterns of relational and regulatory speech that were three to six units in length (see Appendix). The algorithm ignored any units that were task-related, unelaborated, off-task, or inaudible. For example, in a sequence of PLANNING → ANALOGY → TASK-RELATED → ANTINOMY, the tool would only acknowledge PLANNING → ANALOGY → ANTINOMY. Theoretically, there could be any number of intervening task-related or other units between a given set of relational or regulation units. Thus, a decision was made to limit the number of “noise” units to a maximum of 50. In other words, the algorithm would return the aforementioned PLANNING → ANALOGY → ANTINOMY sequence as long as there were no more than 50 task-related, unelaborated, off-task, or inaudible units between any of them. Prior research using the relational coding scheme (Dumas et al., 2014; Jablansky et al., 2016, 2019) has shown that 50 speech units can be verbalized in a relatively short period of time in CPS contexts and, depending on task length, may only account for a small proportion of the overall amount of talk. However, the cutoff of 50 was also made on the basis that relational or regulatory patterns with more than 50 noise units between them might be less related to one another and therefore not represent a meaningful pattern.

One additional constraint on the algorithm was to “compress” the transcript by unit type when the speaker stayed the same. For instance, if one speaker verbalized a sequence of ANTINOMY → ANTITHESIS → ANTITHESIS → ANTITHESIS, the algorithm would compress the sequence into Antinomy → Antithesis. This decision was made for several reasons. First, because full sentences are often broken up into several speech units, it is often the case that subsequent units of the same type are elaborations of the initial unit. In the case described above, an individual may have been describing several ways in which one design was superior to another. Compressing them into one large antithesis would therefore make the overall transcript “cleaner,” enabling the algorithm to focus more on finding meaningful interactions between different types of reasoning and regulatory speech. The decision to compress units of the same type at the *speaker* level was made so that any resulting patterns captured the social nature of the discourse. For example, if the algorithm returned a sequence of ANALOGY → ANALOGY → ANALOGY, it would necessarily mean that different speakers contributed to the pattern (or that there were 50 or fewer intervening units by other team members before the initial speaker voiced an analogy again).

With these conditions pre-programmed, the algorithm would proceed to determine the number of possible three to six unit sequences within a transcript. In this step, a given speech unit could be considered both with the previous two to five units as well as its succeeding two to five units. For instance, take the given sequence of units: PLANNING → MONITORING/CONTROL OF UNDERSTANDING → ANALOGY → ANTINOMY → ANTITHESIS. The analogy unit could be considered both a part of a PLANNING → MONITORING/CONTROL OF UNDERSTANDING → ANALOGY pattern as well as an ANALOGY → ANTINOMY → ANTITHESIS pattern. Although this resulted in many more sequences than simply counting each unit once, this more liberal constraint made it possible to identify a broader range of potentially informative patterns.

At this stage, the algorithm would return all possible sequences three to six units in length ranked in descending order of frequency. Given the exploratory nature of this analysis, no threshold was set for the number of occurrences needed to return a sequence. The most common sequences for each team transcript were then examined. Additionally, charts of each team's speech units over time were constructed to visually display when in the course of the meeting these sequences occurred and the individuals who contributed to them.

CHAPTER IV

RESULTS AND DISCUSSION

Descriptive Analysis

Prior to any analyses, transcripts of the discourse from 4 team meetings were segmented into speech units, which roughly equate to a unit of language expressing a complete thought. These units were then coded as relational reasoning (RR), socially shared regulation of learning (SSRL), task-related, or other (i.e., unelaborated, off-task, inaudible). The 4 team meetings ranged in length from approximately one to two hours. As shown in Table 3, these teams collectively produced 5723 speech units. Teams verbalized on average 1431 speech units (*SD* = 266.93), with Team Baby verbalizing the fewest units (n = 1192) and Team Ambulance verbalizing the most (n = 1870). Overall, relational reasoning (RR) accounted for an average of 6.71% (*SD* = 2.11%) of teams' total speech units, socially shared regulation of learning (SSRL) an average of 12.34% (*SD* = 1.63%), and task-related and other speech an average of 80.95% (*SD* = 3.63%). These results align with previous studies of group problem solving that applied the same RR coding scheme (Dumas et al., 2014; Jablansky et al., 2016, 2019). In those studies, RR utterances comprised approximately 10% of total speech units and the majority of the remaining speech units were task-related.

Within the RR category, teams tended to employ analogies, antinomies, and antitheses, and only rarely referred to anomalies. This may have been because the task was less about identifying abnormalities or aberrations within a larger pattern and more about comparing and evaluating novel ideas side by side. This result partially coheres with previous work in engineering design that revealed that all four forms of relational reasoning were related to ideation success (Dumas & Schmidt, 2015; Dumas et al., 2016). However, this result diverges

Table 3

Frequency (and Percentages) of RR, SSRL, and Other Speech Units by Team

TEAM	SPEECH UNITS													
	RR				SSRL				TASK RELATED/OTHER					
	AG	AM	AN	AT	PL	MCU	MCC	MCP	RE	TR	OT	UN	IN	Total
Kayak	10 (0.71)	2 (0.14)	46 (3.25)	54 (3.81)	54 (3.81)	52 (3.67)	45 (3.18)	17 (1.20_	16 (1.13)	849 (59.92)	58 (4.09)	191 (13.48)	23 (1.62)	1417
Baby	34 (2.85)	1 (0.08)	42 (3.52)	25 (2.10)	42 (3.52)	52 (4.36)	35 (2.94)	15 (1.26)	20 (1.68)	577 (48.41)	7 (0.59)	301 (25.25)	41 (3.44)	1192
Toilet	11 (0.88)	12 (0.96)	33 (2.65)	26 (2.09)	20 (1.61)	75 (6.03)	35 (2.81)	6 (0.48)	21 (1.69)	717 (57.64)	23 (1.85)	231 (18.57)	34 (2.73)	1244
Ambul ance	31 (1.66)	5 (0.27)	26 (1.39)	9 (0.48)	58 (3.10)	22 (1.18)	48 (2.57)	50 (2.67)	9 (0.48)	994 (53.16)	293 (15.67)	229 (12.25)	96 (5.13)	1870

Note. Percentages reflect proportions of overall speech within each team. RR = relational reasoning; SSRL = socially shared regulation of learning; AG = analogy; AM = anomaly; AN = antinomy; AT = antithesis; PL = planning; MCU = monitoring/control of understanding; MCC = monitoring/control of consensus; MCP = monitoring/control of progress; RE = reflection; TR = task-related; OT = off-task; UN = unelaborated; IN = inaudible.

from research in the medical domain in which doctors relied heavily on anomalies (Dumas et al., 2014). These different findings may point to the domain and task as important drivers of a team's resultant reasoning and regulation in a problem-solving context. Thus, in the present study, it seemed quite reasonable that teams would use more analogical, antinomous, and antithetical reasoning in order to meet the demands of the task: namely, to generate new ideas or combine pre-existing ideas, to discern the boundaries between designs, and to weigh the merits and disadvantages of designs.

Within the SSRL category, teams appeared to draw more on monitoring and control strategies devoted to understanding the task and content (e.g., team members' design ideas) and less on reflective activities. For example, individuals on Team Toilet, who were working on a modification to a toilet seat to help people raise themselves more easily, spent considerable time determining how to apply the methodology learned in class for evaluating designs, asking for details on each other's ideas, and reviewing relevant engineering concepts (e.g., normal force). In part this was done to bring others up to speed on aspects of the project that had been worked on outside of class, as well as to erase any gaps in knowledge before moving forward with the task. Teams devoted similarly high proportions of their SSRL speech to establishing plans and monitoring and controlling consensus. Previous work has demonstrated a relation between task difficulty and regulatory activity, such that more difficult tasks, like those in the current study, tend to be associated with longer and more frequent metacognitive activity, particularly monitoring and control strategies directed toward co-constructing knowledge and understanding (Iiskala et al., 2011; Lobczowski, Lyons, et al., 2020). This knowledge and understanding can then be used to set appropriate goals and establish plans.

It is unclear why teams did not engage in more reflection. It is possible that reflection is a more advanced regulatory technique that requires both backward and forward thinking involving recall of what was done and prospective thought related to what can be done differently in the future. Regardless of the reason, studies have documented that groups of all manner of experience and domain rarely engage in spontaneous reflection (Lobczowski, Allen, et al., 2020; Lobczowski, Lyons, et al., 2020; Sobocinski, Malmberg, & Jarvela, 2017), and that significant increases in team reflection are typically associated with explicit prompts to do so (Azevedo, Guthrie, & Seibert, 2004; Bannert, 2006; Sonnenberg & Bannert, 2015).

Within teams, there was a large degree of variability in the amounts of RR, SSRL, and task-related (TR) and other utterances (i.e., unelaborated, off-task, and inaudible) verbalized by individuals (see Table 4). Individuals verbalized on average about 260 speech units (*SD* = 172.18), with a mean of approximately 17 RR utterances (*SD* = 13.65) and 31 SSRL utterances (*SD* = 24.42). Interestingly, individuals who manifested lower instances of RR also tended to have lower instances of SSRL. For instance, on Team Toilet, Ryder and Sterling verbalized no RR units at all, and only 1 or 2 units of SSRL utterances. The inverse was also true, such that individuals who produced more RR units tended to produce more SSRL units, as well. This was apparent for Jeffrey, on Team Kayak, and Springer, on Team Baby, who both verbalized close to 50 speech units of each. It is possible that simply speaking more gave individuals more opportunities to express reasoning and regulation, as those who verbalized higher quantities of RR and SSRL generally verbalize higher quantities of total talk. However, there were individuals, such as Freddy on Team Kayak and Sam on Team Ambulance, who spoke regularly but were more focused on task-related and other types of utterances, offering potential support for the idea that some individuals demonstrated a higher capacity for both reasoning and regulation irrespective of their contributions to the team's overall speech.

There were some individuals whose speech was clearly more regulation-oriented. While Sarita, on Team Baby, verbalized a total of 21 RR speech units, she verbalized 67 SSRL speech units, more than anyone else on the team. Similarly, Brice, on Team Ambulance, verbalized 20 speech units of RR and 87 speech units of SSRL. This finding fits with prior research in which some individuals take on a regulatory role within the team environment, acting as a "more-regulated other" (Lobczowski, Lyons, et al., 2020; Rogat & Adams-Wiggins, 2015).

Proportions of Relational Reasoning and Socially Shared Regulation of Learning

Research Question 1 for this study sought to ascertain the extent to which teams expressed differential proportions of relational reasoning and socially shared regulation of learning discourse during a collaborative problem-solving task. For this analysis, I first present the findings for the relational reasoning discourse and then the data for socially shared regulation of learning.

Types and quantities of relational reasoning. The first chi-square test of independence evaluated the extent to which teams differed in their proportions of speech units devoted to analogies, antinomies, and antitheses. Speech units pertaining to anomalies were excluded from this analysis because they did not meet the assumptions of the chi-square test (i.e., the value of expected frequencies of each cell should be at least 5 or more in 80% of the cells). The omnibus chi-square indicated that proportions of RR speech units differed significantly across teams, $\chi^2(6, n = 347) = 48.77$, $p < .001$.

Table 4

Frequency of Speech Units by Team Members

TEAM	MEMBERS	SPEECH UNITS													
		RR				SSRL					OTHER				
		AG	AM	AN	AT	PL	MCU	MCC	MCP	RE	TR	OT	UN	IN	Total
KAYAK	BRAD*	1	1	2	2	9	2	4	3	1	90	10	32	1	158
	JEFFREY	6	0	24	20	7	16	23	6	3	261	19	47	4	436
	ARI	0	0	1	5	1	11	7	3	1	40	2	12	3	86
	BERT	3	1	8	13	21	14	5	3	3	235	10	54	4	374
	TOBIAS	0	0	9	8	12	2	5	1	8	116	8	17	3	189
	FREDDY	0	0	2	6	4	7	1	1	0	107	9	29	8	174
BABY	COLBY	6	0	5	9	5	6	6	5	3	147	1	74	7	274
	SARITA	10	0	5	6	18	21	14	8	6	116	1	105	16	326
	ALVIN	3	0	3	0	4	8	4	0	2	62	1	44	7	138
	SPRINGER	10	1	26	8	15	14	11	2	9	211	4	57	4	372
	CIARA	5	0	3	2	0	3	0	0	0	41	0	21	7	82
TOILET	TUNG	0	2	2	11	12	20	20	1	2	163	2	61	7	303
	LUTHER	6	4	11	3	2	35	6	1	6	180	10	52	10	326
	RYDER	0	0	0	0	0	2	0	0	0	38	1	24	6	71
	GALEN	5	6	10	9	6	13	9	4	11	226	4	73	4	380
	JUDD	0	0	10	3	0	4	0	0	2	101	6	16	7	149
	STERLING	0	0	0	0	0	1	0	0	0	9	0	5	0	15
AMBULANCE	NASH	15	4	10	2	21	5	23	10	0	265	99	44	30	528
	BRICE	6	1	10	3	18	9	17	38	5	352	83	104	41	687
	SAM	6	0	6	3	9	5	6	2	4	255	81	47	16	440
	GRADY	4	0	0	1	2	2	2	0	0	61	22	16	2	112
	LING	0	0	0	0	8	1	0	0	0	61	8	18	7	103

Note. *All names are pseudonyms. RR = relational reasoning; SSRL = socially shared regulation of learning; AG = analogy; AM = anomaly; AN = antinomy; AT = antithesis; PL = planning; MCU = monitoring/control of understanding; MCC = monitoring/control of consensus; MCP = monitoring/control of progress; RE = reflection; TR = task-related; OT = off-task; UN = unelaborated; IN = inaudible.

A series of post-hoc comparisons were run with a Bonferroni-adjusted *p*-value (α = 0.05/6 comparisons = .008) to determine the source of those differences. These tests revealed that Team Kayak differed significantly in their proportions of RR from Team Baby [χ^2 (2, *n* = 211) = 23.58, $p < .001$] and Team Ambulance [χ^2 (2, *n* = 176) = 39.95, $p < .001$]. Team Toilet also differed significantly from Team Ambulance [χ^2 (2, *n* = 136) = 18.51, $p < .001$; see Figure 9]. These differences appeared to be tied to the proportion of RR talk involving analogies and antitheses. Team Kayak did less analogical reasoning and more antithetical reasoning than would be expected, whereas by comparison Teams Baby and Ambulance did more analogical reasoning and less antithetical reasoning than expected. Similarly, Team Toilet did less analogical and more antithetical reasoning than expected, with the opposite pattern occurring for Team Ambulance.

