Orchestrating Combined Collaborative and Individual Learning in the Classroom

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Abstract

In the classroom, teachers make use of different combinations of social planes (e.g., individual, collaborative) to support learning. However, little is known about the complementary strengths of individual and collaborative learning or how to combine them so that they are more effective than either social plane alone. One roadblock to this investigation is an ability to orchestrate, or manage, more complex, but theoretically effective, combinations of collaborative and individual learning in the classroom. Prior research has created orchestration tools that support the planning and real-time management of classroom activities, which reduces the cognitive load and time needed for instructors to support the activity, allowing for more complex activities to become more manageable. Current orchestration tools do not, however, support a wide range of combinations of collaborative and individual learning activities in a flexible manner. To fully investigate the combinations of collaborative and individual learning, orchestration tools need to be developed that can support the researcher in a way that can be integrated into the classroom by accounting for teachers' values.

My thesis work addresses two related goals. First, my work addresses the questions: Do collaborative and individual learning have complementary strengths and is a combination of the two social planes better than either alone? In my work, I developed an intelligent tutoring system (ITS) to support collaborative and individual learning. Through three studies, using this ITS, with over 500 4th and 5th grade students, I demonstrate that a collaborative ITS can be used to effectively support learning with elementary school students and that a combination of collaborative and individual learning is more effective than either alone. However, my studies did not find any support for complementary strengths and many other combinations of social planes are left to investigate. Additionally, during my experiments, I encountered challenges in orchestration that, along with the need to research more complex combinations of collaborative and individual learning, informed the next steps of my research.

The second question my thesis work addresses is: How does an orchestration tool that supports researchers in exploring this space need to be designed to align with teachers' values for easy integration in the classroom? Specifically, I aimed to support fluid transitions between social planes where students do not all have to be working in sync, which is not currently supported in existing orchestration tools. To support the orchestration tool design, I present a framework that structures the space that a researcher can explore when combining individual and collaborative learning. The framework can act as the set of requirements to be met in the orchestration tool from the point of the researcher as well as a lens to analyze and design combined social plane activities. As a first step towards supporting fluid transitions as laid out in the framework, I present a set of statistical models that extend domain-level individual modeling into the space of collaborative environments. Finally, I developed an orchestration prototype built around my framework that can be used as a research tool to further explore combined collaborative and individual spaces. To develop the tool to be successful within the classroom, I worked with teachers through a co-design process and validation of the prototype to incorporate their values into the tool.

Taken together, my dissertation has six primary contributions. My dissertation contributes to the learning sciences through advancing our knowledge of (1) the strengths of collaborative and individual learning, although I did not find any complementary strengths, and (2) if a combination is better than either alone, which I did find support for. It contributes to educational technology through (3) the design of an effective ITS that supports collaborative and individual learning for fractions and educational data mining through (4) the advancement of models that can more accurately predict individual learning within a collaborative setting than the existing individual models. Finally, it contributes to computer supported collaborative learning and human-computer interaction through (5) a framework, which provides a lens for designing and analyzing combined collaborative and individual learning spaces, and (6) an orchestration prototype that supports fluid transitions between social planes in a way that can be a useful to both researchers and teachers in the classroom.

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1 Introduction

When designing a learning activity, there are trillions of paths that could be followed within the instructional design space and it is important to limit the choices based upon the learning goals of the activity (Koedinger, Booth, & Klahr, 2013). The social plane (i.e., whole class, group, individual) that students will be working within during the learning activity is one such choice. While often being an afterthought or a constraint of available resources or space, different social planes, and the learning processes that they elicit, should instead be considered an additional resource that can help to promote the learning of target skills (Koedinger, Corbett, & Perfetti, 2012). To be able to effectively take advantage of multiple social planes when designing a learning activity, it is important to have an understanding of when collaborative and individual learning would be effective and in what combinations. Currently, it can be a struggle to investigate a combination of collaborative and individual learning in the classroom because there is not the support to easily design and manage the learning activities in real-time. For researchers to be able to investigate a range of combined collaborative and individual learning designs, we need tools that can support these investigations in a way that can be orchestrated and used in a classroom by teachers. Without considering the needs of the teacher, the tool will not fit into the classroom environment, which can cause artificial scenarios and lower the ecological validity. Additionally, by designing with the values of the teacher in mind, the tool can also be used by the teachers to support learning activities.

Research in education has demonstrated the strength of using collaborative learning within the classroom. Computer Supported Collaborative Learning (CSCL) has had a history of investigating how we can better support collaborative instances for improved student learning (Lou, Abrami, & d'Apollonia, 2001; Lou, Abrami, Spence, Poulsen, Chambers, & d'Apollonia, 1996). Collaboration is supported through the use of scripts that can be static (Fischer, Kollar, Stegmann, Wecker, Zottmann, & Weinberger, 2013), adaptive (Magnisalis, Demetriadis, & Karakostas, 2011; Rummel et al., 2008), or integrative (i.e., scripts that incorporate multiple social planes) (Dillenbourg, 2004; Dillenbourg & Tchounikine, 2007). There has been significant progress made towards supporting collaborative learning and understanding the processes that student engage in while collaborating (Chi & Wylie, 2014). However, there has been less research on what the strengths of collaborative and individual learning are, so that we can better use them within the learning process. Additionally, although integrative scripts within CSCL have taken advantage of multiple social planes, there has been little research into if these combinations are actually better than either social plane alone. Before we can efficiently use combinations of collaborative and individual learning within the classroom, it is important that we can address these questions as to their strengths and how best to combine them, which is one goal of my research.

Before the theoretical question of when it would be most productive for students to be working in different social planes can be fully explored, more support is needed for researchers to be able to orchestrate their learning designs within the classroom. When putting technology in the classroom, it is important to not only consider what the researchers' needs are but also how this would fit into the context of teachers' needs. If the technology does not support the teacher's classroom values, it will not be used by the teacher in the classroom and when used, will not be as effective because it does not align with classroom expectations. In recent years, there has been an increased focus on providing technology that is teacher-centric through the use of teacher dashboards and orchestration systems (Prieto, Dlab, Gutiérrez, Abdulwahed, & Balid, 2011; Verbert et al., 2014). These systems support the teachers in the implementation, running, and monitoring of the classroom through the use of technology to lower their cognitive load and more effectively identify students that need support so that teachers can spend more time teaching and supporting the learning process. Specifically, in terms of supporting multiple social planes within the classroom, research into the development and support of orchestration systems has recently gained popularity. Orchestration systems can support the design of the learning activity, the adaption and planning of the activity for a specific class, and the real-time management of that activity

(Dellatola & Daradoumis, 2014; Kollar & Fischer, 2013; Prieto et al., 2011). Using an orchestration system, support can be provided to the teacher or researcher for the management of an activity that allows them to engage in more complex learning scenarios that may not have otherwise been possible. Current orchestration tools often focus on providing support for current classroom procedures to make them more efficient and to provide better monitoring (Prieto et al., 2011) rather than extending support to allow for more complex learning designs. To be able to fully explore the space of how collaborative and individual learning can effectively be combined, we need to develop more robust tools and orchestration systems that allow for more complex transitions between social planes. For the tool to be used by researchers, the research space needs to be considered and used to guide the design. For the tool to be effective and integrated into use in the classroom, the needs and values of the teacher need to be considered. Even if the tool can support the needs of the researcher, if the support does not fit into the classroom, it will not be ecologically valid and will never be used outside of formal research. In addition to investigating the support of student learning using collaborative and individual learning, within my work, my second goal is to enable new forms of learning activities in the classroom by finding a balance between teacher autonomy and system automation that can be used to further investigate the use of collaborative and individual learning.

In the classroom, students starting or transitioning between social planes can be challenging, especially if students are not all working in sync within the class. In my research, I am specifically interested in supporting these fluid transitions between social planes as they are individualized to student needs. In other words, I want to support students transitioning between different social planes asynchronously based upon their pace between activity phases or adapting to their individual needs within an activity phase. When transitions are synchronous across the class, we lose some of the flexibility in being able to support individualized student learning. Students are forced to go at the same pace regardless of their skill level. Additionally, supporting fluid transitions allows for the social plane to be adapted to student needs rather than just being part of the activity structure. Although there are many other aspects that are important components of classroom orchestration, the transitions between social planes can be particularly complex. As part of this process, we need to have a better understanding of the feature space for combining collaborative and individual learning as well as effective student models for individual learning in a collaborative setting as these models are currently limited to individual learning (Cen, Koedinger, & Junker, 2007; Corbett & Anderson, 1995; Pavlik et al., 2009).

Taken together, the contributions of my work fall into six categories across two main themes. First, I investigate the use of an intelligent tutoring system (ITS) for supporting collaborative and individual learning for young students. As part of this process, (1) I developed and tested a successful tutoring system for learning fractions. The tutoring system supports learning across both individual and collaborative social modes across three different problem types. My tutoring system extends the work of current ITSs to support collaborative learning for elementary school students. Using these ITSs, (2) I investigate the complementary strengths of collaborative and individual learning, which begins to address the gap of why some previous research has found collaborative learning to be more effective than individual while others have found the opposite (Lou et al., 2001). Additionally, (3) I investigate whether a combination of collaborative and individual learning is more effective than either alone. Although integrative scripts (Dillenbourg, 2004; Dillenbourg & Tchounikine, 2007) combine different social planes, they have not explored how a single social plane alone compares to a combination. Within these studies, I encountered external challenges in orchestrating the different learning designs in the classroom in terms of creating new pairs of students when students were absent of left early. These challenges, along with the lack of real-time support for managing more complex theoretical designs in combining collaborative and individual learning, led me to the second theme of my work.

The second theme of my contributions involves developing an understanding of the needs and constraints when designing an orchestration tool that supports researchers in investigating the combined collaborative and individual learning space in the context of the classroom. To develop a tool that can be used to investigate the range of theoretical questions that researchers may have within this space, the dimensions that can be manipulated to combined collaborative and individual learning must first be understood. In my work, (4) I present a framework that defines the dimensions to be considered when designing a collaborative and individual learning activity that can be used to advise the design of an orchestration tool to support researchers, as I do in my research. Additionally, this framework provides both guidelines in how to design a combined learning environment as well as a way to categorize and compare current learning environments. To begin the process of supporting the adaptation of social planes to student needs through fluid transitions, (5) I also present new student models for individual learning in a collaborative learning environment. These models extend current individual student models to account for collaborative features. The models are an initial step towards being able to track student learning across social planes to be able to provide adaptations to student needs. Finally, (6) I developed an orchestration tool prototype that supports researchers in investigating the combination of collaborative and individual learning in the context of a classroom. For this tool to be effective in the classroom, it must meet the needs of both the researcher and the teacher. By meeting both of their needs, the tool can be useful as a research platform that is ecologically valid and can be used by teachers in their every day classroom activities. As part of the design process, I conducted co-design sessions with teachers to investigate how to balance teacher autonomy and system automation for learning activities that include fluid transitions. I then developed and validated my orchestration prototype to meet the needs of the teacher as specified through the co-design sessions, the researcher as presented through my framework, and the challenges encountered in my previous studies. My orchestration tool adds to the current orchestration literature by both extending support to activities that do not have all students in the same state at the same time as well as exploring the boundaries of automation within the orchestration tool. The two themes of my contributions are not separate but can be taken together to contribute to and advance the research agenda into how we can best integrate collaborative and individual social planes into the classroom to support student learning.

1.1 Theoretical Framing

Within this chapter, I will present the theoretical framing for my dissertation work. Because of the breadth of the work, I will provide an in depth look into the current state of the art research and technology in subsequent chapters.

Collaboration is often used in the classroom in some capacity, and research has shown it to be beneficial for student learning (Lou et al., 2001; Slavin, 1996). However, when comparing collaborative and individual learning, *collaboration has not always been found to be more productive* for learning gains compared to individual learning (Lou et al., 2001). Part of this explanation is that students need to receive the correct collaborative support for their current knowledge (Dillenbourg, 2002). Collaboration does not occur spontaneously (Kollar, Fischer, & Hess, 2006) and support is needed to guide students in productive collaborative interactions. However, if students already have internalized productive collaboration moves, it is possible to provide too much support, which can stifle the collaboration. If the collaboration support is not appropriate for the students, they may not effectively collaborative and will have lower than expected learning gains (Dillenbourg & Tchounikine, 2007).

CSCL research has partially addressed the discrepancy in results when comparing collaborative and individual learning through improving the support for collaborative learning by implementing more adaptive support for collaboration. There are many different ways of implementing this adaptation by considering what assistance is needed, when should it be given, in what quantities, and how should the adaptation take place (Kapur & Rummel, 2009). Within collaborative learning, adapting to student needs by fading support over the course of a session has been beneficial to students (Rummel et al., 2008) as has adapting to the students' characteristics and current interactions (Demetriadis & Karakostas, 2008; Gogoulou, Gouli, & Grigoriadou, 2003; Karakostas & Demetriadis, 2011a; Paramythis, 2008). In terms of learning domain knowledge, research suggests that adaptable scripts are more successful than their fixed counterparts (Karakostas & Demetriadis, 2011b; Kumar, Rose, Wang, Joshi, & Robinson, 2007; Tsovaltzi, Melis, McLaren, Meyer, Dietrich, & Goguadze, 2010). In addition, students who were in adaptive conditions tended to enjoy working in the learning environment more (Tsovaltzi et al., 2010) and reduced unwanted actions while increasing elaborations (Diziol, Walker, Rummel, & Koedinger, 2010). These studies have shown that adapting to students' needs by providing conversational agents that adapt to student chats (Kumar et al., 2007), fading collaboration scripts (Beers, Boshuizen, Kirschner, & Gijselaers, 2005), or adapting prompts to student actions (Diziol et al., 2010) can be effective both for the students' learning as well as for supporting productive learning processes. However, these studies have not yet considered adapting the social plane that students are working in to more effectively support learning. Even when collaborative learning is well supported, students working collaboratively still may not have higher learning gains than those working individually. When students engage in collaborative and individual learning, they tend to engage in different learning processes (Chi & Wylie, 2014; Koedinger et al., 2012), which may have different strengths and be more conducive to learning different types of skills. Few studies have investigated the complementary strengths of collaborative and individual learning to help explain the differences found between learning results across studies (Diziol, Rummel, & Spada, 2009; Mullins, Rummel, & Spada, 2011) and how they can best be combined and adapted to support learning.

Collaborative and individual learning are often combined in the classroom, but it is not clear if this *combination is more effective than either alone*. Within CSCL research, collaborative support that combines social planes across phases of an activity is known as integrative scripting (Dillenbourg, 2004; Dillenbourg & Tchounikine, 2007). Different phases of an activity within integrative scripts are intended to complement each other to support the learning of the domain material. There is a flow between each of the phases; the output from one phase is used as input to the next (Dillenbourg, 2004). Many well-known collaboration scripts (e.g., Jigsaw and ArgueGraph) use the individual phases to prepare students for a productive collaboration phase (Dillenbourg, 2002; Diziol, Rummel, Spada, & McLaren, 2007). Other designs, such as productive failure, allow students to work collaboratively or independently on complex problems to prime them for a whole class direction instruction (Kapur, 2010; Kapur, 2014). Although there are many learning designs that compare a combination of collaborative and individual learning, very few have compared these to working in either social plane alone or how to best combine these social planes. It is still an open question of how collaborative and individual learning can be effectively combined compared to either social plane alone. My research addresses this gap by investigating the complementary strengths of collaborative and individual learning and how these can be effectively combined. When considering how to combine collaborative and individual learning, the combinations can range in complexity. To allow for the research of more complex designs, we first need to develop the support needed to correctly conduct these designs in a way that teachers are able to use them in the classroom and with enough flexibility for researchers to investigate the learning space. Before bringing collaboration into the classroom, it is important to consider what the goals of the collaboration are. Within the literature, there are different theoretical framings for why collaboration is effective for learning, which can impact how the collaboration is implemented and supported in the classroom and in research (Jeong, Hmelo-Silver, & Yu, 2014). Within my work, I take an individual cognitive approach to collaboration, in which collaboration is used to enhance the individual learning process. This approach aligns with how collaboration is often used in the classroom, where students are encouraged to work with other students so that they are exposed to additional thought processes. By grounding my work in an individual cognitive approach, I can build upon individual learning techniques and technologies, such as ITSs.