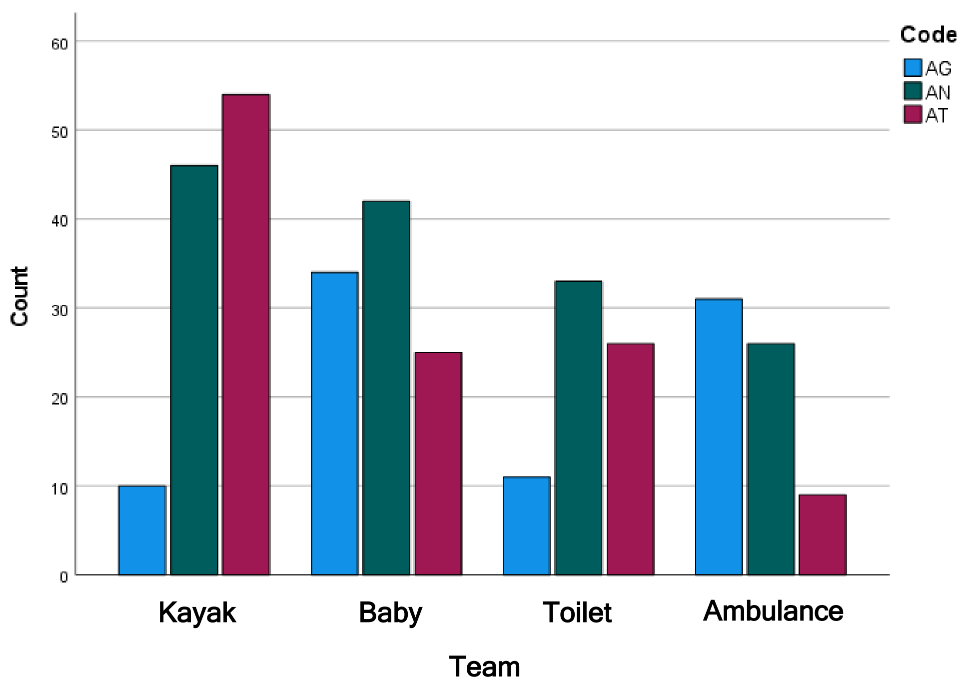

Figure 9. Proportions of team reasoning devoted to analogies, antinomies, and antitheses. AG = analogy; AN = antinomy; AT = antithesis.

Although overall counts of relational reasoning units were fairly comparable among teams (*M* = 91.75, *SD* = 18.63), the results of the chi-squares suggest that the teams used different types of relational reasoning as they approached the task of evaluating and selecting design ideas. Specifically, whereas Teams Baby and Ambulance focused proportionally more on relations of similarity, Teams Kayak and Toilet relied more heavily on relations pertaining to differences. These variations in pattern could be due to several factors. One plausible explanation is that the teams were at different stages of narrowing down the candidates for their project. Indeed, it was evident from meeting transcripts that Teams Kayak and Toilet had already made final decisions as to the pool of design ideas they would be evaluating, whereas Teams Baby and Ambulance routinely considered changing aspects of their designs or generating new designs altogether. This process of combining similar ideas and generating new ones might have led these teams to use more analogical reasoning. The other teams, however, having solidified their corpus of designs, could focus on evaluating each idea on a specific set of criteria, potentially leading to more antithetical reasoning.

Types and quantities of socially shared regulation units. The next chi-square test of independence examined the extent to which teams differed in their proportions of speech units related to planning, monitoring and control of understanding, monitoring and control of consensus, monitoring and control of progress, and reflection. The result revealed a statistically significant difference between teams in their proportions of regulatory utterances χ^2 (12, *N* = 692) = 103.19, $p < .001$ (see Figure 10).

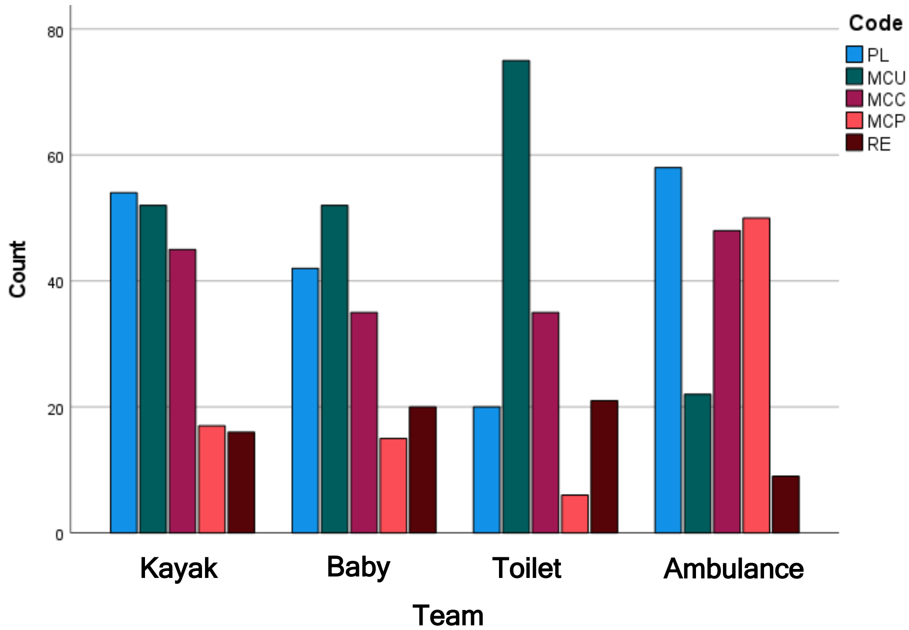

Figure 10. Proportions of team regulation devoted to planning, monitoring and control of understanding, monitoring and control of consensus, monitoring and control of progress, and reflection. PL = planning; MCU = monitoring/control of understanding; MCC = monitoring/control of consensus; MCP = monitoring/control of progress; RE = reflection.

Again, a series of post-hoc comparisons were run with a Bonferroni-adjusted *p*-value of 0.008 to determine the source of these differences. All but one of the six comparisons were statistically significant. Team Toilet differed significantly from Team Kayak [χ^2 (4, N = 341) = 24.99, $p < .001$] and Team Baby [χ^2 (4, N = 321) = 15.71, $p < .001$], manifesting lower proportions of speech devoted to planning but higher proportions of units pertaining to monitoring and control of understanding. Based on their speech units, Team Toilet also spent proportionally fewer utterances monitoring progress in comparison to Team Kayak. Given the amount of speech spent on co-constructing knowledge about the task and content, these results suggest that Team Toilet may have found the task more challenging than the other two teams, or that they were potentially less organized coming into the meeting. In contrast, as the speech patterns suggest, Teams Kayak and Baby were able to set goals and subsequently monitor their progress toward them, Team Toilet needed to do the prerequisite work of explaining ideas to one another and determining how to properly apply the methodologies learned in class to the task of evaluating designs.

Team Ambulance differed significantly from Team Kayak [χ^2 (4, N = 371) = 30.60, p < .001], Team Baby [χ^2 (4, N = 351) = 38.44, p < .001], and Team Toilet [χ^2 (4, N = 321) = 15.71, p < .001]. Consistent across these results, Team Ambulance had proportionally higher counts of speech units devoted to monitoring and control of progress and proportionally fewer counts of monitoring and control of understanding. These results may point to a difference in priorities between the teams or simply a difference in team norms. Although the members of Team Ambulance devoted time to asking about and explaining their ideas to one another (i.e., monitoring/controlling understanding), they appeared to be more focused on how much time had elapsed, how much work they had gotten done, and what work remained to be done. One plausible explanation for this is that Team Ambulance was simply composed of more highly regulated individuals. Another possibility is that monitoring progress was a strategy they employed out of necessity. For instance, off-task utterances for Teams Kayak and Baby only accounted for 4.09% and 0.59% of overall utterances, respectively, whereas Team Ambulance's off-task utterances accounted for 15.67% of their total talk. Thus, it is possible that team members were aware of their tendency to rove off topic and compensated for this with more frequent regulatory check-ins.

The results also revealed that Team Ambulance demonstrated proportionally fewer quantities of reflection in comparison to Teams Baby and Toilet, but proportionally higher quantities of planning. This may reflect the fact that Team Ambulance was still finalizing their pool of ideas and therefore at an earlier stage of the task in which planning was crucial to making progress, but not enough progress had been made to warrant much reflection.

Distribution of Problem-Solving Activity among Team Members

The second research question pertained to how collective activity within problem-solving episodes was shared among team members as well as the extent to which certain individuals emerged as central to these exchanges. Given the time intensive nature of the analysis, only one team transcript (i.e., Team Kayak) was segmented into episodes and coded for its distribution of activity as being *guided* by one or more individuals or more equally *shared* by the team. A total of 40 episodes were distinguished within the team's 1417 speech units (see Table 5). Seven of the episodes consisted primarily of off-task talk and were excluded from further analysis.

Distribution of activity. Of the remaining 33 episodes, 11 were coded as *guided*, and 22 were coded as *shared*. Consistent with prior research, a larger proportion of episodes was characterized by a more equal sharing of team activity (e.g., Lobczowski, Lyons, et al., 2020). Episodes were quite varied in length, ranging from 11 to 121 speech units, and contained an average of 41 speech units (*SD* = 25.04). This pattern held across episodes of both guided and shared activity, with guided episodes averaging approximately 38 speech units (*SD* = 30.09) and shared episodes averaging approximately 43 (*SD* = 22.71). Of the 11 episodes coded as guided, nine were led by only one individual and two were led by two team members. Four of the six team members guided at least one episode, suggesting that individuals took turns leading group problem solving efforts. One individual led seven of the episodes either by himself (Leader 1) or with another team member (Leader 2), potentially emerging as the team's "more-regulated other" (Lobczowski, Lyons, et al., 2020). In terms of when in the course of the meeting these episodes occurred, guided episodes both started and ended the meeting, and were fairly evenly

Table 5
List of Team Kayak Episode Codes with Primary Leaders Identified

EPISODE	SPEECH UNITS	CODE	LEADER 1	LEADER 2
1	22	Guided	Brad	
2	29	Shared		
3	21	Shared		
4	11	Guided	Tobias	
5	44	Shared		
6	49	Shared		
7	47	Shared		
8	78	Shared		
9	16	Shared		
10	46	Shared		
11	8	Off-task		
12	25	Guided	Bert	
13	14	Shared		
14	28	Shared		
15	37	Shared		
16	24	Shared		
17	20	Shared		
18	45	Guided	Bert	
19	18	Off-task		
20	13	Shared		
21	57	Shared		
22	6	Off-task		
23	32	Guided	Bert	
24	24	Off-task		
25	44	Shared		
26	121	Guided	Bert	
27	35	Guided	Bert	
28	21	Shared		
29	16	Off-task		
30	76	Shared		
31	37	Guided	Tobias	
32	13	Guided	Jeffrey	
33	82	Shared		
34	50	Shared		
35	19	Off-task		
36	27	Off-task		
37	58	Shared		
38	25	Guided	Bert	Brad
39	84	Shared		
40	49	Guided	Bert	Jeffrey

spaced throughout. This may provide support for the notion that teams not only cycle through the stages of regulation, but also through periods of more and less equal sharing of activity.

Node centrality. Next, social transition plots were formed by creating adjacency matrices of each dyadic interaction within each episode. As mentioned, team members were represented with nodes, and dyadic exchanges were represented with directed ties. For example, if Jeffrey spoke to Tobias, an arrow was drawn from Jeffrey's node to Tobias's node. Similarly, if Tobias spoke to Freddy, an arrow was drawn from Tobias to Freddy. From these plots, it was possible to calculate individuals' degree centrality, flow betweenness, and eigenvector centrality scores. As can be seen in Table 6, Jeffrey manifested the highest averages in all three categories across the 33 episodes. Specifically, Jeffrey sent and received more ties than anyone else, mediated a higher proportion of team discussion than others, and was more closely connected to other influential teammates. However, in episodes coded as *guided*, Bert manifested the highest scores, on average, of degree centrality, flow betweenness, and eigenvector centrality. This result seems reasonable, given that Bert was identified as the individual leading or guiding seven of these episodes. In fact, in the majority of cases, the individual coded as guiding the episode's activity also had the highest centrality scores. Consequently, these results might indicate that leadership is not simply a matter of communicating more often but also of managing the communication of others.

Table 6

Means (SD) of Degree Centrality, Flow Betweenness, and Eigenvector Centrality Scores across Episodes for Team Members

		Team Members					
Distribution	Statistic	Brad M*(SD)*	Jeffrey M*(SD)*	Ari M*(SD)*	Bert M*(SD)*	Tobias M*(SD)*	Freddy M*(SD)*
GUIDED	Centrality	9.82 (10.64)	11.09 (12.39)	2.00 (2.83)	15.36 (15.38)	5.82 (6.72)	6.45 (6.25)
	Flow	0.20 (0.25)	0.21 (0.15)	0.04 (0.06)	0.42 (0.30)	0.24 (0.26)	0.24 (0.28)
	Eigenvector	0.58 (0.39)	0.70 (0.25)	0.09 (0.12)	0.75 (0.35)	0.42 (0.43)	0.44 (0.23)
SHARED	Centrality	5.55 (6.15)	19.36 (10.90)	5.45 (5.70)	13.18 (11.73)	8.36 (7.59)	9.91 (6.23)
	Flow	0.12 (0.19)	0.54 (0.25)	0.11 (0.11)	0.24 (0.19)	0.14 (0.11)	0.19 (0.14)
	Eigenvector	0.31 (0.33)	0.95 (0.11)	0.30 (0.23)	0.58 (0.35)	0.49 (0.33)	0.59 (0.25)
TOTAL	Centrality	6.97 (8.03)	16.61 (11.90)	4.30 (5.15)	13.91 (12.86)	7.52 (7.31)	8.76 (6.36)
	Flow	0.15 (0.21)	0.43 (0.27)	0.08 (0.10)	0.30 (0.25)	0.17 (0.18)	0.20 (0.19)
	Eigenvector	0.40 (0.37)	0.87 (0.20)	0.23 (0.22)	0.64 (0.35)	0.47 (0.36)	0.54 (0.25)

Note. Centrality = degree centrality; Flow = flow betweenness; Eigenvector = eigenvector centrality.

General patterns of communication. When considering the broader patterns involving the dimensions of distribution of activity and the content of communication, a few themes emerged. One finding was that regulatory utterances, but not relational utterances, were found in episodes that were *guided.* A second finding was that the majority of relational reasoning utterances occurred in *shared* episodes. Finally, relational reasoning almost always co-occurred with regulatory utterances, regardless of the sharedness of activity. Each of these patterns is explained in further detail below.

Presence of regulatory utterances in guided episodes. Guided episodes of regulatory talk appeared to be important for exposing misconceptions about the task or content and recalibrating team plans and expectations. This is reflected is Episode 12 (see Figure 11 below), in which Bert paused team activity to express his belief that team members were doing the evaluation task incorrectly (i.e., monitoring/controlling understanding). Tobias then proposed a plan to Bert that members show their work to the instructor the next day to get his feedback, with Freddy adding that they could explain why they used the evaluation criteria they did (i.e., planning). Bert, however, rejected the plan by explaining his understanding of what the task was and how they needed to proceed. After discussing it further, the team aligned themselves with Bert's view of the task and moved on (i.e., monitoring/controlling consensus).

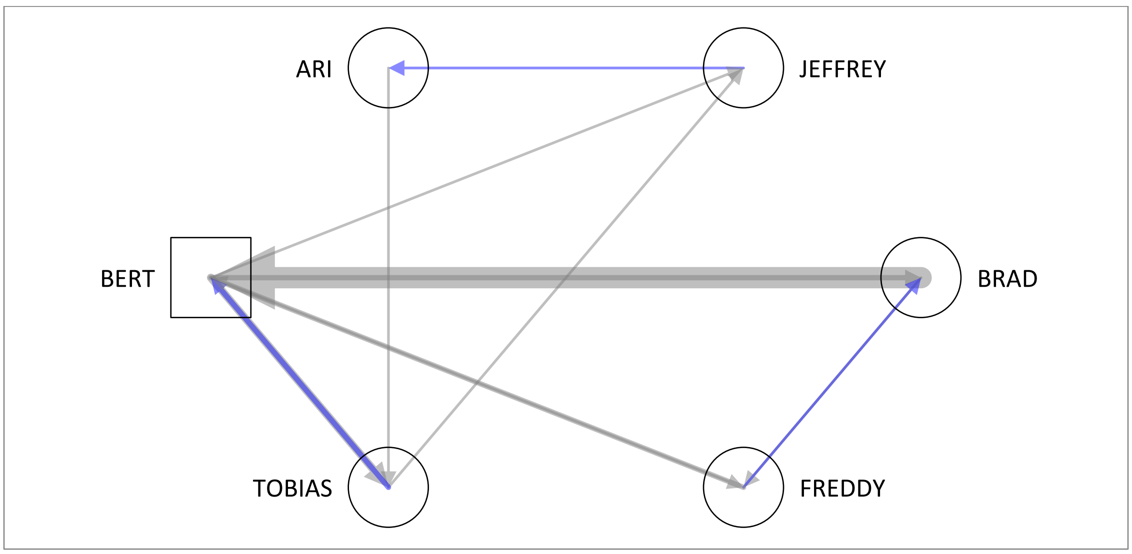

Figure 11. Team Kayak's Episode 12. The square shape denotes the individual who guided the episode, while circles represent all other speakers. The width of ties corresponds to the frequency of that dyadic exchange. Gray denotes task-related or other utterances, while blue denotes regulatory utterances.

The team was able to continue with its design evaluations until Tobias interrupted activity in Episode 18 (see Figure 12) with a monitoring statement about how he thought members were missing something important in their ratings and raised a question about whether their plan for the next part of the task made sense. Bert again stepped in as an authority and told the team how the task was supposed to work and how they should move forward. The team deliberated about the best way to continue at this point, but ultimately accepted Bert's suggestion and proceeded with his plan.

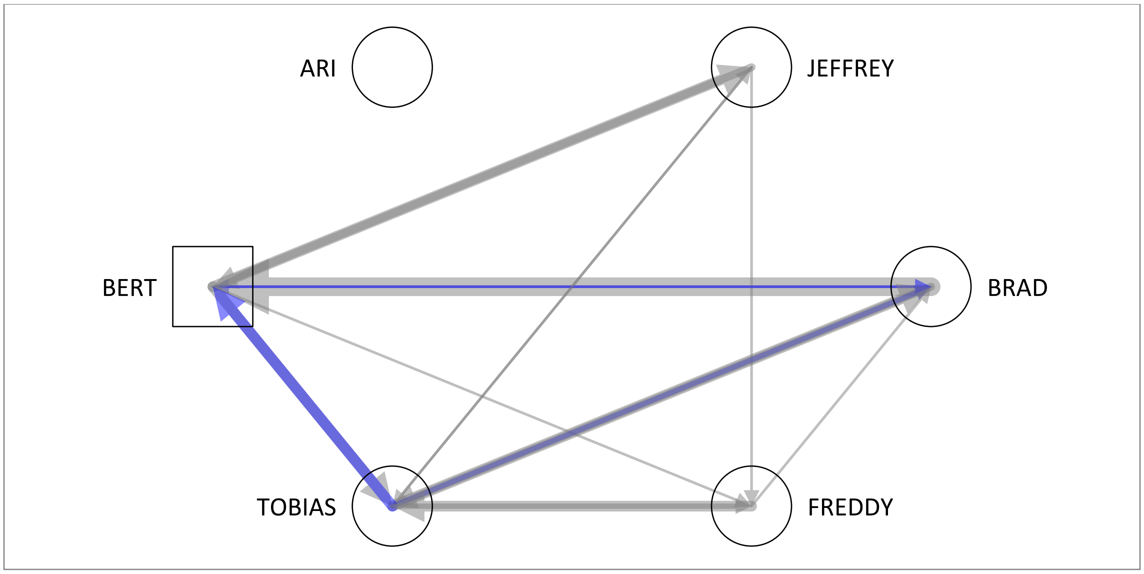

Figure 12. Team Kayak's Episode 18. The square shape denotes the individual who guided the episode, while circles represent all other speakers. The width of ties corresponds to the frequency of that dyadic exchange. Gray denotes task-related or other utterances, while blue denotes regulatory utterances.

The pattern discussed above continued throughout the meeting, such that every few episodes, prompted by a question or point of confusion, one or two team members stepped in to resolve the issue and get the team back on track. Bert served as this person in the majority of cases, which could reflect a greater understanding of the task, or perhaps an inclination to exert control over his peers. Altogether, these episodes pointed to a broader cycle in which misconceptions or erroneous understandings of task and content arose at each stage of task completion, and that it was important to explore these misunderstandings, re-formulate plans, and generate consensus about how to continue.

Presence of relational reasoning utterances in shared episodes. Interestingly, relational utterances almost always occurred in episodes characterized by relatively equal contributions of activity from each team member (i.e., *shared* episodes). Upon further scrutiny of the conversations taking place in these episodes, it was apparent that the team actively reasoned together, at times expanding on relational utterances made by teammates and at others refuting them. In Episode 6 (see Figure 13), for example, the team was exploring the idea of creating a more buoyant paddle float to aid kayakers in capsizing accidents. Brad began by posing the antinomous question of whether the paddle float, as imagined, could be used as is or whether it needed to be prepared for use. Jeffrey then responded with an antinomy himself, explaining that the paddle did need to be inflated, which could be done *either* manually or automatically, depending on how they wanted to design it. He added, however, that they were assuming (analogically) that the paddle would have to be inflated as most inflatable things are, by mouth. This pattern continued as the team evaluated other ideas in terms of whether they needed to be prepped for use. As they were discussing an idea for a kayak with outriggers, or built-in supports, Jeffrey made the analogy that outriggers operate similarly to paddle floats. Bert, however, footnoted this comparison with the important (i.e., antinomous) distinction that outriggers are typically built *into* the kayak, whereas paddle floats exist *separately* from the kayak.

Co-occurrences between relational reasoning and regulation utterances. The final pattern of interest was that reasoning and regulation utterances often co-occurred and appeared to work in concert. For instance, in Episode 10 (see Figure 14), the team was discussing an idea for something a kayaker could wear to protect themselves in the case of a capsizing accident. Jeffrey posed the antinomous question of whether the device would be a class two personal flotation device (PFD)—meant for offshore use in rougher waters—or a class three PFD—meant for inshore use in calmer waters. Ari, Freddy, and Tobias continued by monitoring their

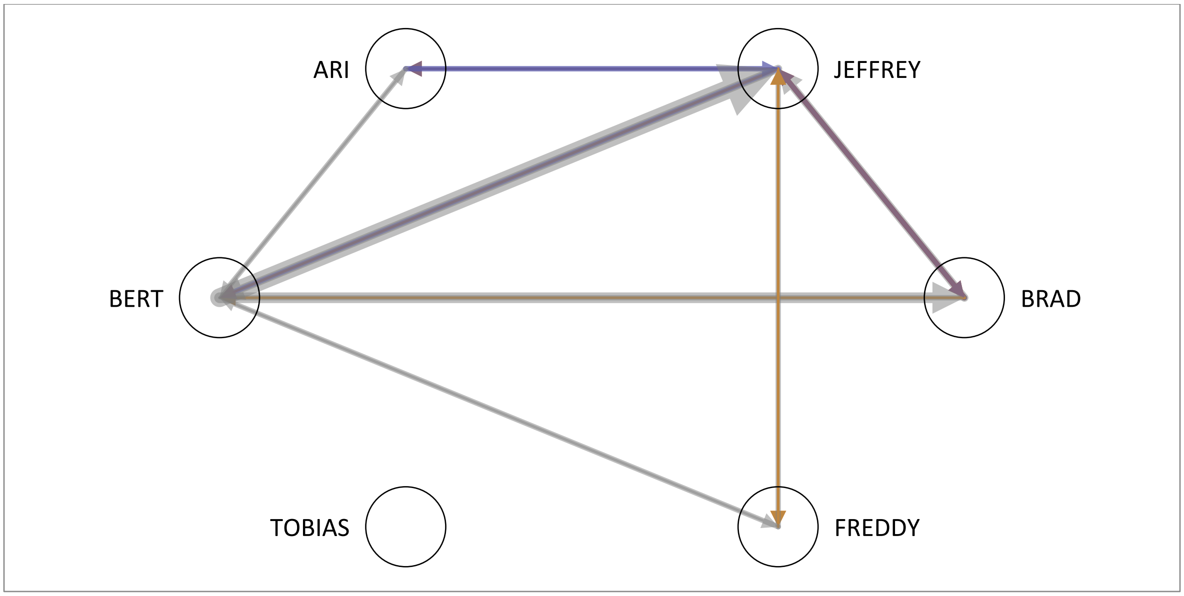

Figure 13. Team Kayak's Episode 6. The width of ties corresponds to the frequency of that dyadic exchange. Gray denotes task-related or other utterances, blue denotes regulatory utterances, and orange denotes relational utterances.

understandings of what characterizes different types of PFDs and which would best address the problem they were trying to solve. Bert then reasoned antithetically that if their idea was a class three PFD, then its weight would be better (i.e., lighter) than the paddle float they envisioned as an alternative idea. In this way, reasoning tended to prompt monitoring and control processes, which would in turn invite more reasoning, eventually leading to a decision point in which team consensus was assessed or a new plan was generated.

Patterns of Reasoning and Regulation Utterances

The third research question asked whether systematic patterns could be uncovered about the ways in which RR and SSRL emerge in real time during a CPS task. To address this question, an algorithm was written to search each team meeting for the most frequently occurring sequences three to six utterances in length. As mentioned, the algorithm was programmed with several parameters: to only consider utterances that were relational or regulatory in nature; to

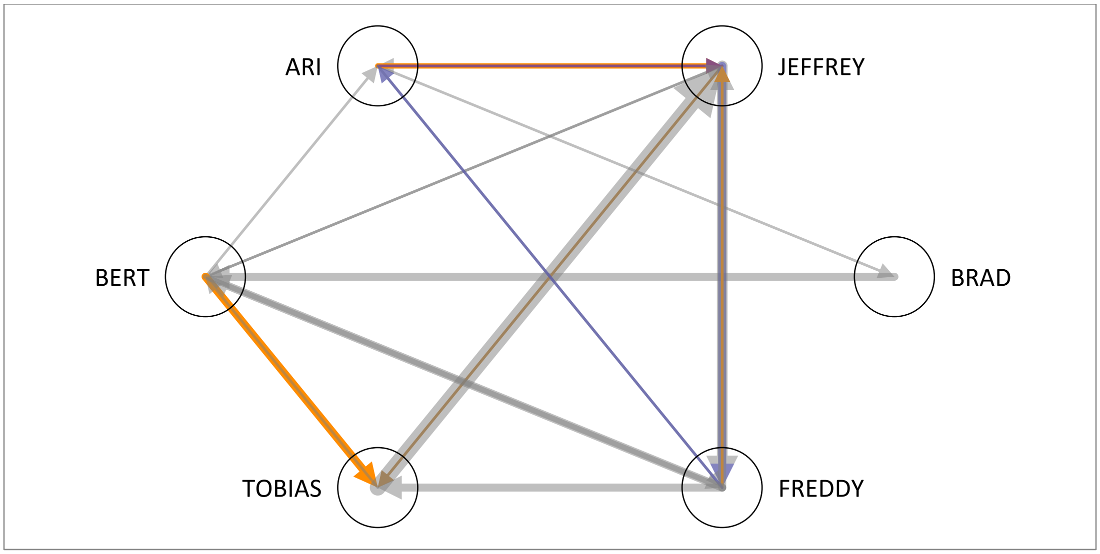

Figure 14. Team Kayak's Episode 10. The width of ties corresponds to the frequency of that dyadic exchange. Gray denotes task-related or other utterances, blue denotes regulatory utterances, and orange denotes relational utterances.

limit the number of noise units between any two relational or regulatory utterances to 50; to compress repeated utterances of the same type by the same person; and to consider an utterance both with its preceding and succeeding two to five utterances in determining the total number of sequences in the transcript. Finally, the algorithm returned all of the sequences found in each transcript, ordered by frequency of occurrence.