Implementing intricate ways of using multiple social planes within a learning activity is very challenging and technology can provide the *support needed to the teacher within the classroom* for an activity to be managed in a way in which it can be successful. Within the classroom, a teacher needs to keep track of multiple factors during any learning activity. On top of providing students with the cognitive support needed to learn the domain knowledge, teachers need to keep track of time, where students are in the activity, and maintain a level of discipline in the classroom. Classrooms also introduce external constraints (e.g., student drop out, absenteeism, behavioral issues) to learning activities, which neither teachers nor researchers have control over and impact the activity design. This creates a high cognitive load for the teachers to regulate, which can make it difficult to support students when they need help. This information load is even higher when a teacher is regulating multiple small groups or students are transitioning between social planes (Van Leeuwen, Janssen, Erkens, & Brekelmans, 2015b). Teachers need to have support that will allow them to have time to recognize issues and intervene when necessary (Van Es & Sherin, 2002). In addition, the support needs to be flexible enough so that it can change with the needs of the lessons and groups (Van Leeuwen, Janssen, Erkens, & Brekelmans, 2013).

Within the field of learning analytics, there has been an effort to support teachers real-time in the classroom (Vatrapu, Teplovs, Fujita, & Bull, 2011). This support can be provided through either *orchestration tools* or *teacher dashboards* (and often a combination of both). Dashboards aggregate student data to a manageable level to reduce information overload and have become a popular tool (Van Leeuwen, 2015). Within a CSCL setting, this support often focuses on either social aspects of the activity or cognitive aspects of the activity. The cognitive support can range from providing an overview of the tasks completed (Charleer, Santos, Klerkx, & Duval, 2014; Van Leeuwen, Janssen, Erkens, & Brekelmans, 2015a) to displaying artifacts created during the work process to show the concepts that the students are addressing (Van Leeuwen et al., 2015a). These different displays can help teachers to identify which students are struggling and to provide more support. When students are working in groups, social support can also be introduced. Like the cognitive support, the tools that have been developed for social support also focus on displaying student data for teacher interpretation (Rayón, Guenaga, & Núñez, 2014; Van Leeuwen, Janssen, Erkens, & Brekelmans, 2014). The social aspects that are often displayed are around participation and discussion including student patterns. Both the cognitive and social tools have shown that providing support to the teacher can help increase their confidence in supporting their students (Van Leeuwen, 2015). Although dashboards have shown the success of using real-time data to support teachers in the classroom, they do not address any of the classroom management aspects of an activity. Using the dashboard, the teacher is able to monitor their students and provide adaptive support based on student needs. However, this adaptation can still be cumbersome, as it is not supported by the system.

Classroom orchestration tools address this gap by supporting teachers with the management and adaptation of classroom activities. Orchestration, in the widest definition, entails the design of the learning activity, the adaption and planning of the activity for a specific class, and the real-time management of that activity (Dellatola & Daradoumis, 2014; Kollar & Fischer, 2013; Prieto et al., 2011). This definition encompasses activities that happen both inside and outside of the classroom. For an activity to run successfully in real-time, it needs to have been successfully planned as well as have enough support for it to be successfully executed within the constraints and changes of the real classroom. Technology can help with this orchestration by making decisions in the planning process more visible and by supporting the regulation and management of the activity, the awareness and monitoring of the activity, and the adaptation of the activity to intrinsic constraints (e.g., student characteristics, domain content) and extrinsic constraints (e.g., time, discipline, extraneous events) in real-time (Dellatola & Daradoumis, 2014; Dillenbourg, 2013; Prieto et al., 2011).

Within CSCL literature, the support of classroom orchestration has been approached from many different angles (more detail provided in Chapter 7). One approach has been to enhance classroom activities through augmented reality (Cuendet, Bonnard, Kaplan, & Dillenbourg, 2011; Munoz-Cristobal et al., 2013; Munoz-Cristobal et al., 2015). For example, Munoz-Cristobal et al. (2013, 2015) developed a tool uses adapters to allow virtual artifacts to be accessed from both virtual and physical spaces. These systems are not intended to change the flow of the activity in the classroom, but instead to enhance what is already being done in the classroom by integrating technology that allows interactions to happen in different ways and spaces.

In contrast to systems that are designed to align with the physical world, other systems focus on centralizing tools within a workbench, which is a centralized space where multiple tools can be accessed (Phiri, Meinel, & Suleman, 2016; Prieto et al., 2014). These tools are designed to allow for easier management of activities that use multiple platforms. In addition, these tools allow for the teacher to be able to implement activity management, including sequencing and time management, all within a single location that can more easily be adapted at run-time. To be able to help support teachers in knowing when adaptation needs to happen, some systems focus on monitoring of the classroom and students (Looi & Song, 2013; Martinez-Maldonado, Clayphan, & Kay, 2015; Raca & Dillenbourg, 2013; Wang, Tchounikine, & Quignard, 2015a). Unlike the centralized workbenches, these systems are much more like teacher dashboards in that they record student data, such as attention, progress, participation, and student artifacts that can be reported to the teacher. This aggregated view allows the teacher to more easily monitor the classroom and to adapt or intervene when needed.

The last set of systems is focused on providing support for classroom activities through connecting students and teachers across devices (e.g., tablets, tabletops) (Manathunga et al., 2015; Martinez-Maldonado et al., 2013; Sharples, 2013). Like the augmented reality systems, these systems are designed to use devices that are already used in the classroom. This allows the teacher to more easily distribute tasks and information for the activity to the class and to have some control over the timing and pacing in the classroom.

Although all of these systems approach the managing of real-time orchestration within the classroom in different ways, when they are supporting transitions between social planes, they are supporting them synchronously for the entire class. Although from a management standpoint it is practical to have all students transition between social planes at the same time, in reality, students work at different paces and come into each lesson with different needs. To be able to investigate how fluid transitions impact student learning, we need to have tools that can support these fluid transitions between social planes otherwise they may cause too much cognitive load to be effective within the classroom. This fluidity in social planes is something that has not currently been implemented in the classroom to the best of my knowledge or within research as there is not currently a tool that can help to support the orchestration of these types of transitions at the classroom level. Within my research, I aim to address this gap through the development of an orchestration prototype that has been developed as a teacher-centric tool that can also be used by researchers for further exploration of collaborative and individual learning space.

In addition to providing a way for teachers and researchers to orchestrate a combined collaborative and individual activity in the classroom, for the system to support fluid transitions between social planes that adapt to student needs, advances in *student modeling* are needed. To better detect when collaborative and individual learning would be beneficial, it is important to be able to model and predict individual learning within these different social planes. Statistical models for assessing individual students' knowledge as it is influenced by collaboration are lacking (von Davier & Halpin, 2013), however, within the field of computer-supported collaborative learning. A number of models have been developed to assess the learning of students working individually (Cen et al., 2007; Zhang, Mostow, & Beck, 2007). These models are widely used in intelligent tutoring systems research and development. Intelligent tutoring systems are computer-based learning environments that provide individualized step-by-step support for students and adapt to student learning in various ways (Corbett, McLaughlin, & Scarpinatto, 2000). Statistical models are used extensively in the offline analysis of log data to yield scientific insight into learning with intelligent tutoring systems and to improve existing systems (e.g., Aleven & Koedinger, 2013). Online, they are used to adapt tutoring systems to individual students' learning, for example, to help students attain mastery on a set of targeted skills (Corbett et al., 2000). However, similar statistical models have not been applied and adapted to modeling collaborative learning. By having better models of individual learning within collaborative environments, we can better evaluate the success of a particular learning design as well as provide more effective instruction to students as we are able to adapt to their learning needs through the use of social planes. It is still an open question of how we can extend statistical models of individual learning to account for learning that occurs in a collaborative environment. Within my work, I aim to take these first steps of extending statistical models to include features of collaborative environments for more accurate learning predictions. These extended models would be able to provide better adaptation and support for the use of collaborative and individual learning within the classroom.

1.2 Summary and Research Questions

Although collaborative learning is already used within many classrooms, there is still a barrier to having students engage in collaborative sessions when it may take time away from domain learning without much benefit. It is therefore important to understand when collaborative and individual learning may be most beneficial and how they can be combined. Although current research has strived towards understanding both how we can support collaborative learning (Soller, Martinez, Jermann, & Muehlenbrock, 2005) and the processes that students engage in that make collaborative learning effective (Hausmann, Chi, & Roy, 2004), there is less work on how collaborative and individual learning may support different processes that fulfill different needs within the learning process. To more effectively support learning, the complementary strengths, if any, of collaborative and individual learning should be understood. Additionally, when collaborative and individual learning have been combined, they have often not been compared to either social plane alone to investigate if there are benefits to the combination. For researchers to fully explore the possible space of ways to combine collaborative and individual learning, we need to have tools that allow and support more fluidity between social planes within the classroom. Current orchestration tools are developed to often support the class moving through the activity as a whole (Looi & Song, 2013; Martinez-Maldonado et al., 2015; Mercier, 2016; Wang et al., 2015a). In reality, students work at different paces and may need different support at different times, which requires the ability for teachers to orchestrate an activity where the students may not all be in the same state at the same time. By creating a tool that is useable within the classroom and allows for fluidity between social planes, researchers can more easily investigate the benefits of collaborative and individual learning. To investigate this space, I aimed to address six main research questions through my research across two themes.

First, as part of my research, I developed ITSs to support both collaborative and individual learning extending literature on the feasibility of supporting collaborative learning through an ITS (see Chapter 2). This ITS was both a research platform as well as an outcome of my research as it provides a set of collaborative ITSs that can be used within the classroom to support fractions learning. My ITS extends support for fractions learning from mainly individual support to include collaborative support.

Next, I explore if collaborative and individual learning have any complementary strengths (see Chapter 3) and how we can effectively combine them within an ITS (see Chapter 4) adding to the CSCL literature (Olsen, Aleven, & Rummel, 2015; Olsen, Belenky, Aleven, & Rummel, 2014; Olsen, Rummel, & Aleven, 2015; Olsen, Rummel, & Aleven, 2016; Olsen, Rummel, & Aleven, 2017). To address these research questions, I conducted a series of three experiments in the classroom and a pull-out setting with over 500 students. These experiments served to investigate the research questions pertaining to the use of collaborative ITSs with elementary school students, if collaborative and individual learning have complementary strengths, and if a combination of collaborative and individual learning are better than either alone. Within these experiments, I also encountered challenges in orchestrating the collaborative and individual learning activities within the classroom. These challenges, along with the need for better orchestration support to research more complex combinations of collaborative and individual learning, informed the next steps of my research in developing an orchestration tool prototype.

My research presents a framework for the design aspects that need to be considered in a combined collaborative and individual environment (see Chapter 5). The framework lays out the space that a researcher can explore when combining individual and collaborative learning and the dimensions that they may want to adjust to investigate how best to combine collaborative and individual learning. For an orchestration tool to meet the needs of the researcher, the dimensions laid out within the framework need to be accounted for.

Next, to allow for fluid transitions between social planes by adapting collaborative and individual learning to student needs, we need better ways of modeling student learning across social planes. Specifically, I aim to address how we can model individual learning in a collaborative environment, which adds to the educational data mining (EDM) literature (see Chapter 6) (Olsen, Aleven, & Rummel, 2015; Olsen, Aleven, & Rummel, 2016; Olsen, Aleven, & Rummel, 2017). Using tutor log data collected through my student experiments, I modified existing statistical models that predict student learning to take into account aspects of the collaboration. These models provide a more accurate prediction of learning for students when working collaboratively than using models developed for individual learning. These models begin the conversation about how to track student learning across collaborative and individual tasks to allow for better adaptation of social planes to student needs, which opens up the design space of combining collaborative and individual learning.

Finally, I developed a prototype of an orchestration tool that focuses on supporting the fluidity between social planes in a way that it beneficial for teacher use in the classroom but can also be used as a research tool to further explore how collaborative and individual learning can best be combine (see Chapter 7). The goal for my orchestration tool would be to support researchers in investigating combinations of collaborative and individual learning in a way that would fit into the context of existing classrooms by meeting the needs of teachers. To address this goal, I conducted a series of co-design session with teachers to better understand what their needs are within the classroom when managing collaborative and individual learning. These co-design sessions, and the subsequent orchestration tool, accounted for the needs of the researcher by using my framework as a guideline for their design needs. I then validated the orchestration prototype with teachers to better understand how it supported their underlying needs within the classroom and how the prototype aligned with the needs of the researcher to investigate the use of collaborative and individual learning.

Together, my research contributes to the learning sciences through advancing our knowledge of the strengths of collaborative and individual learning and how they can best be combined, educational technology through the design of an effective ITS that supports collaborative and individual learning for fractions, educational data mining through models that can more accurately predict individual learning within a collaborative setting than the existing individual models, and computer supported collaborative learning and human-computer interaction through a framework and subsequent prototype that supports the design space for combining collaborative and individual learning and extends this space to support the orchestration of fluid transitions between social planes.

2 Collaborative and Individual Intelligent Tutoring Systems

Within my work, I supported student learning through ITSs. Although most prior research on ITSs has focused on students working individually (Steenbergen-Hu & Cooper, 2013), there has been some work combining ITSs and collaboration with high school students (Baghaei, Mitrovic, & Irwin, 2007; Diziol, Walker, Rummel, & Koedinger, 2010; Walker, Rummel, & Koedinger, 2009). Walker et al. (2009) found that students working with a tutor that had been redesigned to support peer tutoring (i.e., the tutoring system provided support to the student in the role of the peer tutor) achieved learning gains at least equivalent to those working individually, demonstrating that collaboration can be successfully combined with ITSs. ITSs are developed to support cognitive processes through step-by-step support through error feedback and on demand hints (VanLehn, 2011). By adding collaboration (through collaborations scripts) to an ITS, we can effectively provide both cognitive and social support. However, much of this work has been done with secondary and college students rather than elementary school students. The support needed for students in elementary school may greatly differ than that needed for older students. Therefore, it is important to investigate how collaborative ITSs can be extended for use with younger students.

Work within the ITS field has been shown to be able to successfully support student learning across multiple domains (Murray, 2003) and specifically within mathematics (Koedinger, Anderson, Hadley, & Mark, 1997; Kulik & Fletcher, 2015; Ma, Adesope, Nesbit, & Liu, 2014; Ritter, Anderson, Koedinger, & Corbett, 2007; VanLehn, 2011). This benefit to learning has not just been displayed within a lab setting, but within large-scale classroom experiments (Koedinger et al., 1997; Pane, Griffin, McCaffrey, & Karam, 2013). Within previous research, ITSs have been found to improve learning by as much as one standard deviation (Anderson, Boyle, Corbett, & Lewis, 1990; Corbett & Anderson, 1991; Koedinger & Anderson, 1993). ITSs may be successful through their ability to create an individualized learning environment for each student. ITSs are able to flexibly adapt to student needs allowing students to work towards skill mastery (VanLehn, 2006). This adaption comes in the form of cognitive support for students as they work through problem solving. An ITS is able to provide step-level guidance for problem solving using error feedback and on-demand hints (VanLehn, 2006), which can be adapted to the cognitive misconceptions that the student is encountering. In addition, the tutors provide cognitive support by modeling the student's proficiency on skills and choosing problems that will target skills for which the student has not yet obtained mastery. These features of an ITS allow the system to support students in their individualized learning based on each student's needs.