The algorithm found an average of nearly 16 patterns (*SD* = 5.80) that repeated at least three times within each meeting. For Teams Kayak, Baby, and Toilet, the most frequent pattern occurred 7-10 times throughout the meeting. Team Ambulance's most frequent pattern, somewhat anomalously, occurred 28 times. Table 7 displays the most common sequences in each team meeting that occurred three times or more. Although the most frequently occurring sequences differed across teams, there were consistencies in the patterns that appeared. For instance, Teams Baby and Ambulance had highly frequent patterns of exclusively regulatory utterances, especially those devoted to planning (e.g., PL→PL→PL) and monitoring/control of understanding (e.g., MCU→MCU→MCU). Teams Kayak and Toilet, by contrast, had highly frequent patterns featuring both reasoning and regulatory utterances (e.g., MCU→AT→AT). From these patterns, a number of broader insights were generated about which patterns were central to team problem solving, when these patterns occurred, and by whom they were voiced. These findings are explored below.

Common sequences across teams. There were a number of patterns regarding the composition of sequences that appeared most frequently in team problem solving. For instance, three of the four teams had frequently occurring patterns involving sequences of planning utterances and sequences of monitoring and control of understanding. There were also, at times, sequences of one form of relational reasoning. Team Kayak frequently verbalized sequences of antitheses and antinomies, and Team Baby verbalized sequences of analogies. These results may suggest that neither reasoning nor regulation utterances occur in isolation (i.e., with only task-related or other utterances surrounding it), but rather occur in clusters. It is possible that these clusters appear because multiple individuals are adding to an initial regulatory or relational utterance, or perhaps because once a relation or regulatory activity is introduced, it is necessary to explicate or explore in more depth.

In addition to finding sequences of the one type of utterance, the algorithm also revealed patterns of varying reasoning utterances, regulation utterances, and reasoning and regulation combinations. Pertaining to RR, the algorithm returned several patterns in which antinomies were paired with another form of reasoning. There were several variations of antinomies and antitheses, such as Team Kayak's AN→AN→AT, AN→AT→AT, and AN→AN→AN→AT. In one instance, Jeffrey posed the antinomous question of whether the team's idea to install an

Table 7

Frequency of Most Common Sequences of Relational Reasoning and Socially Shared Regulation of Learning Three to Six Units in Length by Team

TEAMS							
KAYAK		BABY		TOILET		AMBULANCE	
PATTERN	*n*	PATTERN	*n*	PATTERN	*n*	PATTERN	*n*
AT-AT-AT	7	PL-PL-PL	10	MCU-MCU-MCU	7	PL-PL-PL	28
AT-MCC-AT	6	PL-PL-PL-PL	7	MCU-AT-MCU	4	PL-PL-PL-PL	21
MCU-AT-AT	5	PL-PL-PL-PL-PL	5	MCU-AT-MCC	3	PL-PL-PL-PL-PL	15
MCC-AT-MCC	5	MCU-AG-AN	5	MCC-MCU-RE	3	PL-PL-PL-PL-PL-PL	10
MCC-MCU-MCU	5	MCU-MCU-MCU	4	MCU-MCU-AT	3	PL-PL-MCC	5
AN-AN-AN	5	MCU-AG-AN-MCC	3	MCU-MCU-MCU-MCU	3	MCP-PL-PL	4
MCU-AT-AT-AT	4	PL-PL-MCC	3	MCU-RE-MCU	3	PL-PL-PL-MCC	4
AN-AN-AT	4	PL-PL-PL-PL-PL-PL	3	RE-MCC-MCU	3	MCU-PL-PL	3
AT-AT-MCC	4	AG-AN-MCC	3	MCU-AG-MCC	3	PL-PL-PL-PL-PL-MCC	3
AT-MCU-AT	4	MCP-MCU-AG	3			PL-PL-MCP	3
AT-AT-MCU	4	MCU-MCU-MCU-MCU	3			PL-PL-MCU	3
AN-AT-AT	3	MCC-MCP-MCU	3			AG-AN-AG	3
MCU-AG-AN	3	RE-RE-RE	3			PL-PL-PL-PL-MCC	3
MCU-PL-PL	3	AN-AG-AN	3			RE-PL-PL	3
AT-MCC-AT-MCC	3	MCP-PL-PL	3				
MCU-MCU-MCC	3	AG-AG-AG	3				
AN-AN-AN-AT	3						
AT-AT-MCC-AT	3						
PL-MCC-MCU	3						
AT-AT-AT-MCC	3						
MCC-AT-MCU	3						
MCC-AT-MCC-AT	3						
PL-MCP-PL	3						

Note. Table displays frequencies of most common sequences that occurred three or more times by team. AG = analogy; AM = anomaly; AN = antinomy; AT = antithesis; PL = planning; MCU = monitoring/control of understanding; MCC = monitoring/control of consensus; MCP = monitoring/control of progress; RE = reflection; TR = task-related; OT = off-task; UN = unelaborated; IN = inaudible.

outrigger on a kayak would involve compressed gas or the user blowing it up themselves. The other team members, in response, reasoned antithetically that if it involved the user blowing it up themselves, then it would be less deployable but cost less than their idea for a more inflatable paddle. Teams Baby and Ambulance similarly demonstrated patterns of antinomies and analogies, including AN→AG→AN and AG→AN→AG. For example, as Team Baby was discussing one idea for a way to measure babies more accurately, Springer mentioned how the idea had a similar issue as another design they had talked about, explaining with an antinomy that the design would not address circumference, as they needed it to, only latitudinal and longitudinal dimensions. Together, these frequent co-occurrences between antinomies and other forms of reasoning may point to the importance of being able to identify categorical boundaries during any type of reasoning.

Pertaining to SSRL, the algorithm revealed several patterns in which monitoring and control of consensus was paired with other forms of regulation. This was apparent in the MCC→MCU→MCU pattern of Team Kayak, the MCC→MCP→MCU of Team Baby, the RE→MCC→ MCU of Team Toilet, and the PL→PL→MCC pattern of Team Ambulance. In these scenarios, MCC sometimes functioned as a jumping off point for discussion, as when Jeffrey on Team Kayak surveyed his fellow team members for their evaluations of a design involving ropes and pulleys in terms of its how deployable it would be. This monitoring of group consensus of design ratings led to the need for several team members to clarify their understanding of the term deployable. In other scenarios, MCC sometimes followed regulatory activity, as when Team Ambulance was planning how they would approach the task. Sam and Brice agreed that the team needed to narrow down their number of ideas and come up with justifications for these decisions, but Sam raised the question of what rules they should use to guide the decision-making process, asking his team members to weigh in with their thoughts. When initiating or following regulatory activity, MCC appeared to serve as an important check-in for team members and an opportunity to ensure that all were on the same page.

Finally, the algorithm found multiple incidences of sequences in which reasoning and regulation were combined. Common strings among all the teams involved monitoring and control of understanding (MCU) or monitoring and control of consensus (MCC) paired with antitheses, analogies, and antinomies (e.g., MCU→AT→AT; AG→AN→MCC). In many cases, a question aimed at better understanding a concept (i.e., MCU) would precede a reasoned judgment of how two ideas compared along a continuum (i.e., AT). At one point, Galen, on Team Toilet, was trying to ascertain how much force a user would have to exert to rise from a toilet seat using one of the proposed designs. This monitoring of his and his teammates' understanding of the design led to a deeper discussion with Ryder, Tung, and Sterling in which they determined that the user would be able to exert less force than with a comparable design. In other co-occurrences of reasoning and regulation, reasoning would sometimes precede an assessment of team consensus or solicitation of team feedback (i.e., MCC). For example, in one exchange, Springer noted that two of the team's ideas for more accurately measuring a baby were similar in that both were made to hold a measuring tape in place, which Colby rebutted by explaining that one would hold itself in place whereas the other would have to be held by someone at all times. This led Springer to open the question more broadly to the group and ask for other members' assessments of how easily each design could be held in place.

Altogether, these co-occurrences of reasoning and regulation indicate that the two processes may work hand in hand, especially in a collaborative context. Discrepancies in team members' conceptions of ideas may invite reasoning that invokes analogies to similar ideas or antinomies that help distinguish between ideas, just as reasoning involving evaluations of ideas along a continuum may invite team members to ask one another to weigh in so that agreement can be established.

Temporality of common sequences. Because both regulation and problem solving have been theorized as cyclical processes, it was critical to ascertain not only which sequences of reasoning and regulation were most common, but also when during problem solving these patterns arose. To address this question, a series of charts were constructed to visually display when selected sequences appeared in each team's discourse. Overall, these charts demonstrated that regulation sequences were occurring throughout the meeting, whereas reasoning sequences occurred more often in the middle of meetings. The composition of regulation sequences, however, differed depending on what stage teams were at in their problem-solving process. For instance, patterns involving planning and reflection tended to bookend meetings. As Figure 15 shows of Team Ambulance, the pattern PL→PL→MCC occurred in the very beginning of the meeting and then again in the final third of the meeting. This was also apparent for Team Baby (Figures 16-17), as planning dominated the beginning of the meeting and reflection ended it.

Processes involving monitoring and control, however, which operated in tandem with reasoning, more often appeared in the middle of problem solving. This can be seen in Figure 18, in which monitoring and control of understanding occurred alongside antithetical reasoning in the middle of Team Kayak's discourse. It is also apparent from this visualization that the reasoning and regulation did not occur in one large mass but was spread out in what might be identified as cycles. This could also be seen in Team Baby's discourse in Figure 19, where sequences of monitoring and controlling understanding, along with analogies and antinomies, appeared in distinct clusters, primarily in the middle of problem solving.

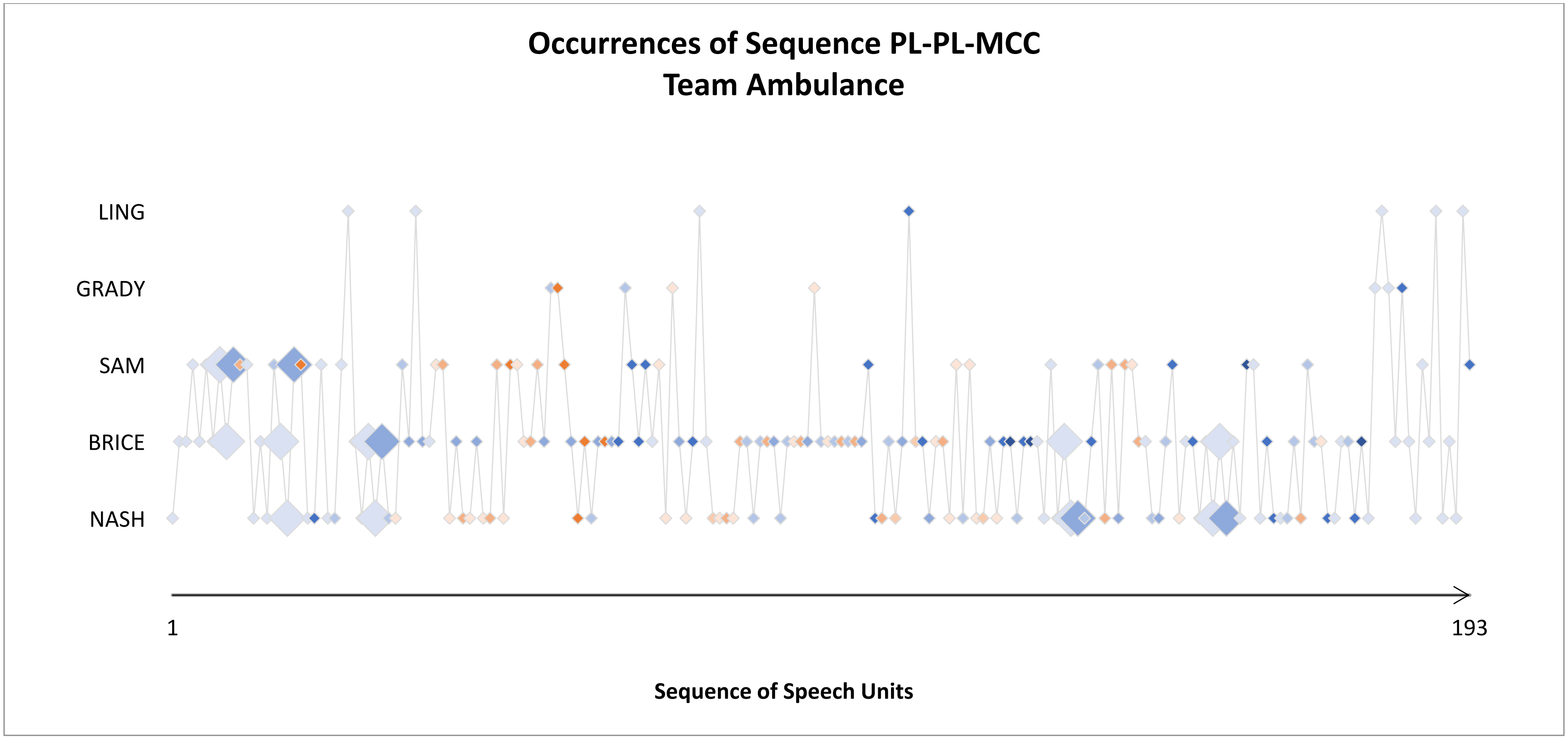

Figure 15. Team Ambulance's speech units in sequence. X-axis values correspond to the first and last utterance in the compressed version of the team transcript. Blue diamonds represent regulatory utterances, while orange diamonds represent reasoning utterances. Diamonds are enlarged if they are a part of the sequence of interest. Here, light blue diamonds correspond to PL while darker blue diamonds correspond to MCC. The individual who voiced each utterance can be found alongside the y-axis of each line.

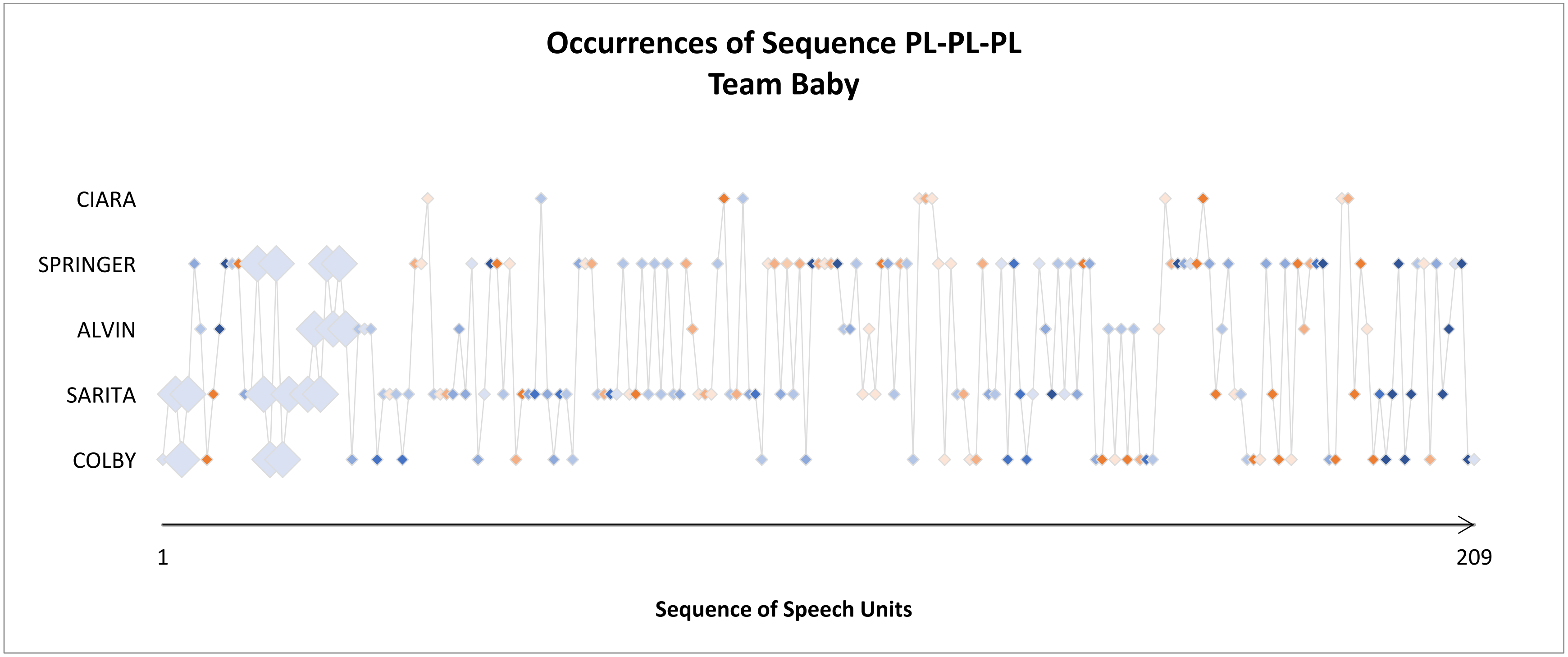

Figure 16. Team Baby's speech units in sequence. X-axis values correspond to the first and last utterance in the compressed version of the team transcript. Blue diamonds represent regulatory utterances, while orange diamonds represent reasoning utterances. Diamonds are enlarged if they are a part of the sequence of interest. Here, light blue diamonds correspond to PL. The individual who voiced each utterance can be found alongside the y-axis of each line.

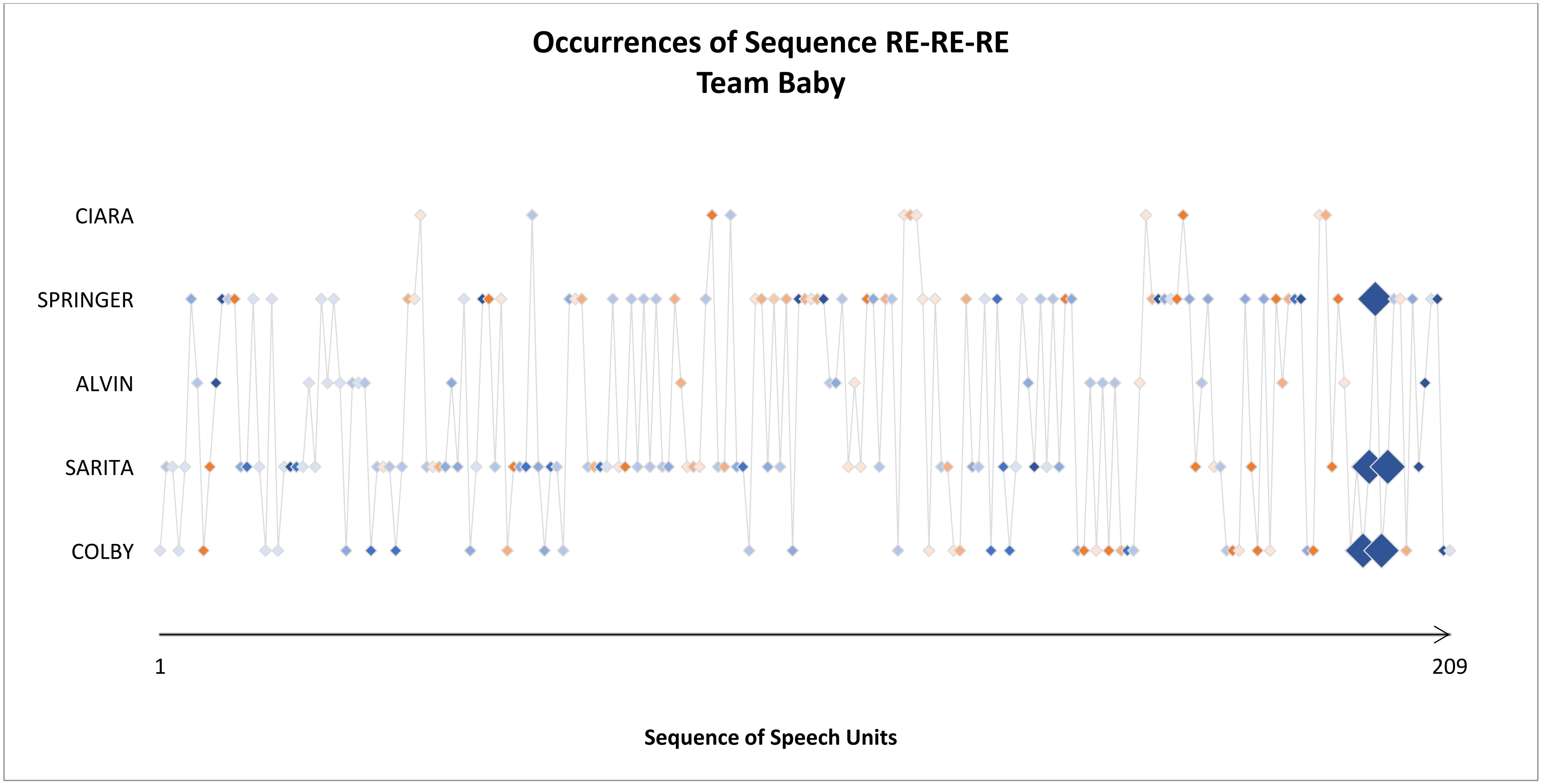

Figure 17. Team Baby's speech units in sequence. X-axis values correspond to the first and last utterance in the compressed version of the team transcript. Blue diamonds represent regulatory utterances, while orange diamonds represent reasoning utterances. Diamonds are enlarged if they are a part of the sequence of interest. Here, dark blue diamonds correspond to RE. The individual who voiced each utterance can be found alongside the y-axis of each line.

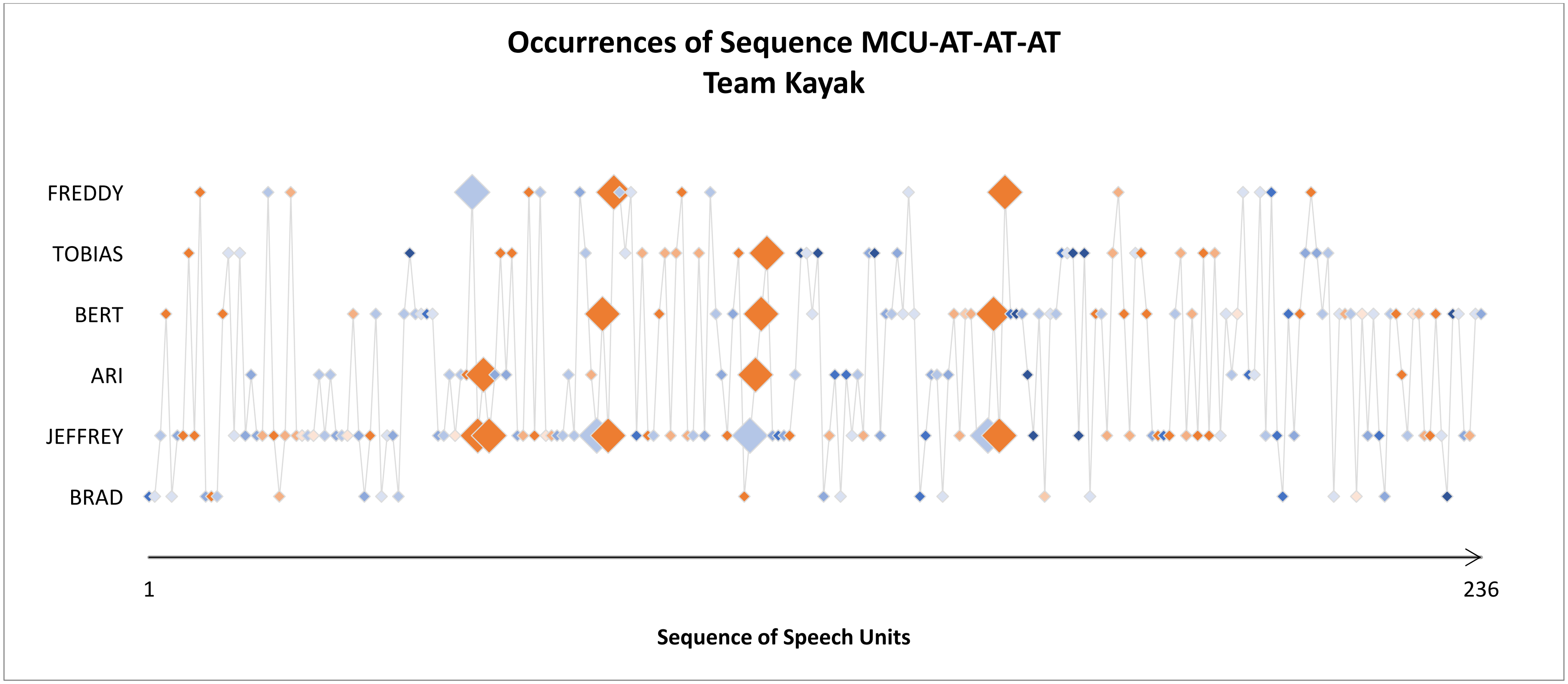

Figure 18. Team Kayak's speech units in sequence. X-axis values correspond to the first and last utterance in the compressed version of the team transcript. Blue diamonds represent regulatory utterances, while orange diamonds represent reasoning utterances. Diamonds are enlarged if they are a part of the sequence of interest. Here, light blue diamonds correspond to MCU, while dark orange diamonds correspond to AT. The individual who voiced each utterance can be found alongside the y-axis of each line.

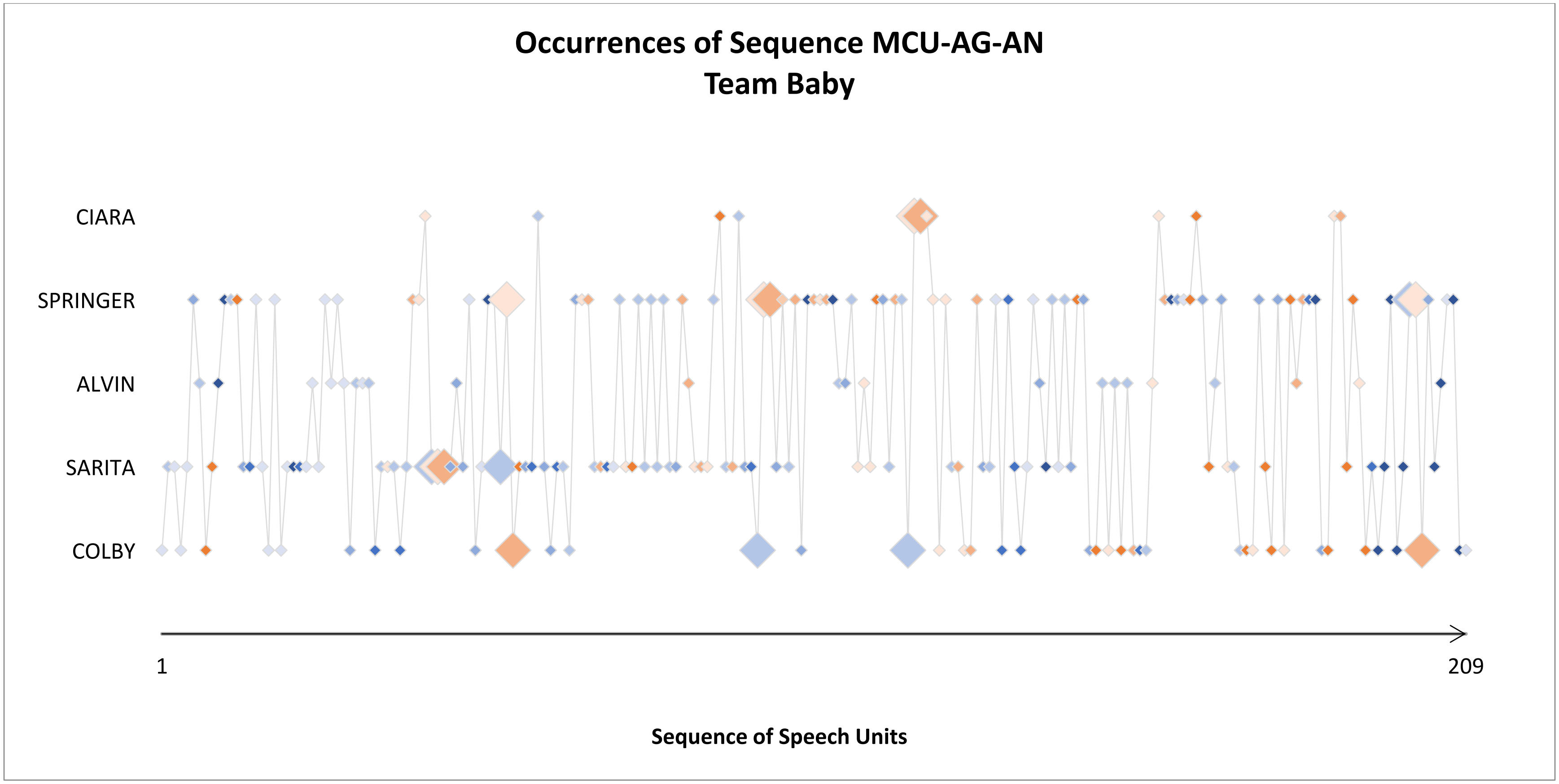

Figure 19. Team Baby's speech units in sequence. X-axis values correspond to the first and last utterance in the compressed version of the team transcript. Blue diamonds represent regulatory utterances, while orange diamonds represent reasoning utterances. Diamonds are enlarged if they are a part of the sequence of interest. Here, light blue diamonds correspond to MCU, while light orange diamonds correspond to AG and dark orange diamonds to AN. The individual who voiced each utterance can be found alongside the y-axis of each line.