With younger audiences, ITSs have been found to be very successful in supporting fractions (Patel, Liu, & Koedinger, 2016; Rau, Aleven, Rummel, & Rohrbach, 2012; Weise & Koedinger, 2014). Although the majority of research conducted with ITSs has been done with students in secondary school or older, there are many studies that have also focused on elementary school students and found learning benefits (Liu, Patel, & Koedinger, 2016; MacLellan, Harpstead, Patel, & Koedinger, 2016; Rau, Aleven, & Rummel, 2014; Rau, Aleven, Rummel, & Pardos, 2014; Steenbergen-Hu & Cooper, 2013). These studies show that ITSs can be beneficial across a wide age range. Within the younger age range, fractions are a very important building block to higher order math skills that is being taught (Siegler et al., 2012). Yet students in both elementary school and middle school tend to struggle with the understanding of fractions (Kaminski, 2002; Person, Berenson, & Greenspon, 2004). Fractions are often the point where math stops making sense to students (Moss, 2005). Learning fractions requires students to be able to apply skills that were learned with whole numbers but work fundamentally different within the fractions domain (Mack, 1995; Mack 1993; Ni & Zhou, 2005). ITSs have been shown to be a successful tool within the fractions domain because they can help to support students in making the new connections that are needed for fractions. ITSs can help to support the learning of fractions by providing grounded feedback for students as they apply their whole number knowledge to the fractions domain (Wiese & Koedinger, 2014), make connections between different fraction representations that can also represent different ways of understanding fractions (Rau, Aleven, & Rummel, 2014; Rau, Aleven, Rummel, & Pardos, 2014), and learning when different rules apply within the fractions domain (Patel et al., 2016).

Although this previous work shows the benefit that ITSs can have for students learning fractions, the students are often working individually with the computer and are not able to deepen their understanding through collaboration with peers.

The majority of ITSs have been developed for individual use. However, students within a class do not always use them individually and communicate with peers when they need help (Ogan et al., 2012). To support students in collaboration so that it can be more effective, scaffolding needs to be provided. Previous research has shown that the integration of collaboration within an ITS can effectively support learning (Baghaei & Mitrovic, 2005; Diziol et al., 2010; Harsley, Eugenio, Green, Fossati, & Acharya, 2016; Lesgold, Katz, Greenberg, Hughes, & Eggan, 1992; Suebnukarn & Haddaway, 2004; Tchounikine, Rummel, & McLaren, 2010; Walker, Koedinger, McLaren, & Rummel, 2006). When supporting collaboration within an ITS, there are many different paradigms that can be used. As examples, students can work in a peer tutoring paradigm where one student is helping another to complete the problem (Walker et al, 2006). Students can also work in a more joint problem-solving paradigm where the students are working together to solve a single problem (Harsley et al., 2016). Across different types of support, the integration of collaboration into ITSs has still been found to be successful. By integrating collaboration into an ITS, the system cannot only adapt to student's cognitive errors, but it can also adapt to students' social situation to support the collaboration (Diziol et al., 2010). For example, an ITS can use a student's actions to identify a student who is making multiple consecutive errors and can prompt them to discuss the step with their partner. This allows the ITS to both provide the cognitive and the social support needed to the students.

Like individual ITS, the majority of CITS have been developed for students in high school and older. For elementary school students, learning collaboratively may be challenging, especially in STEM domains such as mathematics (Mercer & Sams, 2006). Elementary school students often do not have fully developed social skills, making collaborative activities more challenging. Also, elementary school students may not have developed the vocabulary to discuss complex math concepts and relations. Despite these challenges, collaboration may still be effective for elementary school students by allowing them to make their thinking explicit and to practice their ability to talk about mathematics (Chi & Wylie, 2014). Even outside of ITSs, few studies have investigated whether CSCL can have a positive impact on learning with elementary school students. The studies that have been conducted in this area have either compared the use of a CSCL setting to face-to-face collaborative learning (i.e., not supported by computers) or have focused on technology interventions that mix individual and collaborative learning tasks without comparing learning collaboratively to learning individually as we propose to do (Chen & Looi, 2013; Lazakidou & Retalis, 2010; Tsuei, 2011). This research has shown positive impacts of young children working in small groups and with computers that can be extended to the use of ITSs.

Additionally, most ITS systems do not support the combination of individual and collaborative learning, despite this being common in the classroom (Ogan et al., 2012). Because ITSs allow students to work at their own pace (i.e., progress in the tutor differs across students), it can be difficult to pair students after they complete a phase of working individually or to find students new partners at the start of a new session if their original partner is absent. Often the collaborative ITSs have addressed this issue by having all of the students change activities as a class. However, forcing all students to switch activities as a class reduces a system's ability to adapt to students' needs and may not align well with their individual progress, which, as discussed above, is a significant benefit of ITSs. Therefore, my goal in developing the fractions collaborative intelligent tutoring system (CITS) was to develop both collaborative and individual versions of the tutors that were designed to support younger students in there collaboration around and learning of the fractions domain and could be combined within a classroom for effective learning. The fractions CITS is unique in that it aims to combine collaborative and individual ITSs for elementary school students.

In this chapter, I describe the development process and final tutors for the fractions CITS. The tutor problems within the fractions CITS are a further contribution of my dissertation work. The fractions CITS has been shown to be a successful tool within the classroom to promote learning. Within this section, I will first describe the development process with which I went through for the different projects to make the tutors. I will then discuss the curriculum that is covered within the tutors and the different type of activities that are included in the fractions CITS. Finally, I will discuss how the collaboration was supported within the fractions CITS.

2.1 Development Process and Iterations

The design of the fractions CITS was an iterative design process. The tutor design took advantage of the child-friendly layout and knowledge of multiple representations from Rau's (2013) Fractions Tutor. The tutor was otherwise developed from scratch to match the learning goals of the curriculum and to provide the support needed for individual and collaborative learning. For each of the experiments, the tutor went through a redesign to both match the goals of the experiment and improve the design based upon data from the previous experiment. Table 2.1.1 summarizes the iterative design process that took place for the design of the tutors.

For experiment 1, the tutors were designed to target a shorter study. As such, the tutors were developed only for the unit on equivalent fractions. For the first five steps in Table 2.1.1, the tutors focused on equivalent fractions. Steps one through three were used to refine the tutors in terms of the cognitive support that was provided for the students as well as the social support for the collaboration. By working with both teachers and students, I was able to 1) refine the tutors based on expert advice, 2) better understand where the tutor directions were not clear for the students and 3) identify where the support was insufficient.

Table 2.1.1. The design process for the collaborative and individual tutors along with the research questions addressed for each experiment.

Design Steps	Participation and Research Approach	Research Question
1. Low fidelity prototyping	1 teacher, HCI methods	
2. Pull-out pilot 1	24 students, HCI methods	
3. Low fidelity prototyping	1 teacher, HCI methods	
4. Experiment 1	84 students, educational evaluation, data mining	Are collaborative and individual learning best suited for different knowledge types? Can collaborative ITSs effectively support learning in elementary school students?
5. Classroom pilot 1	64 students, educational evaluation, data mining	
6. Low fidelity prototyping	1 teacher, HCI methods	
7. Classroom pilot 2	151 students, educational evaluation, data mining	
8. Experiment 2	189 students, educational evaluation, data mining	Are collaborative and individual learning best suited for different knowledge types? Can collaborative ITSs effectively support learning in elementary school students?
9. Low fidelity prototyping	2 researchers, HCI methods	
10. Classroom pilot 3	25 students, educational evaluation, data mining	
11. Experiment 3	382 students, educational evaluation, data mining	Is the combination of collaborative and individual learning more effective than either alone?

For experiment 2, the tutors were used in a real class setting. Because of the longer time with the tutors, I expanded the problem sets to include all seven units (described below in the curriculum section). The classroom pilots provided insight into how the collaboration differed between lab and classroom settings and how the support for the orchestration of the collaboration needed to change for the collaboration to be successful across multiple days within a classroom.

For experiment 3, the design of the tutors changed based upon the analysis of the process data from experiment 1. The problem design was changed to support erroneous examples, which is where I found evidence that collaboration may be productive. In addition, the combination of collaborative and individual learning was piloted within the classroom to investigate how the orchestration of the two social planes would work within a single class session.

The main focus was to develop problems that supported students in their understanding of fractions concepts and supported them in collaborating. All of the tutor versions were developed using an enhanced version of Cognitive Tutoring Authoring Tools (CTAT) that allowed for the development and deployment of collaborative tutors (Aleven et al., 2015; Olsen, Belenky, Aleven, Rummel, Sewall, & Ringenberg, 2014). Students do not spontaneously have fruitful collaboration and need to be supported through the use of collaboration scripts until their own internal collaboration scripts develop (Dillenbourg, 2002; Kollar, Fischer, & Hesse, 2006). Through the use of CTAT, I was able to develop my tutors with embedded collaboration scripts allowing me to have the individual and collaborative tutors as similar as possible besides the support for the collaboration.

2.2 Curriculum

The fractions CITS covers seven different fractions topics across seven units. Within each unit, there are three different problem types (conceptually oriented, procedurally oriented, erroneous example problems) that target the fractions knowledge that is being targeted within that unit (discussed in the section below). Each of the units is designed to align with both PA State Standards and the U.S. Common Core (Common Core State Standard Initiatives, 2017; PA State Standards, 2017). As seen in Table 2.1.2, the skills that are addressed in each unit address requirements within the standards. This alignment with standards allows the fractions CITS to be used in the classroom, which is the environment that it was designed for. The current fractions CITS units are available for free on a website for middle school math (Aleven, McLaren, & Sewall, 2009). During the class, the tutors are designed for the students to be able to work independently or in groups, but for the teacher to be able to support the students with the curriculum as needed.

As the studies progressed, the curriculum covered by the fractions CITS also developed. For Experiment 1, the scope was limited to a single unit, equivalent fractions. Within this unit, there were two different problem types that focused on the concept of equivalent fractions and how to find equivalent fractions both through reducing and multiplying. With Experiment 2, the scope of the units was expanded to the full seven that the fractions CITS covers. These units again had two problem types that focused on a main concept within the unit and procedures within the unit. For experiment 3, instead of adding more units, an additional problem type was added for each unit, erroneous example problems. Together these three problem types within all seven units comprise the fractions CITS.

Table 2.1.2. The curriculum alignment with PA State Standards and Common Core Standards for the fractions CITS

Unit 1: Naming Fractions	
Conceptually oriented: Make connections between where the denominator and numerator are shown on the pie chart, rectangle, or number line	PA State Standard CC.2.1.3.C.1 Common Core Standard 3.NF.A.2
Procedurally oriented: Determine what fraction is shown on the pie chart, rectangle, or number line	PA State Standard CC.2.1.3.C.1 Common Core Standard 3.NF.A.2
Erroneous examples: Addressing misconceptions about how the numerator and denominator are represented in the pie chart, rectangle, and number line	PA State Standard CC.2.1.3.C.1 Common Core Standard 3.NF.A.2
Unit 2: Making Fractions	
Conceptually oriented: Make connections between where the denominator and numerator are shown on the pie chart, rectangle, or number line	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.3.3.A.2 Common Core Standard 3.NF.A.2
Procedurally oriented: Make the given fractions using a pie chart, rectangle, or number line	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.3.3.A.2 Common Core Standard 3.NF.A.2
Erroneous examples: Addressing misconceptions about how the numerator and denominator are represented in the pie chart, rectangle, and number line	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.3.3.A.2 Common Core Standard 3.NF.A.2
Unit 3: Equivalent Fractions	
Conceptually oriented (Experiment 1): Making connections between the amount of space a fraction takes and equivalence, the relative change to the numerator and denominator, and the uniformity of pieces	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.1.4.C.1 Common Core Standard 3.NF.A.3 Common Core Standard 4.NF.A.1
Procedurally oriented (Experiment 1): Making equivalent fractions by reducing the fraction and by multiplying the numerator and denominator by the same number	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.1.4.C.1 Common Core Standard 3.NF.A.3 Common Core Standard 4.NF.A.1
Conceptually oriented: Making connections between the relative changes between the numerators and denominators and the space a fraction covers for equivalent fractions	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.1.4.C.1 Common Core Standard 3.NF.A.3 Common Core Standard 4.NF.A.1
Procedurally oriented: Choosing the correct numerator and denominator to make an equivalent fraction	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.1.4.C.1 Common Core Standard 3.NF.A.3 Common Core Standard 4.NF.A.1
Erroneous examples: Addressing misconceptions about the relative changes between the numerator and denominator in equivalent fractions	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.1.4.C.1 Common Core Standard 3.NF.A.3 Common Core Standard 4.NF.A.1
Unit 4: Least Common Denominator	
Conceptually oriented: Making connections between multiples of a number and the least common denominator	PA State Standard CC.2.1.5.C.1 Common Core Standard 4.NF.A.2
Procedurally oriented: Finding the least common denominator between two fractions	PA State Standard CC.2.1.5.C.1 Common Core Standard 4.NF.A.2
Erroneous examples: Addressing misconceptions about the difference between least common multiples and factors and that the least common denominator is not always the product of the two	PA State Standard CC.2.1.5.C.1 Common Core Standard 4.NF.A.2

denominators	
Unit 5: Comparing Fractions	
Conceptually oriented: Making a connection between the size of the numerator or denominator when one is held constant between fractions	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.1.4.C.1 Common Core Standard 3.NF.A.3 Common Core Standard 4.NF.A.2
Procedurally oriented: Compare fractions by converting them using the least common denominator	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.1.4.C.1 Common Core Standard 3.NF.A.3 Common Core Standard 4.NF.A.2
Erroneous examples: Addressing misconceptions about comparing fractions when the numerators or denominators are the same and how to use the least common denominator to compare fractions	PA State Standard CC.2.1.3.C.1 PA State Standard CC.2.1.4.C.1 Common Core Standard 3.NF.A.3 Common Core Standard 4.NF.A.2
Unit 6: Adding Fractions	
Conceptually oriented: Making connections between the addends and the sum	PA State Standard CC.2.1.4.C.2 PA State Standard CC.2.1.5.C.1 Common Core Standard 5.NF.A.1
Procedurally oriented: Adding fractions by converting to common denominators	PA State Standard CC.2.1.4.C.2 PA State Standard CC.2.1.5.C.1 Common Core Standard 5.NF.A.1
Erroneous examples: Addressing misconceptions about the conversion of the numerators and denominators as well as the denominators not being added	PA State Standard CC.2.1.4.C.2 PA State Standard CC.2.1.5.C.1 Common Core Standard 5.NF.A.1
Unit 7: Subtracting Fractions	
Conceptually oriented: Making connections between the difference and the original numerators	PA State Standard CC.2.1.4.C.2 PA State Standard CC.2.1.5.C.1 Common Core Standard 5.NF.A.1
Procedurally oriented: Subtracting fractions by converting to common denominators	PA State Standard CC.2.1.4.C.2 PA State Standard CC.2.1.5.C.1 Common Core Standard 5.NF.A.1
Erroneous examples: Addressing misconceptions about the conversion of the numerators and denominators as well as the denominators not being added	PA State Standard CC.2.1.4.C.2 PA State Standard CC.2.1.5.C.1 Common Core Standard 5.NF.A.1

2.3 Problem Types

At the beginning of each experiment, the students were asked to complete a tutorial that consisted of six problems. These problems introduce the concept of the unit for each of the three representations (i.e., pie chart, rectangle, and number line) that the students will interact with over the course of the seven units. By going through the tutorials, the students are able to learn what the different interactions types are that they will have with the interface and how the interface will provide feedback. In addition, when the students are collaborating, the tutorial allows them to understand how their interactions are shared within the interface. The tutorial provides practice for the students to become acquainted with the interactions and social support provided in each of the three problem types (i.e., conceptually oriented, procedurally oriented, erroneous examples).

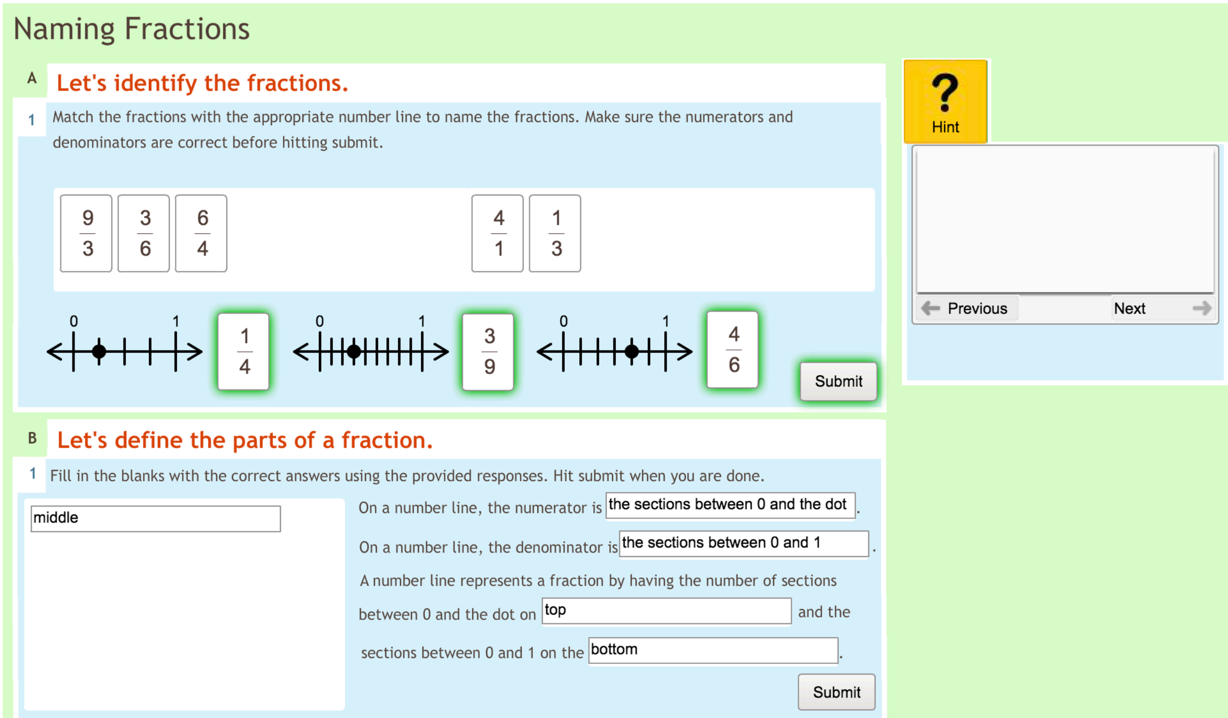

Figure 2.1.1. An example of a conceptually oriented tutor used in Experiment 2. In Section A, the students first name multiple fractions to find the pattern. In Section B, they make this pattern more explicit through fill in the blanks.

The conceptually oriented problems were designed to provide students with an opportunity to make connections between different elements within the domain. Conceptual knowledge is the implicit and explicit understanding of the principles in a domain and how they are interrelated (Rittle-Johnson, Alibali, & Siegler, 2001). As each skill can take a range of conceptual and procedural knowledge to complete, the conceptually oriented problems do not purely consist of conceptual skills but instead are oriented towards the teaching of conceptual knowledge. Within the conceptually oriented problems, the students are asked to first to interact with a set of fractions related to the concept being taught within the unit. After completing this first task, the students are asked to answer a series of questions intended to guide them towards the underlying principle being used within the unit. For example, in Figure 2.1.1, the students are asked to match the correct symbol fraction with what is shown on the representation for naming fractions. After matching the fractions, the students are asked to fill in the blank describing how the numerators and denominators are represented within the graphical representation. The conceptually oriented problems are intended to make the underlying principles more explicit for the students so that they can make connections within the domain. For Experiment 1, the tutors were designed with the same intended purpose for the conceptually oriented problems. Within these problems, instead of completing matching tasks at the beginning of the problem, the students were asked to make new fractions where the numerators and denominators were manipulated in different ways (see Figure 2.1.2). After these manipulations, the students were again asked to answer questions that were intended to make the patterns of change more explicit and the underlying principals.

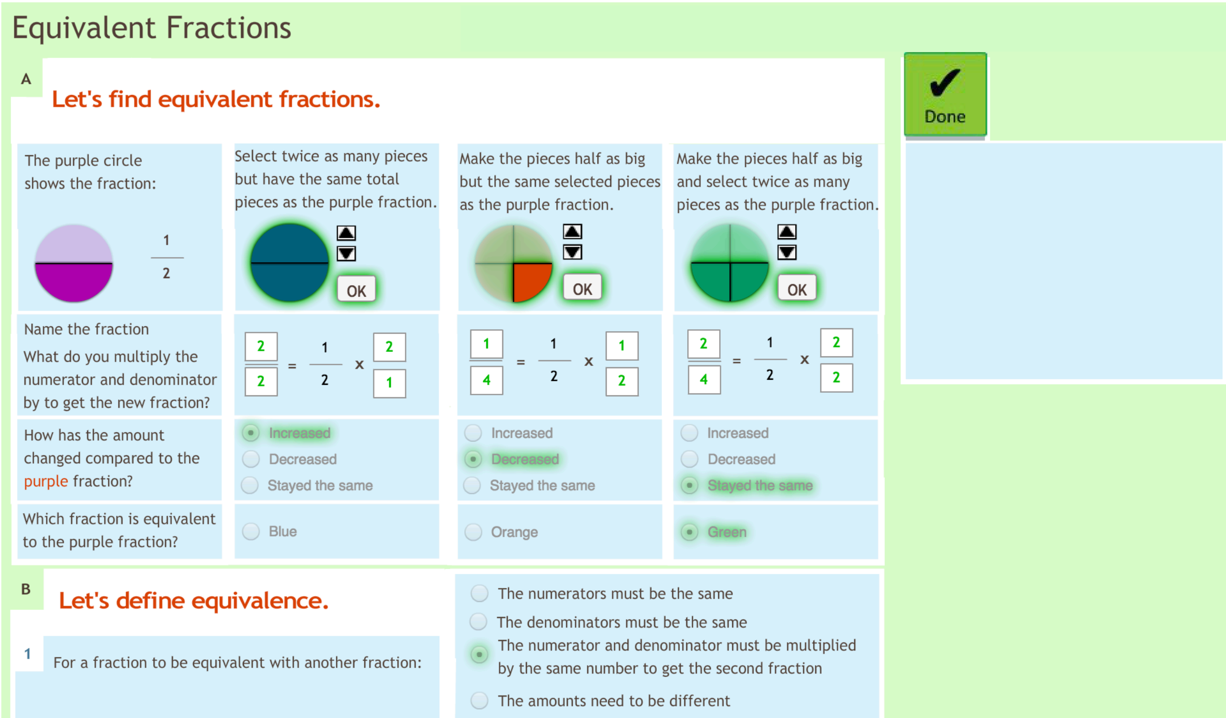

Figure 2.1.2. A conceptually oriented tutor from Experiment 1 where the students are led in discovering the patterns that define an equivalent fraction.

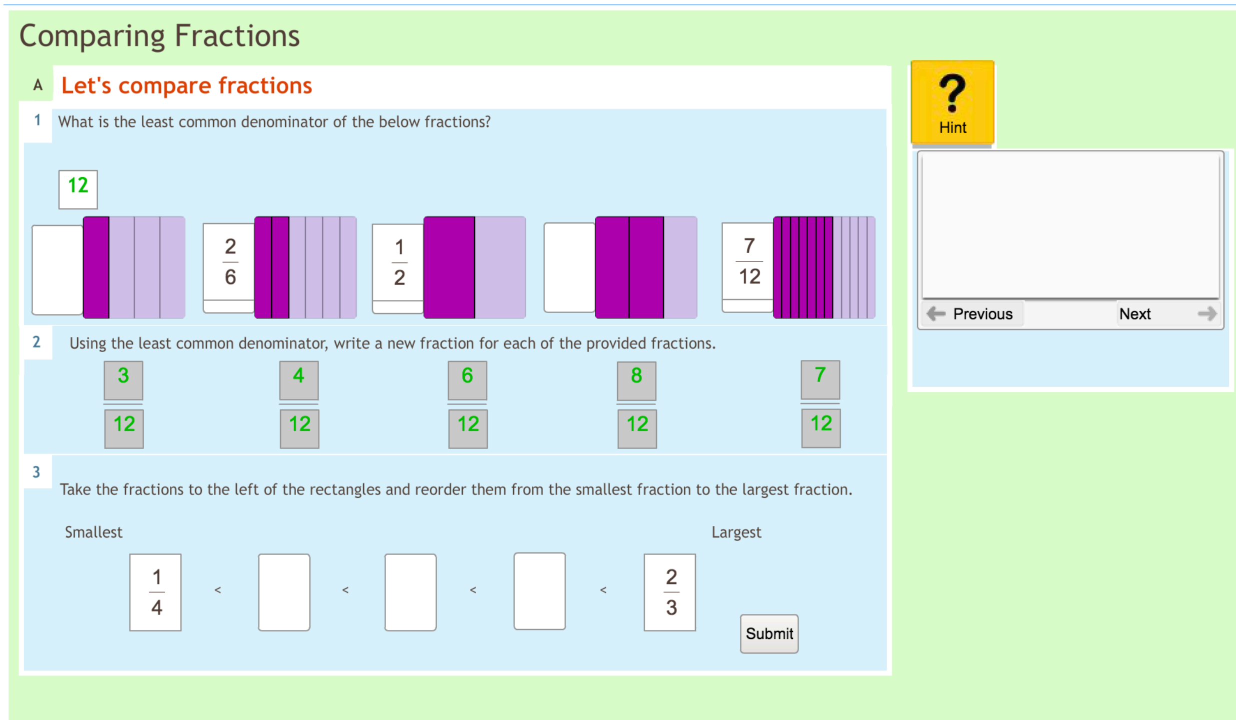

Figure 2.1.3. An example of a procedurally oriented tutor for comparing fractions used in Experiments 2 and 3. The students are guided in finding a common denominator for comparing fractions.

In contrast to the conceptually oriented problems, the procedurally oriented problems were designed to provide students with practice completing the steps needed to solve the problem type within the unit. Procedural knowledge is the ability to be able to perform the steps and actions in sequence to solve a problem (Rittle-Johnson et al., 2001). Within the procedurally oriented problems, the students are asked to go through the steps to solve the problem within the unit. For example, Figure 2.1.3 shows a problem for students comparing fractions. The students are first asked to find the least common denominator for all of the fractions. They are then asked to convert the fractions into equivalent fractions using the least common denominator. After this step, since the fractions can now be more easily compared, the students are asked to order the fractions from smallest to largest. The procedurally oriented problems are intended to allow the students practice in completing the steps to solve a problem. For Experiment 1, again the tutors were designed with the same purpose in mind. For equivalent fractions, the procedurally oriented problems focused either on reducing fractions to find if they are equivalent (see Figure 2.1.4) or making equivalent fractions through multiplying the numerator and denominator by the same number. The main change between the Experiment 1 problems and the expanded units used in Experiment 2 and 3 was to have the steps not as isolated so that there could be more discussion around each of the steps instead of just waiting for the tutor to provide feedback.

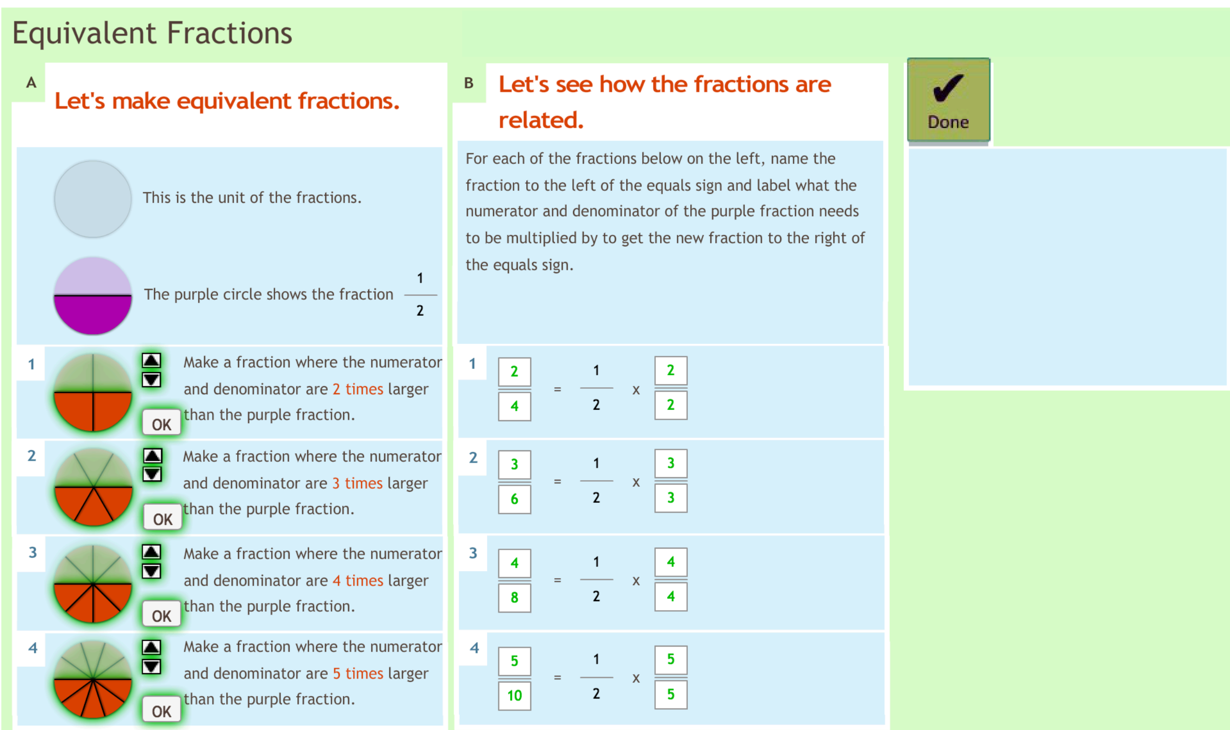

Figure 2.1.4. A procedurally oriented tutor from Experiment 1 where the students made equivalent fractions by multiplying the numerator and denominator by the same whole number.

The last problem type developed for each unit was erroneous example problems. The erroneous example problems were developed based upon analysis from Experiment 1 that found students may have had more productive collaborations after an error occurred (Olsen, Rummel, & Aleven, 2015). The erroneous example problems were designed to address the misconceptions that students were making within the procedural problems. To find these misconceptions, we analyzed the log data collected from Experiment 2 through DataShop (Koedinger et al., 2010). For each unit, we found the common errors that students were making across problems and developed problems to directly address these misconceptions. For the erroneous example problems, each problem had a fictitious student that had made an error when solving the problem (see Figure 2.1.5). By providing an identity for each problem, the students solving the problem could feel more connected and invested in helping the student (Lester, Converse, Kahler, Barlow, Stone, & Bhogal, 1997). When beginning the problem, the students were first asked to identify the error that the fictitious student had made when solving the problem. After identifying the problem, the students were asked to correct the errors within the problem, After correcting the errors, they were asked to write to the fictitious student to provide them with advice on what they could do better the next time. Through these steps, the students were asked to identify the misconceptions, correct the error, and then to provide advice for what could be done instead to prevent the error. Together these three problem types form the fractions CITS.