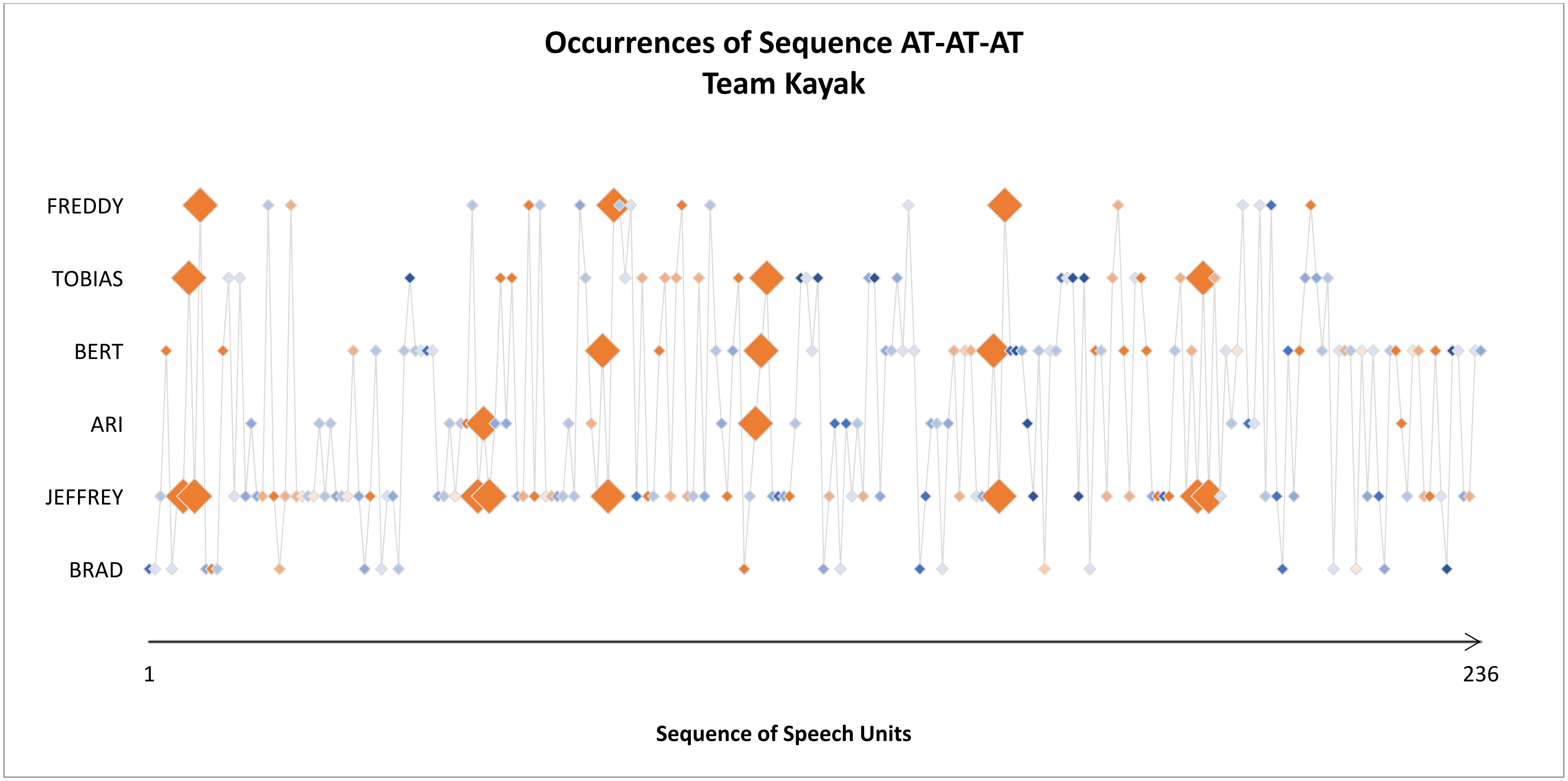

Figure 20. Team Kayak's speech units in sequence. X-axis values correspond to the first and last utterance in the compressed version of the team transcript. Blue diamonds represent regulatory utterances, while orange diamonds represent reasoning utterances. Diamonds are enlarged if they are a part of the sequence of interest. Here, dark orange diamonds correspond to AT. The individual who voiced each utterance can be found alongside the y-axis of each line.

The temporality of teams' most frequent sequences suggests that there may be macro-level and micro-level patterns playing out during problem solving. On a macro level, it seems that teams begin with a set of plans, then engage in problem solving, and finally reflect on performance and plan for the future. On a microlevel, teams appear to demonstrate smaller, dynamic cycles of reasoning and regulation that help to adjust plans, clarify understandings, resolve disagreements, and make decisions.

Distribution of utterances among team members in common sequences. A final question of interest was how individuals contributed to these sequences of reasoning and regulation. For example, were certain patterns most distributed across individuals than others? Were certain people more apt to contribute to specific types of patterns? Did the level of collaboration change over time? As the results from Research Question 2 suggested, there were times (i.e., episodes) when reasoning and regulation were highly distributed, but others when only one or two individuals contributed. Upon examination of the charts of team sequences over time, it was clear that most team members contributed to reasoning and regulation sequences at some point, but most sequences were distributed over only two to three people at any given time. The chart of Team Kayak's antithetical reasoning sequences, shown in Figure 20, are a case in point.

Over the course of the meeting, all but one of the team members were part of an antithetical reasoning sequence. However, at any one time, only three individuals were actively reasoning. This could also be seen in Team Baby's planning sequences in Figure 16. Although four of the five team members participated at some point, there were discrete moments featuring only Colby and Sarita; Colby, Sarita and Springer; and finally, Sarita, Springer, and Alvin. These results held over time, such that, even by the end of the meeting when reflection was occurring (Figure 17), there were generally just two or three team members contributing. These results may indicate that even if overall activity—including task-related and other talk—is being shared by everyone, there may be alternating dyads and triads of team members controlling the reasoning and regulation of the group.

CHAPTER V

CONCLUSIONS, LIMITATIONS, AND IMPLICATIONS

Broadly, the current study aimed to examine the interplay of relational reasoning (RR) and socially shared regulation of learning (SSRL) during a collaborative problem solving (CPS) task. More specifically, nested in the domain of mechanical engineering, this study sought to determine: (a) whether the forms of RR and SSRL were employed in relatively equal proportions during problem solving or whether certain forms were privileged over others; (b) how collective activity was distributed across team members and whether specific team members emerged as more central to exchanges than others; and (c) whether patterns of co-occurrences between RR and SSRL could be uncovered and linked with particular individuals and points in time. In this chapter, I will overview key findings and acknowledge certain limitations to this investigation. Then, I will discuss what I regard as the important substantive and methodological contributions of this work, and forward recommendations for future studies of CPS.

Key Findings

Teams Exhibit Differential Patterns of Relational Reasoning and Socially Shared Regulation of Learning

The results from this study demonstrated that all four engineering design teams engaged in unprompted relational reasoning (RR) and socially shared regulation of learning (SSRL), but in differing proportions. Although there were some commonalities, including comparable usage of antinomous and monitoring and control of consensus (MCC) utterances, teams exhibited unique profiles of reasoning and regulation. Pertaining to RR, Teams Baby and Ambulance voiced proportionally more analogies, while Teams Kayak and Toilet made proportionally more antithetical utterances. With regard to SSRL, there were teams that voiced proportionally more planning utterances, and others that voiced proportionally more monitoring and control of understanding or progress utterances. Research suggests that the task—both its focal domain and its level of difficulty—shape the landscape of reasoning and regulation to some extent (Dumas et al., 2014; Jablansky et al., 2016, 2019; Lobczowski, Lyons, et al., 2020). Indeed, this was reflected in the relatively comparable proportions of antinomy and monitoring and controlling utterances that seemed to be keys in understanding the differences between ideas, soliciting feedback, and making decisions. However, there were several other factors that may have influenced teams' reasoning and regulation.

One possible explanation for the differential patterns of reasoning and regulation is that the teams were at different stages of the task when they were observed. In other words, although all four teams were working toward the same ultimate goal, some may have progressed farther than others. For instance, it was clear from the transcripts that Teams Baby and Ambulance were at the earlier stages of narrowing down their pool of ideas and were still open to the idea of generating new designs or reimagining existing designs. This may have led them to use proportionally more analogical utterances, as they thought of other ideas after which they could model their designs. Teams Kayak and Toilet, by contrast, appeared to be engaged in the process of eliminating project ideas, which may have necessitated more antithetical utterances to examine the differences between their designs on several criteria.

Similarly, the teams may have been differentially prepared prior to their meetings, which had downstream effects on their regulation. As a case in point, Team Toilet's transcript revealed that one team member had developed the list of criteria with which to rank proposed designs and had preliminarily completed all of the comparisons and rankings on his own. He subsequently spent precious meeting time explaining to his teammates the criteria he chose and how the rankings were done, and then obtaining and incorporating their feedback into their evaluations. This approach to the task may have resulted in larger proportions of monitoring and control of understanding (MCU) as team members came to better understand the task and formed mental representations of their team members' designs.

Individual differences were another possibility for the differing proportions of RR and SSRL documented in this study. Research suggests that prior knowledge and experience with a task may account for differences in the types and depth of regulation used by teams (King, 1992; Volet et al., 2009). For example, students with more domain knowledge may be able to pose higher-level questions, which have been found to stimulate the activation and use of prior knowledge, analysis of relations, and explanation of concepts (King, 1990, 1992). Additionally, both open questions, in which information is requested, and critical questions, in which claims are challenged, have been linked to the co-construction of knowledge and group consensus-making activity (Visschers-Pleijers, Dolmans, de Leng, Wolfhagen, & Van der Vleuten, 2006). On the other hand, having less domain knowledge could also encourage more reasoning and regulation. For instance, Ball and Christensen (2009) found that teams of engineering designers at a medical plastics company used analogies to help resolve uncertainty by identifying problems, generating solutions, and explaining concepts. Accordingly, it is possible that in the present study students had different levels of knowledge and experience that either afforded or constrained specific types of reasoning and regulation.

Finally, there may have been group-level factors that influenced proportions of reasoning and regulation. Socioemotional interactions have been identified as a key contributor to team functioning and performance in CPS contexts (Jarvenoja & Jarvela, 2009; Rogat & Adams-Wiggins, 2015). Collaboration can lead to moments of positive interactions, marked by active listening, respectful exchanges, and group cohesion, as well as negative interactions such as disparaging comments, disrespect of others, and social comparison. Whereas positive socioemotional interactions may facilitate socially shared regulation by promoting communication and monitoring, supporting joint and inclusive planning, and encouraging group feedback, negative interactions may discourage participation, undermine monitoring and content understanding, and promote off-task behavior (Rogat & Linnenbrink-Garcia, 2011). Although the present study did not examine the character of students' socioemotional exchanges, there were some notable differences in how team members interacted. For instance, Nash (Team Ambulance) made consistent, concerted efforts to involve and obtain feedback from Grady and Ling, who rarely spoke. This may have promoted a more positive socioemotional climate in which everyone felt comfortable offering evaluations of ideas or monitoring their understanding. By contrast, the individuals on Team Toilet made no attempt to include Sterling, who made only 15 utterances throughout the entire meeting, and routinely discussed his ideas without involving him. These more negative interactions may have hindered group cohesion and prevented team members from effectively co-constructing knowledge.

Antinomous Reasoning and Monitoring and Control of Consensus are Key Processes involved in Collaborative Problem Solving

One finding of interest was that antinomous reasoning and monitoring and control of consensus (MCC) were present in relatively equal proportions in all of the teams' problem-solving discourse. This may suggest that the cognitive capacity to reason about the incompatibilities among ideas, and the social ability to promote awareness and facilitate cohesion are important for CPS. Indeed, theories of group learning and problem solving have emphasized that CPS requires maintaining a joint problem space (Roschelle & Teasley, 1995).

This necessarily involves setting goals, establishing shared understanding, and resolving conflicts (Scoular et al., 2017), none of which can be accomplished without monitoring team consensus (i.e., soliciting feedback, building agreement, aligning task representations). Theories of CPS also highlight the importance of analyzing problems and developing coherent task representations to begin with. Although this can be done with many forms of reasoning, antinomous reasoning may be especially important during CPS because it demands the ability to classify and organize elements of a problem (Slotta et al., 1995). In effect, antinomous reasoning entails the categorization of what something *is* by explaining what it is *not* (Alexander & DRLRL, 2012). In the present study, teams often paired antinomies with analogies and antitheses, using them to note where the similarities between ideas diverged, or explain why certain ideas ranked higher than others on certain criteria. It is unclear whether the ubiquity of antinomous reasoning and monitoring and control of consensus in team discourse would generalize to other domains or tasks, but it seems plausible that these processes would prove important in ill-defined tasks involving the comparison of ideas and the coordination of multiple perspectives.

Collaborative Problem Solving Alternates between Shared and Guided Activity

Another finding of interest was that team problem solving alternated between periods of shared and guided activity. Shared activity was characterized by relatively equal contributions from participating team members, while guided activity was led or controlled by one or two group members. Although research has found evidence of both shared and guided episodes (Lobczowski, Lyons, et al., 2020; Rogat & Adams-Wiggins, 2015), the current study was unique in being able to show *when* these episodes occurred during a problem-solving session. This cycling between periods of more tightly controlled and more collaborative activity coheres with conceptualizations of CPS rooted both in educational psychology and organizational psychology. For instance, Marks and colleagues' (2001) recurring phase model of team processes theorizes that team activity occurs in discernible and recursive cycles of *action phases,* which consist of the monitoring and coordination processes that contribute to goal accomplishment, and *transition phases*, which involve the planning, reflection, and evaluation that punctuates engagement with task. The action phases described by Marks et al. (2001) align fairly well with the shared episodes identified in the current study, in which team members often monitored their understanding of task and content and reasoned relationally about designs. The transition phases aligned well with the guided episodes, which almost exclusively featured regulatory activity such as planning and reflection.

Similarly, Roschelle and Teasley's (1995) theory of shared knowledge construction describes periods of group activity marked by a withdrawal from some participants followed by periods of intense interaction which incorporate individual insights generated in the previous period into the joint problem space (i.e., shared knowledge structure). The theories of both Marks et al. (2001) and Roschelle and Teasley, in combination with the findings of the current study, suggest that collaborative problem solving has an identifiable rhythm to it, although these rhythms may differ by group, task, and environment.

Planning and Reflection Act as Bookends to Collaborative Problem Solving, While Relational Reasoning and Monitoring Co-occur in the Interim

The analysis of teams' most frequent patterns of reasoning and regulation revealed that sequences of planning and reflection utterances were present at the beginning and the end of problem-solving sessions. In contrast, relational reasoning and monitoring co-occurred in the interim. More specifically, teams spent time at the beginning of the meeting discussing work that had been done in previous sessions and then setting goals for the current session; in the middle, they worked on the task, reasoning about the similarities and differences among designs and monitoring their progress and understanding as they pushed forward; at the end of the meeting, teams would often sum up what they had done, evaluate whether they were happy with the end product, and decide what their objectives would be for the next time.

This pattern is consistent with the framework for SSRL offered by Hadwin and colleagues, which posits that regulatory activity unfolds in loosely sequenced phases (Hadwin et al., 2011; Jarvela & Hadwin, 2013; Winne & Hadwin, 1998). These phases include task definition, goal setting and planning, enacting tactics and strategies, and adaptations to metacognition. In the context of the current study, the planning observed at the outset corresponded with the beginning phases of SSRL in which team members built a representation of the task, established goals, and devised steps to attain those goals. The relational reasoning that co-occurred in the interim could be linked to the third phase of the SSRL framework of enacting tactics and strategies. Finally, the reflection that occurred at the end (or preceded activity in the beginning), could be mapped onto the fourth phase, in which team members evaluated the success of their strategies and made modifications as necessary.

As Winne and Hadwin (1998) noted, however, these phases do not always unfold in a fixed sequence or in equal proportions. For instance, Team Baby spent a lot of time planning at the outset of the meeting, whereas Team Toilet jumped right into the task and cycled through to planning toward the middle of the meeting. Similarly, Team Ambulance engaged in planning and reflection processes in the middle of the meeting as they completed one task and set goals for the next. In this way, the results provide evidence for recursive cycles of reasoning and regulation and help to elucidate why current models stress the loosely sequential nature of these constructs.

Collaborative Problem Solving Can be Viewed at a Micro Level, Meso Level, and Macro Level

Finally, this study was able to examine team meetings at three levels of granularity, which afforded a unique set of insights into how problem solving iterates in collaborative contexts. At the most granular level, or micro level, the sequence mining algorithm identified patterns of reasoning and regulation three to six utterances in length. The sequences made it possible to see not only how reasoning and regulation intersected in real time, but also how different individuals contributed to them moment-to-moment. At the next level, or meso level, episodes illustrated the extent to which activity was shared among team members or controlled by one or two individuals as they were addressing different aspects of the task. Further, examining the temporality of shared versus guided activity shed a light on the unique rhythms of team problem-solving. Patterns of dyadic exchanges also helped illustrate which individuals emerged as more central members of their team. At the highest level, or macrolevel, it was possible to see which forms of reasoning and regulation were most prominent at the beginning, middle, and end of each meeting. Even though the most frequently occurring sequences of reasoning and regulation differed among teams, this higher-level analysis showed that there were some commonalities in when certain forms were likely to occur. With these three levels of analysis, the current study was able to provide a singular degree of nuance to the understanding of CPS processes.

Limitations

Although this study offered valuable insight into the interplay of reasoning and regulation in CPS contexts, it was constrained in several ways. First, I was not able to collect outcome data on the quality of teams' designs after the semester-long project had concluded. Consequently, I could not conclude that certain teams manifested more optimal patterns of interaction than others. In actuality, teams received feedback on their projects throughout the semester and were able to make changes to their designs at many stages. As a result, an analysis of their final product (i.e., a prototype of one design) might not have been related to their problem solving in the meeting that was observed in this study. Compounding this issue, team effectiveness has been characterized as a particularly difficult construct to measure, and psychological researchers are still struggling to define what team effectiveness is (Barrick, Stewart, Neubert, & Mount, 1998; Gorman, Grimm, & Dunbar, 2018; Hackman, 1987).

A second limitation is related to the generalizability of this study. It is unclear whether the results observed in the current study would extend to other teams, tasks, or domains. For one, because teams self-selected into the study, it is possible that there were systematic differences between the groups observed and those who chose not to participate. The groups who volunteered for the study may have been more motivated to work on their design projects or may have felt more confident in their ability to work together as a team. Indeed, course procedure allowed students to choose their teammates, meaning some individuals may have known each other, been friends, or worked together on other projects. Research has shown that working with friends on academic tasks can facilitate performance outcomes (Wentzel, Jablansky, & Scalise, 2018); thus, differences between teams observed in the present study may have been due, in part, to existing friendships between teammates or a lack thereof. A greater degree of familiarity with teammates may have also allowed for a better socioemotional climate, which may have, in turn, promoted certain types of reasoning and regulation. Interestingly, Bakhtiar and colleagues (2018) found that socioemotional interactions among group members may be impacted by a number of factors, including (a) the incoming conditions (i.e., prior knowledge, preparation, emotions) upon which individuals base their evaluations, judgments, and decisions; (b) the regulation of emotions during the planning phase; (c) the presence of negative emotions during challenging episodes; and (d) the use of encouragement and motivational statements to create a positive climate. Thus, it is possible that the teams in the present study displayed differential patterns of reasoning and regulation due to the ways in which they regulated their emotions. Future research could explore this further by employing coding schemes that deal with emotion regulation (e.g., Lobczowski, Lyons, et al., 2020), or by using random assignment to teams from the start.

Research has found that team effectiveness is also influenced somewhat by the attributes of team members (Guzzo & Dickson, 1996) and certain facets of team composition, which may have been at play in the current study. For example, individual differences such as agreeableness, cooperation, and trust tend to facilitate amicable interactions, prompt information sharing, and facilitate team coordination (Fisher, Bell, Dierdorff, & Belohlav, 2012). Team-level constructs such as collective efficacy, racial, and gender diversity have also been linked to team outcomes. Higher collective efficacy, for instance, is associated with better team performance in tasks requiring high levels of interdependence (Katz-Navon & Erez, 2005). Findings have been somewhat mixed with regard to the racial and gender balance of teams, with some work reporting that such diversity hinders performance by creating a distinction between in-groups and out-groups, which may prevent social integration and harm group functioning (O’Reilly, Caldwell, & Barnett, 1989). However, other work suggests that diversity promotes better team performance by giving teams access to a broader range of past experiences and perspectives to draw on (Bantel & Jackson, 1989).

As a case in point, Woolley and colleagues (2010) found that group collaboration is greatly improved by the presence of women in the group. Given that women are generally underrepresented in science, technology, engineering, and mathematics (STEM) fields, these findings have important implications for engineering design in particular. In the current study, two teams were entirely male-dominated, while the other two teams included one or two women apiece. It is possible that, consistent with research suggesting women can improve team performance by enhancing collaborative group processes and establishing cooperative norms (Fenwick, Graham, & Neal, 2001), the females in the current study contributed to Team Baby's openness to new design ideas or Team Ambulance's emphasis on monitoring and control of consensus. Future research that systematically assembles teams of varying levels of so-called surface-level diversity could provide further clarity on this important topic.

Beyond generalizing to other teams out of the study, it was unclear whether the patterns of reasoning and regulation observed might generalize to other tasks or domains. Although the three forms of reasoning that were most prominent in the current study (i.e., analogy, antinomy, and antithesis) have been observed in other engineering design tasks (Christensen & Schunn, 2007; Dumas & Schmidt, 2015), it is impossible to determine with certainty whether such reasoning is necessary for all engineering design tasks or whether the relation was spurious. For instance, it may have been that the engineers sampled in this study were specifically taught to employ those types of reasoning. Similarly, while high proportions of monitoring and control processes have been documented in ill-defined CPS tasks in several scientific domains (e.g., veterinary medicine, pharmacy; Khosa & Volet, 2014; Lobczowski, Lyons, et al., 2020), it is difficult to say definitely that the profile of regulation observed in this study would hold in tasks of a different difficulty. Future research must therefore strive to sample teams in a wide variety of domains completing tasks of differing levels of complexity.

An additional concern pertains to the generalizability of the coding scheme employed in this study. Indeed, a common issue in qualitative research is the reliability of codes and the extent to which results can be replicated by other researchers. In fact, I was able to successfully adapt both the RR and SSRL coding schemes of other lab groups without any noticeable problems with the reliability of any singular code. However, one phenomenon which remains somewhat underexamined in the literature is the extent to which individuals' speech patterns, or idiolect, impacts coding. For instance, the monitoring and control of consensus (MCC) code involved soliciting feedback and determining levels of understanding and agreement among team members. As such, a student asking his teammates "Do you know what I mean?" might reasonably be coded MCC. However, in coding Team Toilet's transcript, I found that one student ended almost every turn by saying, "Do you know what I mean?" In many cases, it was clear that this verbalization was more of a speech habit than a genuine attempt to ask his teammates for their level of understanding, and therefore was generally coded as task-related (TR). Thus, it seems important to advise that when performing qualitative coding, researchers must be sensitive to idiosyncratic verbal patterns and adapt coding as necessary.

A third limitation was that, in the case of SSRL, the depth of regulation was not measured. Whereas relational reasoning, by definition, implies a higher-order process, regulation has been conceptualized as having dimensions of more and less depth. Volet and colleagues (2009) describe low-level regulatory activity as an attempt to clarify basic facts, versus high-level regulatory activity as engagement in the co-construction of knowledge. Thus, it is possible that teams demonstrated different proportions of high- and low-level regulatory activity within any given form of regulation. For instance, Team Toilet's high proportion of monitoring and controlling of understanding (MCU) might have reflected their need to gather information rather than a propensity to make inferences, link ideas, or ask high-level questions. Future research that codes for the quality of regulation could therefore provide invaluable information not only about the composition of high- and low-level regulation within individuals or within a group, but also across teams. This could, in turn, help researchers clarify the link between process and product in CPS contexts.

A final limitation related to the potential conceptual overlap between RR and SSRL. As mentioned, some frameworks of SSRL consider the forms of RR as manifestations of regulation. For example, Lajoie et al. (2015) regarded analogies as an instantiation of evaluation processes, and anomalies as instantiations of monitoring. Indeed, there were utterances observed in the current study that appeared to have components of both RR and SSRL, such as when Bert, on Team Kayak, asked, "How is [the doggy paddle design] more impact resistant than a paddle float?" Bert appeared to be monitoring his understanding of the designs but also noting an antithetical relation between them. Although it was important to make clear distinctions between RR and SSRL in the current study so that the interrelations between them could be made more visible, it may be that the two are not entirely distinguishable in practice. Future research might attempt to clarify this link by allowing utterances to be double-coded, or by expanding current theoretical frameworks of reasoning and regulation.

Major Contributions

Even with the acknowledgment of its limitations, this study has extended prior research in both substantive and methodological ways. For example, to my knowledge, this is the first study to empirically explore the interplay between relational reasoning (RR) and socially shared regulation of learning (SSRL) in collaborative problem solving (CPS). Although there is research on how RR iterates in collaborative contexts (Dumas et al., 2014; Jablansky et al., 2016), it has not been meaningfully tied to regulatory activity through an analysis of team problem-solving discourse. Additionally, while those prior studies summarized patterns of RR co-occurrences in a narrative format, the current study was able to empirically and quantitatively uncover frequently occurring sequences of RR within the analysis. Similarly, there has been research on SSRL that has analyzed team discourse in collaborative learning activities, but it has often examined reasoning as an aspect of regulation, rather than as a distinct but co-occurring process. Further, this study contributes to the literature on SSRL by examining its iterations in larger groups, as opposed to two to four individuals, and within a naturalistic environment, as opposed to a computer-supported collaborative learning environment. This study was also novel in examining manifestations of RR and SSRL in the domain of mechanical engineering, and, more specifically, an engineering design task in which success is predicated on effective teamwork.

On the methodological front, through this investigation, I was able to align the conceptualizations of constructs with their measurement; that is, to use dynamic methods to capture dynamic constructs. CPS and SSRL have been theorized as dynamic in nature, but they have traditionally been studied in more static ways. However, by using a small grain size (i.e., utterances) to observe RR and SSRL, leveraging data mining techniques, and assembling compelling visualizations, the present study was able to show the dynamic and cyclical character of these critical CPS processes. Consequently, this study was able to uncover systematic co-occurrences of reasoning and regulation at three different levels. At the micro level, there were recurring sequences of reasoning and regulation occurring moment-to-moment; at the meso level, there were discernible episodes of more and less shared activity among team members; and at the macro level, there were identifiable patterns of when certain forms of reasoning and regulation co-occurred.

Implications

The present study offers implications for research and practice in the areas of RR, SSRL, and CPS in general. Regarding RR, the study provides further evidence for the proposition that there are systematic co-occurrences between different forms of RR as individuals and groups engage in problem solving (Dumas et al., 2014; Jablansky et al., 2016, 2019). However, the study may also advance theory by shedding light on the potentially critical role of antinomous reasoning when reasoning about similarities *and* differences. In previous studies, researchers have seemed to implicitly assume a division between relations of similarity and difference; the current study shows that it may be necessary to use a combination when drawing any higher-order relation between two things. This may have implications for practitioners who wish to train students or professionals how to reason relationally. Rather than teaching the forms of reasoning as separate types of relations (Kendeou, Butterfuss, Van Boekel, & O'Brien, 2017; Richland, Begolli, Simms, Frausel, & Lyons, 2017), educators may want to demonstrate how multiple forms of relational reasoning can be used in concert.

Pertaining to SSRL, the current study supports previous work demonstrating the cyclical and recursive nature of regulatory processes during CPS (Jarvela & Hadwin, 2013; Winne &

Hadwin, 1998). Although regulation did not always flow linearly, most teams began by setting plans, then monitoring their engagement with the task, and finally reflecting on their work and setting plans for the future. This study also builds on theoretical work by showing key sequences of regulatory activity that occurred within those broader phases of regulation. A case in point was monitoring and control of consensus, which accompanied planning, monitoring and control of understanding and progress, and reflection at various points during problem solving. Future research on CPS in naturalistic environments should see whether these findings generalize to other teams, tasks, and domains.