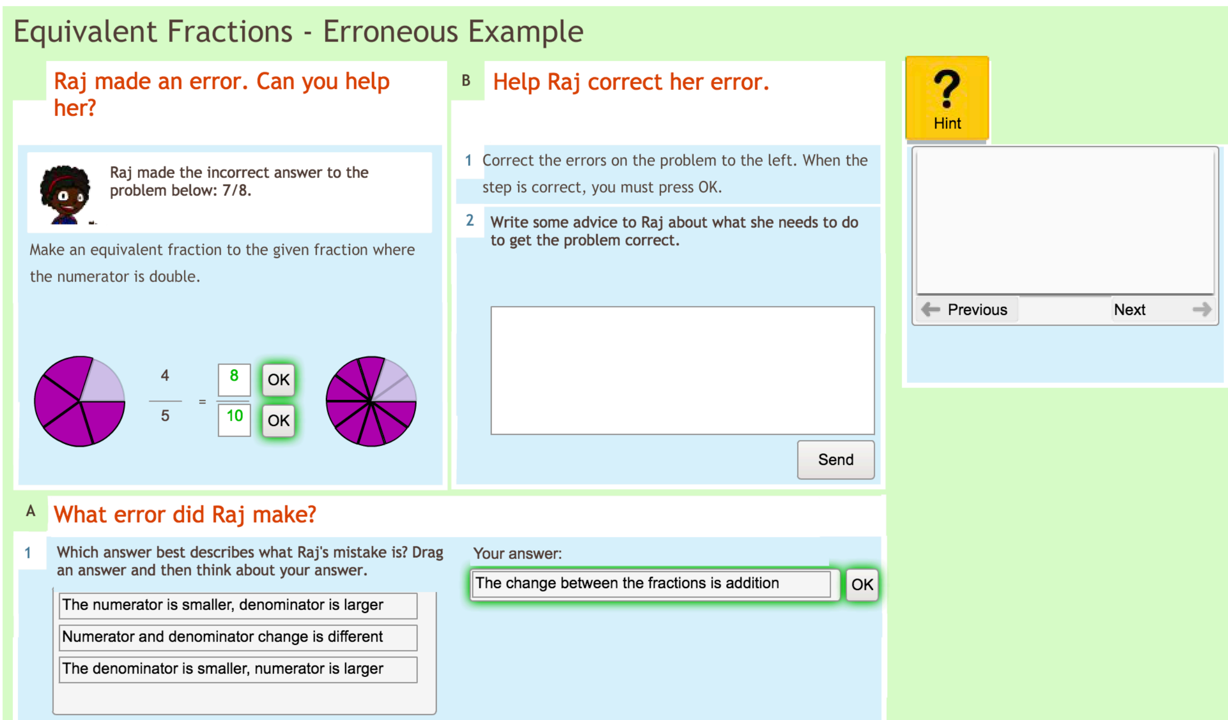

Figure 2.1.5. An example if an erroneous example problem used in Experiment 3. The students were instructed to find and correct the error and then provide the student with advice for next time.

2.4 Collaborative Support

For each of the units and problem types covered in the fractions CITS, problem sets were designed for both individual use and collaborative (dyadic) use. The individual and collaborative problem types were designed to have the same format and to go through the same set of steps. The students also had the same access to error messages and on demand hints for the tutors. The individual and collaborative tutors did differ in the social support that was provided to the students in the collaborative tutors through an embedded collaboration script and the sharing of information across tutor interfaces between partners.

The collaboration tutors used synchronized, networked collaboration. Each student sat at their own computer and had a shared but differentiated view of the problem. The students were able to see their partner's actions before being checked by the tutor, which allowed them to have a discussion around the answer. However, because the students also each had their own screen, each student was able to receive different information or take different actions on the problem. For example, for making equivalent fractions, one student could be put in charge of the numerators while the other in charge of the denominators (see Figure 2.1.6). To be able to make a full fraction, each student would have to interact with the problem. Additionally, you could allow the students to only *see* the parts of the fraction that they are allowed to interact with as well. Although all of the collaboration was designed for students to be at separate computers, the actual features of the collaboration script were designed to correspond with the learning objectives of the individual problems (Kollar et al., 2006). Within fractions CITS, I used three main collaboration features to support learning: roles, cognitive group awareness, and group accountability through the use of separate information and actions. By using these features together, the tutors could better engage each member of dyad in the problem solving rather than allowing one member of the team to free ride. Although the different features together do not provide an overall design concept, each feature works to support the goal of accountability within the group.

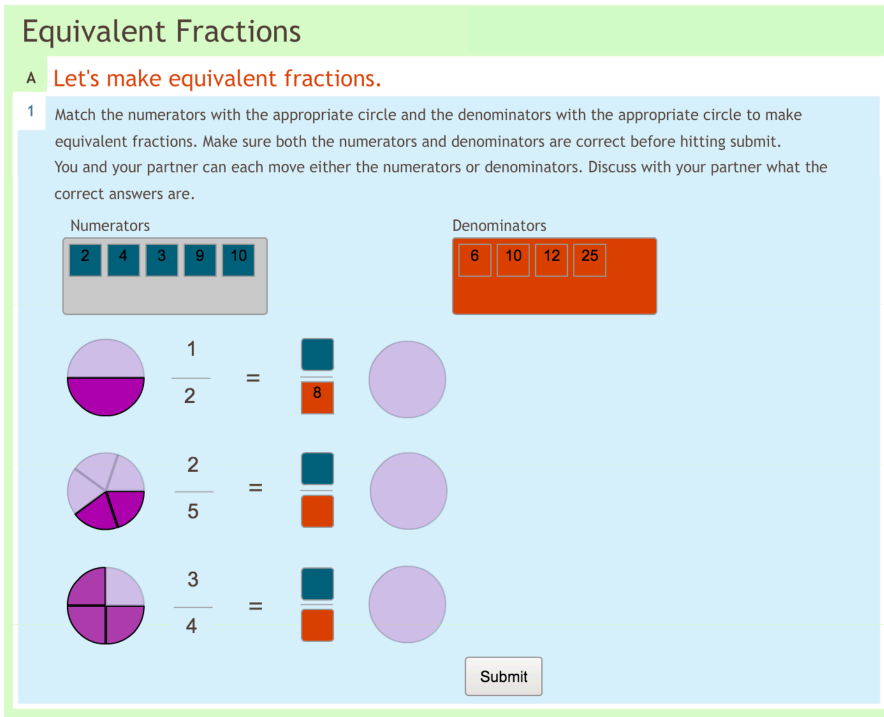

Figure 2.1.6. An example of division of responsibilities. Each student can see the numerators and denominators but can only interact with one set.

The use of roles has been shown to be a successful collaboration feature (Burton, 1998; King, 1999). Roles allow students to approach the problem from a different perspective and to practice different skills that may be important to the collaboration. Within a problem-solving environment, roles also provide students with specific individual goals that can provide them focus in their interactions with their group members and on task completion. Within my tutors, I supported roles in two different ways. For the Experiment 1 equivalent fractions problems roles were explicitly taught and shared with the students in both the conceptually oriented and procedurally oriented tutors. The students were assigned to either be in a 'doer' role or a 'helper' role. When a student was assigned to the doer role, they were responsible for making sure that the correct answer got entered into the tutoring interface. When a student was assigned to the helper role, they were responsible for making sure that both members of the group understood why the answer was correct and to ask any questions to check for that understanding. Before working with the interface, the students watched a short video explaining the roles to them. When working on the problems, the role the student was currently assigned to would be displayed next to the step through a small icon (see Figure 2.1.7). For the other problem sets, roles were supported through the distribution of actions. Within the conceptually oriented and procedurally oriented problems for all seven units, on some steps within the problem, students would only be able to interact with half of the available answer choices. For example, within the procedural equivalent fractions, one student would be able to move the numerators while the other student could only move the denominators (see Figure 2.1.6). Through the limited actions for each student, the students were put into a role where they were responsible for the answers they could take action upon.

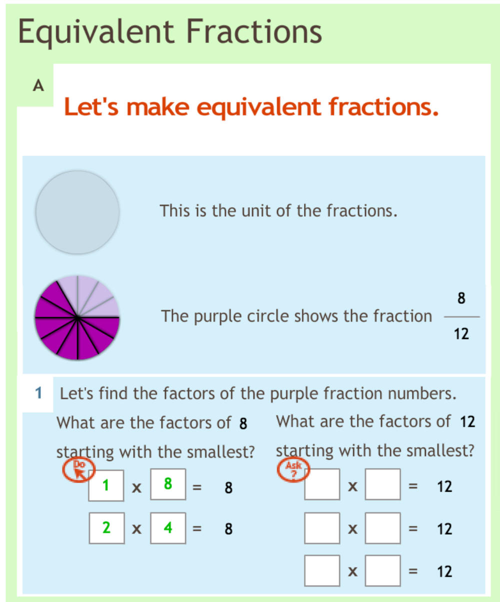

Figure 2.1.7. To support roles, each student has either a "do" icon or an "ask" icon to indicate if they are responsible for completing the steps.

The second form of collaborative support that was used within the fractions CITS was cognitive group awareness (Dehler, Bodemer, Buder, & Hesse, 2011; Janssen & Bodemer, 2013). Cognitive group awareness is a way of providing information to the group members about the other group members' knowledge, information, or opinions. Within collaborative learning, providing cognitive group awareness tools to students has been found to be effective in supporting their learning (Janssen & Bodemer, 2013). When students are more aware of their group members' expertise, they are better able to learn from their partners and to coordinate the task. Additionally, by making the knowledge and opinions of the different group members more salient, the students can be more aware of when they have differing answers, which call lead to more discussion. Within the fractions CITS, cognitive group awareness was supported by giving the students an opportunity to answer a step individually before working on the step as a group (see Figure 2.1.8). After each student enters an answer, the individual answers are shared with the whole group so that each group member can see what their partner answered. The group is then asked to choose a group answer. Only on the group answer does the system provide correctness feedback. By supporting cognitive group awareness through this method, students are provided with an equal opportunity to express their opinion on the answer before getting feedback from the system, which can lead to more conversations between the students, especially when their answers are not the same.

The final form of collaborative support that was implemented in the fractions CITS was producing group accountability through the use of separate information and actions. Individual accountability has been argued to be essential for group work to be successful (Slavin, 1989). By having individual accountability within a group, it presented a few group members from doing all of the work and from ignoring group members that may not contribute as much. Within the fractions CITS, we produce individual accountability through the use of separate information and actions. Within the tutors, the students may receive information on their screen that they are asked to share with their partner (see Figure 2.1.9). For the students to be able to complete the problem successfully, both partners need to be aware of this information, making it essential that the partner shares. As mentioned under the roles, the students can also be assigned different actions to take within the interface (see Figure 2.1.7 and 2.1.9). By assigning the students to take different actions, each student has some responsibility for the step being completed successfully. No one student is able to do the step alone without input from their partner. Each member of the group is then responsible for some part that is needed to reach the common group goal of completing the problem. Within the fractions CITS, these different collaboration features are embedded directly into the system influencing and supporting the social dynamics of the students as they work through the different problem sets. Although all three features are not often used within a single problem, instead they are distributed throughout the problems to better align with the goals of each of the individual steps.

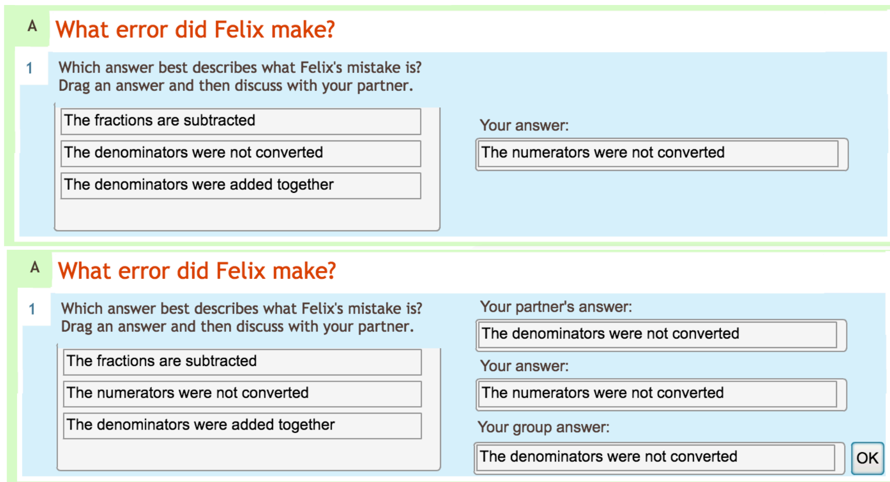

Figure 2.1.8. To support cognitive group awareness, the students are first asked to answer the question individually before answering as a group.

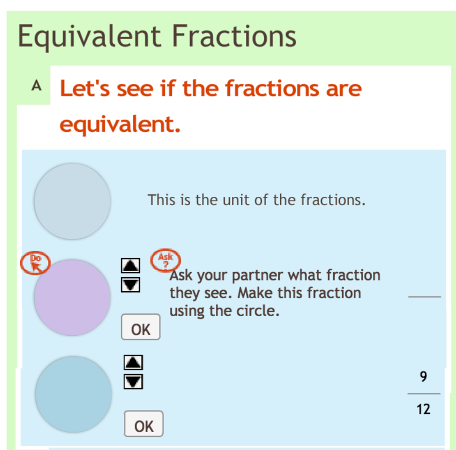

Figure 2.1.9. To complete the step, one partner must share the symbol representation with the other partner to complete the circle representation.

2.5 Summary and Discussion

The fractions CITS provides a novel contribution in supporting collaboration in an educational technology. I developed an ITS that could provide social support intended for elementary school students as students do not spontaneously collaborate effectively (Kollar et al. 2006) and need support adjusted to their level (Dillenbourg, 2002). Within the fractions CITS, I developed three different problem types for seven different units, each with an individual and collaborative version. Within the collaborative version, I embedded a collaboration script that used proven collaborative features to support the students in the collaborative process. My goal in developing the fractions CITS, was to provide support for young students in their fractions learning in a way that provides both cognitive and social support. Collaborative ITSs allow for this integration of supports by combining standard ITS support with embedded collaboration scripts. The fractions CITS is both a resource for others to use in teaching fractions as well as a tool for me to use within my experiments.

Across three experiments (detailed in Chapters 3 and 4) I evaluated the effectiveness of the fractions CITS. Across these experiments, I was able to make iterative improvements to the fractions CITS to have the final form of three problem types across seven different fraction units. Results from the most resent experiments to use the different types of problems support that the fractions CITS is effective. In Experiment 2, students who worked on the conceptually oriented fractions tutor saw in increase in their conceptual test scores from pretest to posttest ($p < .05$, $r = .73$). Students working on the procedurally oriented tutors saw an increase in their procedural test scores from pretest to posttest ($p < .05$, $r = .71$). In Experiment 3, the erroneous example test items and procedural test items were not analyzed separately. However, across conditions, there was a significant increase in test score from pretest to posttest, including erroneous example items ($p < .05$, $r = .59$). Although the students only worked with the tutors for three days, these high effect sizes demonstrate the success of the tutors for supporting fractions learning.

The fractions CITS makes a novel contribution to ITS research by extending a primarily individual field to include collaborative instances. Most of the work with ITSs has been done with individual learning (Liu et al., 2016; MacLellan et al., 2016; Rau et al., 2014a; Rau et al., 2014b; Steenbergen-Hu & Cooper, 2013). When ITSs have been expanded to include collaboration, it has mostly been done to support older students (Baghaei & Mitrovic, 2005; Diziol et al., 2010; Harsley et al., 2016; Lesgold et al., 1992; Suebnukarn & Haddaway, 2004; Tchounikine et al., 2010; Walker et al., 2006). The fractions CITS extends this work to support collaboration within an ITS for younger students. Additionally, the fractions CITS provides an example of how to embed collaboration scripts into the ITS to provide collaboration support directly in the ITS when students are working on different computers. In past research, the collaboration support has been provided through hints or other types of prompts (Diziol et al., 2010). However, adding more text to the screen can be difficult for young learners. In the fractions CITS, I demonstrated that student collaboration can be directly supported in the tutor actions and information displayed.

The fractions CITS also makes a novel contribution to CSCL research by providing an integrated collaborative and individual learning environment. Because the fractions CITS was developed to have both individual and collaborative problem sets for all fractions problems, it creates the ability to customize the learning environment to student needs. Often in CSCL, collaborative interventions are developed to have all students go through the same steps at the same time. The fractions CITS allows students to work at their own pace and different students can be assigned to work in different social planes when it is appropriate for their learning. Additionally, the fractions CITS integrates the collaboration support directly into a system that already provides adaptive cognitive support. CSCL has stressed the need for both cognitive and social support (Weinberger, Ertl, Fischer, & Mandl, 2005) and the fractions CITS is able to provide both of these supports seamlessly.

Together, these contributions demonstrate the impact that the fractions CITS can have on the field. It has been shown to be a successful system for supporting learning across multiple experiments. It has also made a contribution to both the ITS and CSCL fields through integrating collaboration directly into an ITS to support young learners.

3 Exploring Complementary Strengths of Collaborative and Individual Learning

Collaborative and individual learning may have complementary strengths. The processes that students engage in during learning can have an impact on their knowledge construction and the types of skills that they acquire (Koedinger et al., 2012). This process makes it important to align instructional choices, which elicit specific learning processes, with the anticipated learning goals so that students can most effectively work towards those learning goals. Within the classroom, switching between social planes (i.e., whole class, group, and individual) is one way to elicit different learning processes. Collaborative learning may be beneficial by supporting students in giving and receiving explanations as well as the opportunity to co-construct knowledge with their partner (Hausmann et al., 2004), which may help students develop a deeper conceptual understanding (Teasley, 1995). On the other hand, for problem-solving practice, individual learning may be more beneficial than collaborative learning. Working individually may allow students to get more practice in the same amount of time and develop fluency (Diziol et al., 2009; Mullins et al., 2011) since students are not sharing tasks with a partner and do not necessarily have to pause to explain their actions. Although there has been substantial research comparing individual and collaborative learning (Lou et al., 2001; Slavin, 1989), it remains an open question if collaborative and individual learning have complementary strengths.

Previous research that has compared the complementary strengths of collaborative and individual learning has been limited. The research that has been conducted has mostly investigated learning with secondary school students working on algebra (Diziol et al., 2009; Mullins, et al., 2011). Within this study, individual work was found to better support the acquisition of procedural knowledge while collaborative work was found to better support the acquisition of conceptual knowledge. These results align with the elicited learning processes for collaborative and individual learning in that the dialogues within collaboration may lead to a deeper understanding that is beneficial for conceptual knowledge while individual learning allows for more practice and fluency, which is beneficial for procedural knowledge. However, it is not yet understood how these results would generalize to other domains and age groups. For elementary school students, learning collaboratively may be challenging, especially in STEM domains such as mathematics (Mercer & Sams, 2006). Elementary school students often do not have fully developed social skills, making collaborative activities more challenging than they might be for older age groups. Also, elementary school students may not have developed the vocabulary to discuss complex math concepts and relations. Despite these challenges, collaboration may still be effective for elementary school students by allowing them to make their thinking explicit and to practice their ability to talk about mathematics (Chi & Wylie, 2014).

In this chapter, I describe a series of two experiments that I conducted to investigate (1) the effectiveness of collaborative ITSs with elementary school students and (2) how collaborative and individual learning may have complementary strengths. I describe each experiment independently before discussing the overall implications of the findings. Together the experiments provide evidence of the effectiveness of supporting elementary school students through a collaborative ITS and the need for future work into when collaborative and individual learning would be most productive.

3.1 Investigating the Strengths of Collaborative and Individual Learning in a Pull-out Setting

Some prior research has indicated that ITS can be a practical way of addressing the challenges of using collaboration in the classroom. Most CSCL environments are missing the cognitive support that can be beneficial to student learning. An ITS can provide the cognitive support (i.e. step-by-step guidance and hint features) that a student needs for collaboration to be successful (Walker, Rummel, McLaren, & Koedinger, 2007), but does not provide support for effective collaboration. The current research investigates if embedding a collaboration script into an ITS so it has both the collaborative and cognitive support can help a student to learn successfully, specifically for elementary school students.

3.1.1 Research Questions and Hypotheses

Even though collaborative learning has been shown to be successful, few studies have investigated whether CSCL can have a positive impact on learning with young children. The implementation and support of collaboration in the classroom is particularly difficult for students in elementary school and may explain why there is less research with this age group. An important question, therefore, is if collaborative learning can be an effective instructional method to use with elementary school students and if it would lead to similar learning gains as students working individually. Some studies have shown successful use of collaboration with elementary school students as well, but have either compared the use of a CSCL setting to face-to-face collaborative learning (i.e., not supported by computers) without comparing it to individual learning or have focused on interventions that mix individual and collaborative learning tasks without looking at each separately (Chen & Looi, 2013; Lazakidou, & Retalis, 2010; Tsuei, 2011). Although this research has shown positive impacts of young children working in small groups and with computers, it is still unknown how the use of a CSCL environment impacts the learning outcomes of young children compared to learning individually. Experiment 1 aims to address this question through an ITS designed specifically to support collaborative learning of children in elementary school. ITSs have been shown to have positive impacts on students in this age group when working individually to learn fractions (Rau, Aleven, Rummel, & Rohrbach, 2012). We now extend this research by testing whether a tutor that supports collaboration can be effective for learning fractions by elementary school students.

In creating a collaborative tutor, it may be important to consider the possibility that individual and collaborative learning activities may be better for acquiring different types of knowledge, such as conceptual and procedural knowledge (Mullins, Rummel, & Spada, 2011). Conceptual knowledge is the implicit and explicit understanding of the principles in a domain and how they are interrelated (Rittle-Johnson, et al., 2001) Procedural knowledge is the ability to be able to perform the steps and actions in sequence to solve a problem (Rittle-Johnson et al., 2001). Mullins, Rummel, and Spada (2011) found that with 9^{th} graders doing algebra, students who worked collaboratively on conceptual tasks outperformed those who worked individually and students who worked individually on procedural tasks outperformed those who worked collaboratively (Mullins et al., 2011). Again, this study was implemented with older students and the question still remains if the same difference will be seen with elementary school students. In the two studies that follow, I investigate this question of complementary strengths with elementary school students working on fractions.

In addition to analyzing the learning gains, what occurs during the learning process can be as informative. Collaborative learning may be more beneficial than individual learning in certain situations because the students engage in different learning processes that can impact how they react to learning events, such as hints and errors. Research in both individual and collaborative learning indicates that hints and errors can be good moments of learning (Koedinger & Aleven, 2007; Rummel, Mullins, & Spada, 2012). However, students frequently do not take advantage of the support that is provided to them through moments of reflection (Roll, Baker, Aleven, & Koedinger, 2014). They often engage in poor help seeking behaviors, for example by not requesting a hint when one would be useful, or by engaging in hint abuse (Roll et al., 2014). It has been shown that students may benefit more when they engage in solution attempts (i.e. making errors) before receiving assistance (Roll et al., 2014). The study by Rummel, Mullins, and Spada (2012) suggests that performing collaborative sense-making activities around errors can be beneficial for learning. Students who participated in sense-making activities around the errors and feedback through elaboration with their partner were less likely to make errors on future problem-solving steps than if they do not engage in sense-making activities. Although Rummel, Mullins, and Spada (2012) explored how collaboration scripts can support students to take advantage of the system feedback around errors, their study does not address specifically how collaboration (and in particular, interactive dialogue, cf. Chi, 2009) can be most beneficial in learning from errors and what role it plays in the process.

It is still an open question how collaboration plays a role in overcoming errors and when collaboration is appropriate in this process on the assumption that errors are frequent and important opportunities for learning (Ohlsson, 1996). Specifically, I am interested in better understanding the degree to which and the conditions under which interactive dialogue as defined by Chi's (2009) ICAP framework happens around errors. ICAP proposes that students who engage in interactive activities (or interactive dialogue) will benefit more from collaborating than students who engage in constructive, active, or passive activities. Interactive activities include the giving and receiving of explanations along with the co-construction of knowledge (Hausmann, Chi, & Roy, 2004; Chi, 2009). These activities happen when a student works with another person, but students may not always engage in interactive activities when collaborating. In my work, I analyze the student dialogues around errors to develop a better understanding for when students engage in interactive activities and how this talk impacts the occurrence or overcoming of errors.

In addition to understanding the role that collaboration may play in overcoming errors, it is important to understand how these behaviors may change over time. To understand how to best support learning with the use of technology, it is important to take this change into account. Within Experiment 1, I address the changes in behavior that may be seen over a short period of time, namely, changes within a single collaborative learning session. I focus my analysis on students' dialogue and how their dialogue is related to behavior in the collaborative CITS. By looking at the dialogue within dyads, we can form a better understanding of when students invoke collaborative behaviors in relation to their actions in an ITS.

Past work with CSCL has focused on changes over time from two different perspectives. The first is how previous dialogue and contributions have an impact on later contributions, which provides insight into the influence of earlier utterances on later utterances and their interdependencies (Chen, Chiu, & Wang, 2012; Molenaar & Chiu, 2014; Wise & Chiu, 2011). The second perspective is to look at how communication and learning unfold over long periods of time in the range of days or months, which lends itself well to discovering more permanent changes in dialogue (Mercer, 2008; Reimann, 2009). However, neither of these perspectives takes into account how behaviors and strategies may change within a single lesson as students learn and may need different support from their partner. Within the analysis of Experiment 1, I focus on an analysis at the single lesson grain size by analyzing the shift in types of collaborative talk that can happen within a session. Analyzing dialogue on this time scale uniquely positions us to investigate the adaptivity of student strategies as students gain domain knowledge. Ogan et al. (2012a) analyzed data on a similar time scale as my study where they looked at the change in behaviors between two sessions. However, their focus was on the change in social cues that take place while we are focusing on the change in collaborative dialogue and how the change relates to signs of learning within the ITS, such as errors.

Within Experiment 1, I hypothesize that students working collaboratively will show learning gains on both procedural and conceptual fractions tasks, supporting that an ITS can support collaborative learning for elementary school children (H1). Also, I hypothesize that on conceptual tasks, students working collaboratively will have stronger learning gains than students working individually (H2a). By contrast, for students doing procedural tasks, I hypothesize that those working individually will have stronger learning gains than those working collaboratively (H2b). For the process data, I hypothesize that students working collaboratively will complete fewer problems than those working individually (H3). Based on the assumption that errors are opportunities for learning, (Ohlsson, 1996), I hypothesize there will be more fruitful collaborative talk after an error occurs than other types of talk (H4). Additionally, as students make fewer errors over time, which can indicate learning, students may engage less in the material and have less interactive talk (H5).

3.1.2 Methods

3.1.2.1 Experimental Design and Procedure

To test the hypotheses stated above, we conducted a study with 84 4th and 5th grade students (42 4th grade, 42 5th grade) from two elementary schools within the same school district near the end of the fall semester. The students came from a total of six classrooms each with a different teacher. Experiment 1 was a pull-out design where the students left their normal instruction during the school day to participate in the study, to allow for more control over the learning environment. All of the students worked on the equivalent fractions problem sets designed for Experiment 1 described above. This ITS consisted of conceptually oriented and procedurally oriented problem sets each with a total of 16 problems. Both problem sets had an individual and collaborative version. Each teacher paired the students participating in the study based on students who would work well together and had similar math abilities. These pairs were then randomly assigned to one of four conditions: collaborative conceptual, collaborative procedural, individual conceptual, and individual procedural. Twice as many students were assigned to the collaborative conditions as to the individual conditions. During the ITS session, the students' eye tracking data was collected. To prevent students from having their eye away from the screen infrequently, we had the students sit across the room from each other. In the individual conditions, this set-up prevented the students from engaging in off task behavior as they worked. In the collaborative condition, we had the students communicate through Skype (only audio) with their partner to be able to discuss the problems.

Before participating in the pull-out session, the students had two whole class sessions during which they worked individually with the Fractions Tutor during their normal class period (on fractions topics other than equivalence) allowing the students to become acclimated with the tutor before the experiment began. During the experiment, the students participated in a 25-minute pretest the morning of their participation. Throughout the day, the pairs of students participated in a one-hour pull-out session. During the session, the students would watch a short tutorial video instructing them on some of the tutor interface interactions and then received 45 minutes of instruction dependent on their condition through the ITS. The next school day, the students participated in a 25-minute posttest in the morning. The study spanned a total of four weeks. After the end of the study, the students again had two whole class sessions where they again worked independently on the Fractions Tutor.

3.1.2.2 Dependent Measures

During the experiment, multiple dependent measures were collected to measure both the student learning and the learning process. These measures include the pretest and posttest scores, student dialogue, and ITS log data. The pretest and posttest scores were collected outside of the main pull-out session while the other measures were collected during the time spent with the ITS.

I designed the pretest and posttest to be equivalent test forms that were administered in a counterbalanced fashion. Each test had a total of 11 questions. The questions aimed to target both conceptual and procedural knowledge types with five procedural and six conceptual questions. The test items were isomorphic to the items used in the practice problems and only targeted equivalent fractions knowledge. The questions were graded without any partial credit. Each question either received a 1 when all parts were correct or a 0 otherwise with 11 total points being available. Examples of the test items can be found in Appendix 1.

During the collaborative interactions, the student dialogues were recorded and later transcribed. To analyze the student dialogues, I developed a rating scheme to align with the different categories of activities described in the ICAP framework (Chi, 2009). Within the ICAP framework, it is hypothesized that interactive talk is more effective than constructive talk, which is more effective than active talk, which is more effective than passive (Chi & Maneske, 2015). Interactive activities include the giving and receiving of explanations along with the co-construction of knowledge (Hausmann, Chi, & Roy, 2004;

Chi, 2009). These activities happen when a student works with another person, but students may not always engage in interactive activities when collaborating. My rating consists of four major code categories: interactive dialogue, constructive dialogue, constructive monologue, and other (see Table 3.1.1). The interactive and two constructive ratings align with the ICAP framework's higher level learning activity categories of the same names. In my rating scheme, the interactive dialogue and constructive dialogue consists of a group of utterances where students are taking turns talking to each other. For *interactive dialogue*, students are discussing the content of the problem by either building on each other's answers, asking for help/confirmation of an answer, or providing reasoning behind an answer. For the *constructive dialogue*, students are engaging each other about the problem, but are not necessarily building on what their partner has said. *Constructive monologues* occur with the same types of behaviors described for interactive dialogues but instead of a dialogue between students only a single student is talking so a self-explanation. My *other* category provides a rating that would encompass active and passive actions as described in the ICAP framework as activities where the student does not provide anything new to the learning environment outside of what was already there and that are less likely to be seen within dialogue along with off topic talk. This talk includes things such as reading the problem out loud.

Table 3.1.1. Rating scheme categories with the types of talk and its mapping to the ICAP framework.

Type of Talk	Overt Actions	ICAP Framework
Interactive Dialogue	Discussing an answer, co-construction, soliciting a request for help or confirmation of agreement	Interactive
Constructive Dialogue	Guessing as a group, argumentation without explanation, agreeing with partner without adding on, explaining the problem surface features rather than the domain	Constructive
Constructive Monologue	Self explanation	Constructive
Other	Telling the answer, work coordination, active reading, and off topic talk	Passive and Active

For my rating scheme, I applied it to segments of dialogue that aligned with subgoals (i.e., a group of problem-solving steps with the ITS that form a coherent task) within the tutor problems. Because the tutoring problems consist of discrete steps that the students have to complete, the discussions often revolved around these steps. By segmenting the dialogues by these steps, I was able to better capture complete thoughts within each segment rather than at set time points, which can often split thoughts across segments, or at the utterance level, which makes it more difficult to capture and account for the interactions between students. For the rating process, each subgoal completed by a dyad in the tutor was assigned a rating category. An inter-rater reliability analysis using the Kappa statistic was performed to determine consistency among raters (Kappa= 0.72).

In addition, I was able to capture the student interactions within the interface through the log data. The log data captured the student's correct answers as well as any errors, hint requests, and the number of attempts. Within the log data, you can then track not only what the action was on the first attempt at a step (i.e., did the student get it correct or not) but also the total number of errors that were made on the step. To analyze the errors made during the tutor, I could then look at the total errors students made as well as the number of steps where an error was made as the first attempt. As with the dialogue data, I divided this data into the subgoals that the students were working on at the time. The reason for this decision was that often an entire subgoal would appear on the student's screen at a time and they would be able to fill out the steps within the subgoal in any order. By then looking at the errors within the subgoal instead of each individual step, we could better understand the errors around the subgoal concept and could better relate it to the type of dialogue that the students were engaging in. The first error count that we then calculated was the total number of errors made on a subgoal by either student in the dyad. The second error count was the number of steps within the given subgoal that contained errors (i.e., had one or more errors).

Because the students were only working with the fractions CITS for one 45-minute session, to analyze how their behaviors changed over time, I calculated the difference between the first half of the session and the second half of the session for the different process variables. This difference gave me the change between the first and second half. Since each dyad completed a different number of subgoals, ranging from 25 to 143, the first and second halves of the session were calculated by dividing the total number of subgoals completed in half. All process measures used in analysis were calculated in proportion to the number of subgoals that were completed.

3.1.3 Results

3.1.3.1 Learning Gains

Table 3.1.2. Percent Correct: means (SD) for conceptual and procedural test items at pretest/posttest.