Importantly, this study was also able to integrate work on regulatory processes with work on the social sharedness of activity. With social transition plots illustrating the dyadic exchanges among team members across an entire problem-solving session, it was possible to identify not only how distributed activity was, but what manner of reasoning and regulation occurred, when it occurred, and who was responsible for these verbalizations. Researchers might consider adding a contextual dimension to current SSRL theories to address the variable nature of sharedness and the temporality of different sequences of regulatory processes.

Finally, this study offers support to theories that emphasize the cyclical nature of CPS (Marks et al., 2001; Roschelle & Teasley, 1995), underscoring the idea that different teams, tasks, and environments may demand different rhythms of problem solving. As reviewed in Chapter 2, theories of CPS range from focusing on the moment-to-moment, to the episodic, to the holistic when describing problem solving. The current study suggests that a comprehensive theory of CPS should incorporate aspects of all three, as there are nuances to be considered at each level. Accordingly, those wishing to study CPS should ensure that they adopt measures that can capture variance at different time scales. With more information about how problem solving changes over time, it may be possible to identify areas for intervention. Further, incorporating measures of individual differences with observations of CPS processes may eventually provide insight into how best to assemble a team.

In addition to potential advancements in theory, this study has several implications for educators and employers hoping to foster CPS in teams. For one, the differential portraits of each team's reasoning and regulation suggest that there may not be one optimal way to problem solve. It may be the case that there are several paths to a solution, dependent on the attitudes, behaviors, and cognitions exhibited by individuals as well as the emergent group dynamics of the team. In some ways, this finding may seem disadvantageous because it does not provide a prescriptive approach that practitioners can use to teach CPS. However, the broader patterns uncovered in this study may be more actionable. For instance, the analysis of Team Kayak revealed that the team alternated between periods of activity that were shared more and less equally among team members. Those periods in which one or two individuals dominated appeared to be key in promoting team regulation, which in turn spurred more reasoning and problem solving. For teams of college students or working professionals, it may be wise to designate someone as the team regulator—someone who will check in with everyone periodically and ensure that team members are on the same page and have completed sufficient planning and reflection to move forward. For younger students in primary or secondary school, it may be advisable for a teacher to explicitly prompt students to engage in regulation at regular intervals to facilitate problem-solving performance. Educators could also communicate to students that problem solving need not occur in a linear fashion, and that they will likely need to revise their plans a number of times before reaching a solution.

Likewise, it is impossible to prescribe one best way to reason relationally in a team setting. Further, unlike the forms of regulation—all of which appear to be present in any manner of problem solving—not all forms of reasoning may be necessary for every task. However, teachers could teach students about the forms of relational reasoning and craft exercises to have them practice it collaboratively. Additionally, educators could construct curricula that describe how to use different types of reasoning together, much like the engineers demonstrated in this study on a moment-to-moment basis. Although many students are taught how to compare and contrast with analogies and antitheses for the purposes of essays and written assignments, there may be added value in developing these skills in a verbal format within team problem-solving scenarios.

Coda

Now more than ever, individuals must be well-versed in collaborative problem solving (CPS) if they are to address the world's most pressing social, economic, and environmental concerns. However, a series of national and international reports continue to document shortcomings in this area. With no universal curricula to teach students or employees, and research distributed across different fields of study, the path forward is uncertain. Current research suggests that successful CPS involves both cognitive and social processes, including the abilities to reason relationally and regulate collective activity. The present study helps shed a light on how these processes unfold during a CPS task, including how often they occur or co-occur, which forms they take, and how different individuals contribute to them. With a better understanding of moment-to-moment changes and the global patterns displayed by these processes, researchers and practitioners alike may gain new and actionable insights into the complexities of problem solving in collaborative contexts.

Appendix

The following is a description of the data structures and algorithm used to represent and analyze a meeting transcript. It is intended to convey the main features of the actual code used. The meetings were first transcribed in Microsoft Word, then coded for speech utterances and episodes in Microsoft Excel. The programming code to analyze the meetings was written in Excel's Visual Basic for Applications (VBA). Therefore, the data structures are presented as Visual Basic code fragments. They form a complete description of the algorithm's internal representation of a meeting. These data structures can easily be translated to other programming language implementations, although small details might need to be altered to accommodate meetings that were not coded in Excel.

The description of the algorithm is written in English pseudo code with Visual Basic style references to data structures. The pseudo code is intended to convey the overall approach to creating an internal representation of a meeting, creating visualizations, and mining data sequences.

Data Structures

```
'SpeechUnit describes a single coded utterance
Type SpeechUnit
   speaker As Integer                  'Index of name of speaker in meeting
                                       teammembers array
   prevSpeaker As Integer              'Index of name of previous speaker in meeting
                                       teammembers array
   text As String                      'Text of the utterance
   SeqNum As Integer                   'Sequence number of the utterance in the
                                       meeting
   code As Integer                     'Number of the specific Code classification of
                                       the utterance
   LineNum As Integer                  'Line number of transcript
   PhraseNum As Integer                'Number of the specific phrase on this line
   Episode As Integer                  'The coded episode during which the utterance
                                       occurs
End Type

'TransciptLine is a row in the transcript with a valid speaker
Type TranscriptLine
   speaker As Integer                  'Index of name of speaker in meeting
                                       teammembers array
   text As String                      'Text of this line
   NumUtterances As Long               'Number of coded utterances on this line
   rowNum As Integer                   'Starting row number in spreadsheet of this line
   EndrowNum As Integer                'Ending row number in spreadsheet of this line
   Utterances() As SpeechUnit          'Description of each utterance
End Type

'Exception is an utterance with unexpected properties, such as a code that isn't defined
Type Exception
```

```
   Category As Integer              ‘Exception type: 1=invalid speaker, 2=invalid
                                    code, 3=all units on line ignored
   SpeakerName As String            ‘Speaker name if this is a speaker exception
   rowNum As Integer                ‘Line of transcript in which anomaly occurs
   PhraseNum As Integer             ‘Number of the specific phrase on this line
   CodeName As String               ‘Invalid Code if relevant
End Type


‘Distribution of Speech Units by TeamMembers Over Time Units (SeqNum)
Type UnitDistr
   IntervalLength As Integer        ‘Length of speech unit sequence over which
                                    bucketing occurs
   numIntervals As Integer          ‘Number of intervals in meeting
   UnitByInterval() As Integer      ‘Count of each unit by team member in each
                                    interval
End Type

‘PatternDescr provides the necessary information to analyze a particular sequence of codes
Type PatternDescr
   SeqLen As Integer                ‘Length of this sequence
   SeqNum() As Integer              ‘Beginning sequence number of pattern in this
                                    transcript
   sequenceText As String           ‘The full text of the sequence codes
   Freqency As Integer              ‘Number of times this sequence occurs in this
                                    transcript
End Type

‘UtterancePointer is a map from an utterance sequence number to the line and phrase where the
                                    utterance occurs
Type UtterancePointer
   LineNum As Integer               ‘The line number where this utterance occurs
   PhraseNum As Integer             ‘The phrase number on the line where this
                                    utterance occurs
End Type

‘Episode describes a discrete episode within a meeting
Type Episode
   StartRow As Integer              ‘Starting row of this episode in transcript
   EndRow As Integer                ‘Ending row of this episode in transcript
   StartLine As Integer             ‘Starting line of this episode in transcript
   EndLine As Integer               ‘Ending line of this episode in transcript
   StartUnit As Integer             ‘Starting unit of this episode on starting row
   EndUnit As Integer               ‘Ending unit of this episode on ending row
   EpisodeCode As String            ‘String designating type of episode (Guided or
                                    Shared)
   Person1 As String                ‘Name of person who guided meeting
   Person2 As String                ‘Name of second person who guided meeting
End Type

‘Transcription is a collection of SpeechUnits
```

```
Type Transcription
   Name As String                          'The name of this transcript object
   NumUtterances As Integer                'Number of coded utterances in the meeting
   RowOfFirstLIne As Integer               'Row number of the first line of the transcript
   TotalLines As Integer                   'Total number of lines in transcript
   Lines() As TranscriptLine               'The collection of parsed lines
   MapToLine() As UtterancePointer         'Map from an utterance sequence number to the
                                           line and phrase where the utterance occurs
   NumAnomalies As Integer                 'Number of anomalies detected
   Anomalies() As Exception                'Description of each anomalous line detected
   MaxCodesOnOneLine As Integer            'The maximum number of speech units we found
                                           on any line of the transcript
   FrequencyMatrix() As Integer            'Count of each utterance by person
   AdjacencyMatrix() As Integer            'Count of times speaker x speaks after speaker y
   MemberByUnitByTime As UnitDistr         'Distribution of Member by Unit by Time
                                           (Sequence Number)
   NumSequences As Integer                 'Number of sequences in SeqList
   NumUniqueSequences As Integer           'Number of unique sequences in SeqList
   SeqList() As PatternDescr               'List of all code sequences in the transcription
   UniqueSeqList() As PatternDescr         'List of unique code sequences in the
                                           transcription
   MaxFrequency As Integer                 'Maximum frequency of any unique sequence
   EpisodeList() As Episode                'Ordered list of episodes in this meeting
   NumberEpisodes As Integer               'Number of episodes in this meeting
End Type

'SeqParam is a set of attributes that applies to a speech unit
Type SeqParam
   code As String                          'The unique two-letter code for this type of unit
   Ignore As Boolean                       'TRUE iff code should be ignored in compressed
                                           transcript
   MapTo As String                         'Alternate code this code should be replaced
                                           with in compressed transcript
   Compress As Boolean                     'TRUE iff consecutive occurrences of this code
                                           should be ignored for the same speaker
   colorR As Integer                       'RGB red value for charts
   colorG As Integer                       'RGB green value for charts
   colorB As Integer                       'RGB blue value for charts
   codeType As Integer                     'RR=1, SSRL=2, OTHER=3
End Type

'MemberData is a collection of attributes for each team member
Type MemberData
   ActualName As String                    'Team members' actual first name
   Pseudonym As String                     'Team members' pseudonym for tables and
                                           charts
End Type

'Meeting describes a discreet team meeting
Type Meeting
```

```
   ProjectName As String                         'Name of team's project ("Kayak", "Toilet", etc.)
   TeamMembers() As MemberData                   'Name of each team member
   Transcript As Transcription                   'Raw transcript of the Meeting
   CompressedTranscript As Transcription         'Compressed and mapped transcript
   Spreadsheet As String                         'Name of spreadhseet with meeting data
   Tab As String                                 'Name of tab in spreadsheet with meeting data
   NumberMembers As Integer                      'Number of members on team
   SpeechCodes() As SeqParam                     'Array of unique speech codes coded for the meeting
   NumberOfCodes As Integer                      'Number of unique speech codes coded for the meeting
   MinSeqLen As Integer                          'Minimum sequence length for pattern mining
   MaxSeqLen As Integer                          'Maximum sequence length for pattern mining
   MaxSkippedLines As Integer                    'Maximum number of skipped lines when compressing transcript
   TotalRowsInSpreadsheet As Integer             'Ending Row of meeting spreadsheet
End Type
```

Algorithm to Analyze Meeting

<u>Initialize Parameters</u>

Allocate a Meeting structure called "thisMeeting"

Read Input Parameters
- Name of spreadsheet with coded transcript
- Populate *thisMeeting.SpeechCodes*
    - Read list of RR, SSRL, and other utterance codes ("AG", "AM", "AN", "AT", "PL", "MCU", "MCC", "MCP", "OT", "IN", "RE", "TR", "UN")
        - For each code
            - Should code be ignored in processing the meeting?
            - Should code be mapped to a different code
            - Should consecutive occurrences of code for same speaker be compressed to one instance?
    - Read minimum and maximum sequence lengths for data mining

<u>Parse Transcript and Build Representation of Meeting</u>

Open spreadsheet with coded transcript

Parse spreadsheet and find the names of each team member who speaks
- Assign a pseudonym for each team member

Populate the data structure *thisMeeting.Transcript*
- Populate the data structure *thisMeeting.Transcript.Lines*
    - For each line k in written transcript…
        - Store the speaker, text of line, number of coded utterances

Populate *thisMeeting.Transcript.Lines.Utterances* with details of each coded utterance

Create a compressed transcript starting with *thisMeeting.Transcript* and using the input parameters as a guide
For each line k in *thisMeeting.Transcript.Lines*…
For each coded unit u in k…
If u is unequal to previous unit, then add u to *thisMeeting.CompressedTranscript*

Populate *thisMeeting.CompressedTranscript.EpisodeList* by building a map of when (what line and unit within the line in *thisMeeting.CompressedTranscript*) episodes occur

Graph each utterance in *thisMeeting.CompressedTranscript*
Arrange team members along the vertical axis with values:
Team member 1 = 1, team member 2 = 2, etc.
For u = 1 to *thisMeeting.CompressedTranscript.NumUtterances*
Plot a data point such that
The x-axis value equals u
The y-axis value equals *thisMeeting.CompressedTranscript.Lines.Utterances(u).speaker*
The color of the data point is given by
RGB(
thisMeeting.SpeechCodes(thisMeeting.CompressedTranscript.Lines.Utterances(u).code).colorR,
thisMeeting.SpeechCodes(thisMeeting.CompressedTranscript.Lines.Utterances(u).code).colorG,
thisMeeting.SpeechCodes(thisMeeting.CompressedTranscript.Lines.Utterances(u).code).colorB
)
Each point is connected by a line to the next point

<u>Analyze Episodes</u>

Calculate a frequency matrix describing how many times each team member utters each type of coded speech in each episode

Calculate an adjacency matrix specifying how many times each team member speaks directly after each other member in each episode

Chart dyadic relationships
For each episode…
Arrange data points along a circle
Each data point represents a team member
Use a square to represent the members, if any, who guided the episode
Use a circle to represent the members who did not guide the episode

For each team member, m_i…
For each team member, $m_j, i \neq j$,…
Draw an arrow from m_i to m_j with the following attributes:
The width of the arrow represents the number of times m_i spoke to m_j

The color of the arrow represents the type of utterance (RR, SSRL, or task-related or other)

<u>Perform Data Mining</u>

For *s* = minimum sequence length to maximum sequence length…

For *i* = first code in transcript to (last code in transcript – minimum sequence length + 1)

Add sequence {*code i* -> *code i+1* -> … -> *code i+s-1*} to list of all sequences

Sort list of all sequences by sequence codes

Count frequency of occurrence of each unique sequence, remove duplicates, and keep a list of where in the meeting each sequence occurs

Sort remaining unique sequences by frequency in descending order and print list of sequences

End Algorithm

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