		Conceptual Test Items		Procedural Test Items	
		Pretest	Posttest	Pretest	Posttest
Conceptually Oriented Condition	Individual Social Plane	0.33 (0.27)	0.42 (0.26)	0.09 (0.13)	0.17 (0.24)
	Collaborative Social Plane	0.34 (0.22)	0.42 (0.20)	0.10 (0.15)	0.16 (0.16)
Procedurally Oriented Condition	Individual Social Plane	0.25 (0.13)	0.27 (0.21)	0.10 (0.17)	0.13 (0.22)
	Collaborative Social Plane	0.35 (0.28)	0.43 (0.24)	0.18 (0.23)	0.18 (0.23)

Because the procedural and conceptual tutor problems were fundamentally different, each of these conditions was treated separately and the collaborative and individual social planes were not compared across problem types. Three students were excluded from the analysis because experimenter error, leaving 81 students. We analyzed the data by individual so we could evaluate each student's learning gain (see Table 3.1.2). To test my hypothesis that, on tutor activities targeting conceptual knowledge, students working collaboratively have higher learning gains than students working individually (H2a), we conducted two multilevel linear models, one for procedural test items and one for conceptual items, with condition (collaborative or individual) as a between-subjects factor and test-time (pretest and posttest) as a repeated measure. I measured the effect size with Pearson's correlation coefficient (r) where 0.1 is a small effect size, 0.3 is a medium effect size, and 0.5 is a large effect size.

For the conceptual test items, there is a significant pre/post difference, $t(39) = 2.06$, $p < .05$, $r = .37$, no main effect of social plane, $t(39) = 0.04$, $p = .97$, and no interaction, $t(39) = 0.08$, $p = .94$ (See Figure 3.1.1). For the procedural test items, there is a marginal pre/post difference, $t(39) = 2.00$, $p = .053$, $r = .30$, no main effect of social plane, $t(39) = 0.03$, $p = .98$, and no interaction, $t(39) = 0.18$, $p = .86$. These results indicate that overall, there were learning gains across the collaborative and individual social planes (H1). However, there was not difference in learning gains between the social planes for either the conceptual or procedural test items.

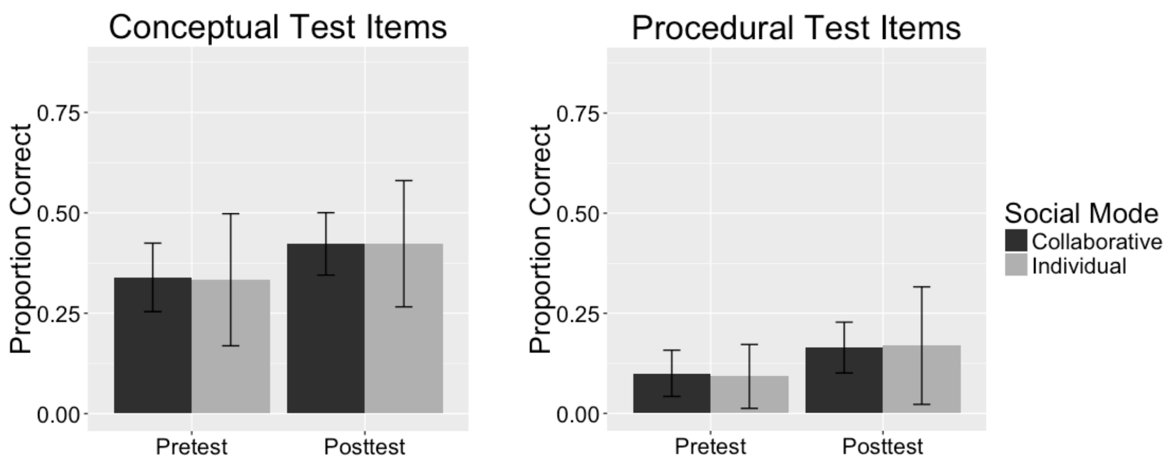

Figure 3.1.1. Pretest and posttest learning gains for students working on conceptually oriented tutors.

To evaluate my hypothesis that students working individually on tutor problems targeting procedural knowledge have higher learning gains than students working collaboratively (H2b), we conducted two multilevel linear models (for procedural test items and conceptual test items, respectively) with condition (collaborative or individual) as a between-subjects factor and test-time (pretest and posttest) as a repeated measure (see Figure 3.1.2). For the conceptual test items, there is no effect of pre/post, $t(38) = 1.45$, $p = .16$, a marginal effect of condition, $t(38) = 1.85$, $p = .07$, $r = .29$, with the collaborative group higher, and no interaction $t(38) = 0.80$, $p = .43$. For the procedural test items, there is no effect of pre/post, $t(38) = 0.47$, $p = .6$, no main effect of condition, $t(38) = 1.06$, $p = .30$, nor an interaction between condition and pre/post, $t(38) = 0.47$, $p = .64$. Within the procedurally oriented condition, there were no significant learning gains overall (H1). Additionally, there was no learning gain difference between the collaborative and individual social planes. The conditional difference reflects the fact that the students in the individual procedural group started lower at pretest and remained lower at posttest.

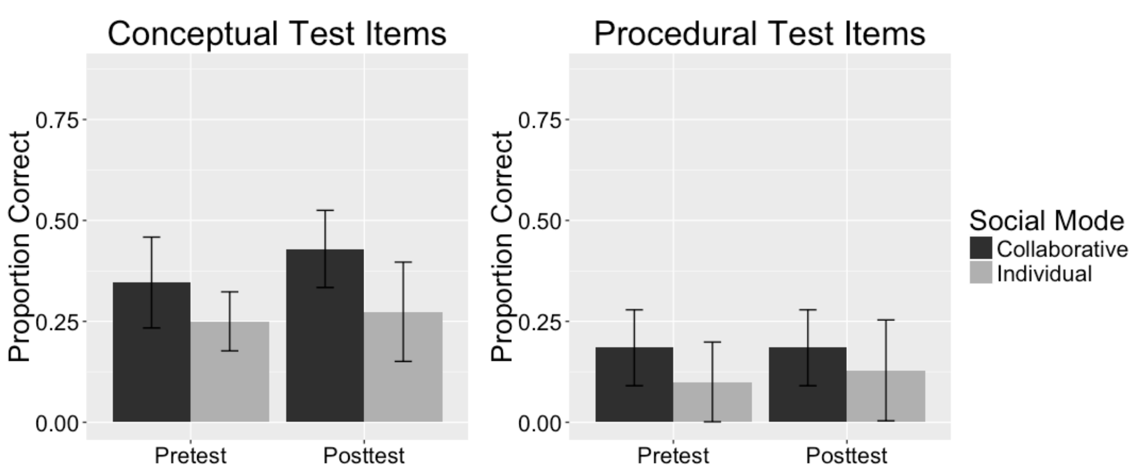

Figure 3.1.2. Pretest and posttest learning gains for students working on procedurally oriented tutors.

3.1.3.2 Problems Completed

To test the hypothesis that the students in the collaborative condition completed fewer problems while working with the tutor (H3), I conducted two t-tests (for the conceptually oriented and procedurally oriented conditions respectively) comparing the collaborative and individual social planes to investigate if there was a difference in the number of problems completed. Because the students working in dyads would always complete the same number of problems as their partner (meaning there was no independence between students in a group), I compared dyads to individuals for this analysis. For the conceptually oriented condition, there is a significant difference, $t(25) = -2.79$, $p < .05$, $r = .49$, between the number of problems completed by students working individually and collaboratively with the students working individually completing significantly more problems by about 4.5 problems (see Table 3.1.3). For the procedurally oriented condition, there is also a significant difference between the number of problems completed by students working individually and collaboratively, $t(25) = -2.29$, $p < .05$, $r = .42$, with students working collaboratively doing fewer problems than students working individually by about 2.5 problems (see Table 3.1.3).

Table 3.1.3. Problems Completed: means (SD) for conceptual and procedural problems completed.

	Individual Social plane	Collaborative Social plane
Conceptually Oriented Condition	11.62 (5.19)	7.21 (2.72)
Procedurally Oriented Condition	9.29 (2.79)	6.69 (3.09)

3.1.3.3 Relationship Between Errors and Dialogue

To better understand the relationship between the type of talk that occurred between dyads and the errors that were made during the tutoring session, I focused the analysis on students that only engaged in the collaborative social plane (26 dyads). Because the errors and talk all occurred during the tutoring process between the dyads, I investigated the relationship between errors and talk at the dyad level. As mentioned in the methods section, both the dialogue and errors were coded at the subgoal level, which is what is used within this analysis. The average number of subgoals completed per dyad was 59.2 (*SD* = 24.6). Of those completed subgoals 78.59% had students talking during the subgoal (i.e., 21.41% of the subgoals were completed in silence, see Table 3.1.4). Of the subgoals where there was student discussion (1196 subgoals), 26.6% had at least one error. How the talk differed between these 318 subgoals where there was dialogue and an error compared to when no error occurred is of interest to better understand how the collaboration may impact the learning process.

Table 3.1.4. Percentage of Subgoals with Different Types of Talk

Interactive Dialogue	Constructive Dialogue	Constructive Monologue	Other	No Talk	Total
24.53%	11.54%	2.10%	40.43%	21.41%	100%

To investigate the association between errors and interactive dialogue (H4), I used a hierarchical linear model with two nested levels to analyze how the talk during subgoals related to the number of errors made. For this analysis, I used the 1196 subgoals that contained talk as my sample size. At level 1, I modeled errors for each of the talk types for the subgoals. I used interactive dialogue as the baseline. At level 2, I accounted for random dyad differences. I found a significant difference in the number of errors found between interactive dialogue and constructive dialogue, $t(1184.90) = -2.34$, $p < .05$, $r = .07$, and interactive dialogue and other talk, $t(1183.70) = -5.70$, $p < .05$, $r = 0.16$ (see Figure 3.1.3). There was not a significant difference between interactive dialogue and constructive monologue, $t(1190.40) = -0.72$, $p = .47$.

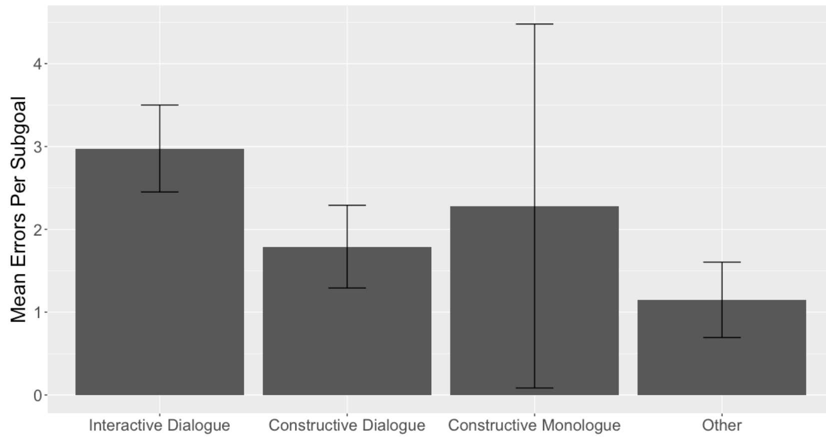

Figure 3.1.3. Errors per subgoal divided by the type of talk students engaged in within that subgoal.

To better understand the patterns of talk that occur around errors, I performed a qualitative analysis on the errors. Four dyads were chosen at random, of which three had above-average learning gains whereas the fourth dyad had below-average learning gains. The four dyads had 61 subgoals in which errors occurred (M = 15.25, SD = 4.99). Of these subgoals, 59% had only one error (M = 2.31, SD = 2.55). Students having interactive talk on a subgoal did not guarantee that they had interactive talk after an error occurred. Of the subgoals that had interactive talk, only 33.3% also had interactive talk occur after the error as well. When interactive talk occurred during a subgoal but was not present after an error, the students would try to answers without any discussion. Below, the students going through different answers, one by one, without discussing why they think an answer could be correct.

Student 2: Yeah, it says answer individually and then as a group.

Student 1: What did you do? I did the second one.

Student 2: Me too. [Tries the second (incorrect) answer.] So…

Student 1: Maybe try the fourth one?

Student 2: [Tries the fourth (incorrect) answer.] No…

Student 1: It's the first one?

Knowing that an error was made did not provide enough support for the students to engage in a productive conversation. When *interactive talk* happened *after* an error occurred, in 88% of these cases, students asking the tutoring system for a hint prompted the interactive talk. Below the students got the answer incorrect, they then request a hint, which they discuss out loud, and are able to continue to discuss what they think the correct answer is with advice from the hint.

Student 2: Um, we're supposed to answer this individually and then as a group.

Student 1: So, I got, um C.

Student 2: Which one is right?

Student 1: Um, let's see…Oh I see what I did wrong. I was thinking of something else. I think it's the last one, D.

Student 2: Uh, yeah. [Tries the fourth (incorrect) answer.] It's incorrect.

Student 1: There's a hint button. "What is the relationship of the numerator and denominator of the equivalent fractions? What is the pattern in the fractions?" We count it up by one each time, if you think about it. And then, cuz the top, the bottom number counted up by four each time, cuz it went eight, twelve, sixteen, and then…

Student 2: Yeah, yeah. It went two, three, four. So the bottom number is multiplied, no, added…

Student 1: Four each time. [Continued discussion about the answer]

Of the subgoals with errors, 90.1% did not elicit any interactive dialogue after the error and in these cases the students did not discuss any hints. Thus, it appears that the hint provided a starting point for the discussion and a way to engage in the interactive talk. For the subgoals on which there was no interactive talk before or after the error, often the students would try to guess the correct answer without discussing their reasoning behind the proposed answers. Even when the tutor logs showed that a hint was requested, which both students could see, the students did not discuss the hint.

3.1.3.4 Change of Errors and Dialogue Over Time

Additionally to analyzing how talk changed immediately before and after errors, I wanted to investigate how both talk and errors changed throughout the session and how these changes might correlate with one another. To test my hypothesis that the percent of subgoals where interactive talk occurs will change from the first to the second half of the session, I conducted two paired t-tests, one for the procedurally oriented condition and one for the conceptually oriented condition. For the procedurally oriented condition, there was no significant difference in the amount of interactive talk between the first and second half of the session, $t(12) = 1.23$, $p = .24$ (See Table 3.1.5). For the conceptually oriented condition, there was a significant decrease in the amount of interactive talk between the first and second half of the session, $t(12) = 3.50$, $p < .05$, $r = .71$. There was also a significant increase in the amount of other talk between the first and second half of the session, $t(12) = -2.75$, $p < .05$, $r = .62$.

Table 3.1.5. Means (SD) for the interactive talk and errors for the first and second half of the session.

Dependent Variables	**First Half**	**Second Half**
Procedurally Oriented Condition (*n* = 13)		
Percent of subgoals with interactive talk	0.24 (0.18)	0.21 (0.19)
Average number of errors per subgoal	1.27 (0.63)	1.44 (1.02)
Average number of steps with an error per subgoal	0.60 (0.24)	0.53 (0.26)
Conceptually Oriented Condition (*n* = 13)		
Percent of subgoals with interactive talk	0.32 (0.20)	0.19 (0.12)
Average number of errors per subgoal	3.46 (2.84)	1.69 (0.96)
Average number of steps with an error per subgoal	0.72 (0.15)	0.58 (0.17)

To better understand how the change in interactive talk may be related to students' problem-solving behaviors with the fractions CITS, I analyzed how my two error measures differed between the first and second half of the session. I used a paired t-test to compare the two time points. In the procedurally oriented condition, there was no significant difference in the total number of errors made between the first and second half of the session, $t(12) = -0.87$, $p = .40$ (see Table 3.1.5), and there was no significant difference between the number of steps where errors occurred, $t(12) = 1.48$, $p = .17$. In the conceptually oriented condition, there was a significant decrease in the total number of errors that were made between the first the second half, $t(12) = 2.36$, $p < .05$, $r = .56$, and there was also a significant decrease in the number of steps where an error occurred, $t(12) = 2.45$, $p < .05$, $r = .58$. Thus, in the conceptual condition, we see a decrease from the first to the second half in both interactive talk and problem-solving errors.

To better understand this relationship between interactive talk and errors (H5), I computed two Pearson's correlations. Outliers were removed based on being more than 3 standard deviations away from the mean. First, I analyzed the relationship between the change in interactive talk and the change in the number of steps with errors. There was a strong positive correlation between the change in interactive talk and the change in the steps with errors, $r(10) = 0.59$, $p < .05$ (see Figure 3.1.4). Thus, both interactive talk and the number of incorrect steps decreased over time and these decreases were strongly associated with each other.

Figure 3.1.4. Correlation between the change in interactive talk from the first to second half of the session compared to the change in the total number of errors.

The second relationship that I analyzed was the correlation between the change in interactive talk and the change in total errors. There was a negative correlation between the change in interactive talk and the change in total errors with marginal statistical significance, *r*(10) = -0.53, *p* = .07 (see Figure 3.1.5). This result indicates that dyads with a greater decrease of interactive talk from the first to second half of the session had less of a decrease in the total errors made.

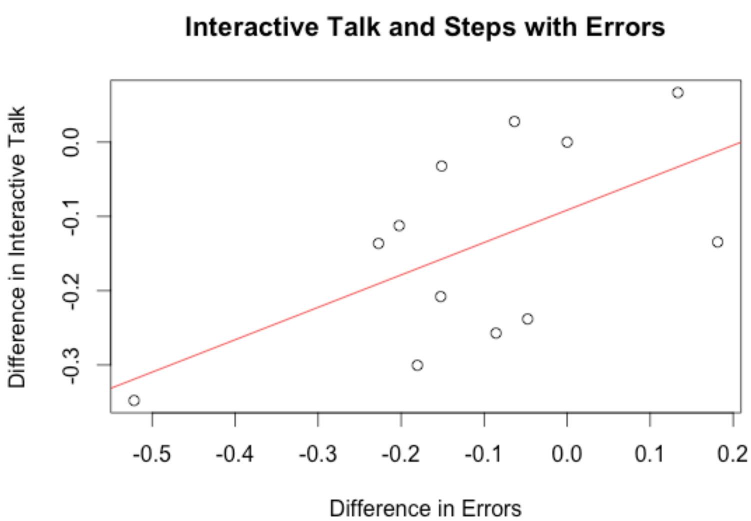

Figure 3.1.5. Correlation between the change in interactive talk from the first to second half of the session compared to the change in the steps with errors.

3.1.4 Discussion

For Experiment 1, 4th and 5th grade students used my fractions CITS to work on either conceptually or procedurally oriented tutor problems working either collaboratively or individually. I hypothesized that elementary school students working collaboratively with a tutor designed to support collaboration would have learning gains from pretest to posttest (H1). The hypothesis was partially confirmed; the students in the collaborative conceptually oriented condition had learning gains comparable to those in the individual condition. In the procedurally oriented condition, neither the collaborative nor individual conditions saw any learning gains. Thus, collaborative instruction was as effective for elementary school students as individual instruction, which extends previous findings in the field where collaborative ITSs were used to support older students (Baghaei, Mitrovic, & Irwin, 2007; Walker et al., 2009; Diziol, Walker, Rummel, & Koedinger, 2010). The fact that there were no learning gains in the procedural conditions may be due to the fact that the procedural problems may have been too difficult for the students. We also saw that overall for all conditions, the average number of problems solved correctly for the procedural test items on either the pretest or the posttest was below one out of five (i.e., 20%, see Table 1).

While students in the collaborative condition saw fewer problems compared to their counterparts in the individual condition, confirming my hypothesis (H3), they still had the same learning gains as the students in the individual conditions. This finding is consistent with other findings in CSCL (Walker et al., 2009). Although students are taking longer on the problems and get through fewer problems, they may get more benefit from each problem when working collaboratively compared to individually. However, I controlled for time and if I had controlled for number of problems, students in the individual condition may have learned as much as the students in the collaborative condition but in less time. Given that the study only lasted 45 minutes though, the students did not have a chance to reach ceiling and over practice, as evidence from their posttest scores. So, even if I had controlled for number of problems, it is unlikely that I would have found a different result.

In terms of hypothesis that the individual condition would yield greater learning gains than the collaborative condition for activities geared towards acquiring procedural knowledge (H2a) and that the reverse would hold for activities geared towards acquiring conceptual knowledge (H2b), I did not find these differences. I may not have found these differences because the instructional period was relatively short. On average the students in the collaborative conceptually oriented condition completed 7 problems. Because the problem types were interleaved and not all knowledge components were present in each problem type, the students did not always get to practice each knowledge component enough to reach mastery. For the collaborative social plane, out of the 16 knowledge components targeted in the conceptually oriented problems, 9 of the knowledge components had (on average, per student) fewer than 5 opportunities to practice the knowledge component. However, the students in the individual condition completed 12 problems on average and had at least 5 opportunities for all 16 knowledge components. By lengthening the practice time with the tutor, such as using the tutor for consecutive days in the classroom, the students would have more time with the tutor and would get more practice.

A second explanation for the fact that the hypothesized differences between the conditions were not confirmed may be that the collaborative learning condition was novel and perhaps more demanding for students. Put differently, students may need more practice with the instructional method of collaborative learning. Especially given that the number of knowledge component opportunities was low, one might expect to see better performance on the posttest. Other studies have also shown that the introduction of new learning strategies can initially lead to worse learning (Westermann & Rummel, 2012). These initial performance losses may initially mask the success of a new learning strategy. Again, lengthening the time with the tutor may help to overcome the novelty effect.

In addition to the learning gains, I analyzed the process data by investigating under what conditions interactive talk happens after an error occurs. Previous work has looked at how supporting collaboration around errors affects learning (Ohlsson, 1996). I hypothesized that there will be more interactive talk after an error occurs than other types of talk (H4). I found that errors are an opportunity for collaborative sense making after students are aware of the misconception *and* request a tutor hint, which provides some measure of support for interactive talk. Although interactive talk does not occur automatically after an error, which does not support my hypothesis, hints can provide a starting point for a conversation by providing domain related language that the students can use in their conversation. When students did not discuss a hint, they often did not have a productive conversation and instead guessed and checked. These findings imply that to support collaborative learning effectively, it may not be enough to just encourage students to collaborate when students are struggling as was done in Rummel, Mullins, & Spada (2012). Especially for younger students, who are still developing the vocabulary needed for effective discussions in STEM domains, it may be important to provide cognitive support around the misconceptions, which can serve as starting points for productive student discussions.

However, as students learn and make fewer errors, there may be less of a need for interactive talk as the students begin to just practice fluency. I hypothesized that there would be a positive correlation between the change in the number of errors students make and the change in the amount of interactive talk that they engage in (H5). Through my analysis I found that in the conceptually oriented condition, students who had a greater decrease in the amount of interactive talk tended to have a smaller decrease in the number of errors that they made, but students who tended to have a greater decrease in the amount of interactive talk tended to have a greater decrease in the number of steps where errors occurred. These results indicate that interactive talk may not be necessary for students to correctly solve a problem, which is supported by the positive correlation of decreased interactive talk and decreased steps with errors, but instead interactive talk may be a tool students can use when struggling, such as around an error. The negative correlation with the total errors would suggest other behaviors are occurring when students make multiple errors on the same step and is an area for future work. I did not find these same patterns for the procedurally oriented condition indicating that there may be different productive learning behaviors for procedural knowledge. The different results may indicate that for procedural knowledge there is less of a need for the deep understanding that is associated with interactive talk to overcome errors.

Experiment 1 showed that collaborative ITSs are a feasible instructional tool to use with elementary school students, with learning gains equivalent to those of students working individually with ITSs and in fewer problems. To the best of my knowledge, this study is the first showing significant learning gains with elementary school students working with collaborative ITSs. Within the study I found that errors might be a point at which collaboration may be most productive. This result was supported by both the correlation of the change in interactive talk and errors over time as well as the qualitative analysis of talk around errors. However, collaboration may not be enough by itself to make errors a moment of learning (Ohlsson, 1996). Cognitive support may also be needed in addition to the social support for students to overcome the impasse (Weinberger et al., 2005). ITSs are able to provide both this cognitive and social support that can help students overcome an error. However, Experiment 1 did have limitations in that the students did not get very much time with the tutor. The students were also pulled-out of their classroom to participate so may not have been as comfortable in collaborating with their partner, as seen in the number of subgoals that were completed without any speech occurring. In a more natural learning environment, the students may be more comfortable talking with their partner. Additionally, the procedurally oriented problems may have been too difficult for the students. These limitations may have led to less pronounced differences between the social planes. Experiment 2 attempts to address these limitations through a longer classroom study.

3.2 Investigating the Strengths of Collaborative and Individual Learning in a Classroom

As with Experiment 1, Experiment 2 aimed to investigate the complementary differences between collaborative and individual social planes. However, to address the limitations of Experiment 1, I conducted Experiment 2 within a classroom setting. Within the classroom setting, I was able to have the study be conducted over multiple days for each student, which addressed the short study time from

Experiment 1. The classroom also provided a more realistic setting for the collaboration compared to the pull-out design from Experiment 1, allowing the students to speak more freely. Additionally, the fractions CITS was updated to address the issue with the procedurally oriented tasks possibly being too difficult. Although the setting for the study was changed as well as the tutoring units, as addressed in the next section, Experiment 2 aimed to address similar research questions as Experiment 1.

3.2.1 Research Questions and Hypotheses

Within Experiment 1, I found evidence that a CITS could be used to support learning for younger students. This finding added to the existing results that have shown that CITS can be effective with older students (Baghaei, Mitrovic, & Irwin, 2007; Walker et al., 2009; Diziol, Walker, Rummel, & Koedinger, 2010). However, students are not often learning in as controlled an environment as takes place in a pull-out design study. Classrooms can often have more variables happening, such as students being absent, students talking with one another when they should be working individually, and students having friction with their group members. These variables are components of real classroom environments, so when developing new technology and interventions, it is important to investigate how they perform within a real classroom.

Within the classroom environment, students also may feel more comfortable in communicating with their partner when they do not feel as monitored. The change in environment can lead to different process behaviors as the students work with the tutors. These behaviors can impact how the students interact with the different learning materials. Within a classroom setting, where students may have more natural behaviors, there may be a greater impact of individual and collaborative social planes for acquiring different types of knowledge (Mullins et al., 2011). As with Experiment 1, Experiment 2 was designed to target conceptual and procedural knowledge. I hypothesized that a CITS can effectively support young learners in a classroom setting (H1). Additionally, I hypothesized that collaborative and individual social planes have complementary strengths for conceptual and procedural knowledge respectively (H2). Because students were given ample time to complete all problems, I hypothesized that students in the individual condition would complete all problems in less time than those working collaboratively (H3).

3.2.2 Methods

3.2.2.1 Experimental Design and Procedure

I conducted Experiment 2 with 189 4th and 5th grade students from two schools across two school districts. The students came from a total of nine classrooms and five teachers. The experiment took place during the students' regular class periods. All students worked with the fractions CITS described above. Within Experiment 2, the procedural and conceptual problem types were used for all seven units. During the study, students either worked on conceptually oriented tasks only or procedurally oriented tasks only, and working either collaboratively or individually for the entire length of the study. Thus, I had 4 conditions that I analyzed as two separate 2-conditions designs as the conceptually and procedurally oriented problem types could not be directly compared. Collaborating students were instructed to sit next to each other while working to allow the students to communicate through speech. This dialogue was then recorded on an individual stream for each student.

I assigned students to individual and collaborative conditions based on class for a quasi-experimental design. This random assignment based on class was done to limit the disruption to the class since students would not have the option to ever work in the other social plane. There were five classes that were assigned to work collaboratively and four classes that were assigned to work individually. Within each class, teachers paired their students based on who would work well together and had similar math abilities. These pairs were then randomly assigned to work on the procedurally oriented or the conceptually oriented problem types. Within the class there was an even split between students working on conceptually oriented problems and procedurally oriented problems.

During the study, if a student's partner were absent when working collaboratively, the student would be paired with another student working on the same problem type (i.e., conceptual or procedural) for the remainder of the experiment. If there were two students that needed partners who had worked together before, they were paired together. If there were an odd number of students who needed a partner, then one student would work individually for the day. The teacher informed student pairings with a new partner when there was more than one option. When students started with a different partner from the day before, they would begin the problem set at the place of the student that had made less progress.

The study ran across five 45-minute periods for each class. On the first day, the students took the pretest individually. When they completed the pretest, they moved onto a tutorial that gave some instruction on how to interact with the tutor (described above); otherwise, the tutorial was done on the second day. The students then worked with the tutor for the next three days within their assigned condition. On the fifth day, the students took a posttest individually.

3.2.2.2 Dependent Measures

I assessed students' knowledge at two different times using two equivalent test forms in counterbalanced fashion. The tests targeted both conceptual and procedural knowledge types for all conditions. Each test had 20 questions, 10 procedural and 10 conceptual where six were isomorphic with the main six fractions units and four were near transfer targeting the four upper level fractions units. For each question on the test, the students were able to get a point for each step completed correctly. On the tests there were 23 possible conceptual test points and 68 procedural test points. Because of the discrepancy in points for the different types of knowledge, for both conceptual and procedural test scores, the percentages were used for all analyses. Examples of the test items can be found in Appendix 2.

In addition to test data, I also collected log data from the students. As with Experiment 1, the log data collected in Experiment 2 provided information around the transactions that occurred within the tutoring system. The log data provided information on the hints and errors that the students made within the system as well as the amount of time that each student spent on the fractions CITS each day.

3.2.3 Results

Due to absenteeism during the study, only 146 of the 189 students were used for the analysis. Students were excluded if they missed either the pretest or posttest. They were also excluded if they missed more than 1 day of working with the tutor. In the collaborative condition, students were excluded if they had more than a total of two partners during the tutors. There was no significant difference between conditions with respect to the number of students excluded, $F(3, 185) = 0.72$, $p = .54$. There was also no significant difference between conditions on the pretest score for either the conceptual test items, $F(3, 142) = 0.49$, $p = .69$, or for the procedural test items, $F(3, 142) = 0.68$, $p = .57$.

As discussed, I used a separate 2-condition between-subjects design to compare an individual and a collaborative learning condition for conceptually oriented and procedurally oriented tutor problem sets. For the analysis, the data was thus treated as two separate data sets within which students working collaboratively or individually could be compared. Out of the 146 students used in the analysis, 70 students worked with the procedurally oriented ITS, and 76 students worked with the conceptually oriented ITS.

3.2.3.1 Pre/Posttest Learning Gains

To investigate whether students learned using the fractions CITS, and if there was a difference in learning between the students working collaboratively and students working individually within the two tutor problem sets (see Table 3.2.1), I used a multilevel approach to take into account the repeated measures of the pretest and posttest and differences between teachers. Within this analysis, I treated all students as individuals. We conducted a hierarchical linear model (HLM) with student at the first level and teacher at the second level. At level 1, I modeled the pretest and posttest scores, and at level 2, I accounted for random differences that could be attributed to the teacher. I did not include dyads as a level because of the added complexity of some students working with no partner (i.e. individuals), some students having one partner, and some students having two partners because of absenteeism. I am aware of non-independence issues such as common fate and reciprocal influence that may impact my results (Cress, 2008). I measured the effect size with Pearson's correlation coefficient (r) where 0.1 is a small effect size, 0.3 is a medium effect size, and 0.5 is a large effect size.

Table 3.2.1. Percent Correct: means (SD) for conceptual and procedural test items at pretest/posttest.

		Conceptual Test Items		Procedural Test Items	
		Pretest	Posttest	Pretest	Posttest
Conceptually Oriented Condition	Individual Social plane	0.51 (0.31)	0.77 (0.22)	0.35 (0.25)	0.52 (0.30)
	Collaborative Social plane	0.48 (0.23)	0.67 (0.24)	0.36 (0.21)	0.51 (0.25)
Procedurally Oriented Condition	Individual Social plane	0.54 (0.29)	0.64 (0.30)	0.42 (0.30)	0.64 (0.34)
	Collaborative Social plane	0.55 (0.20)	0.68 (0.20)	0.40 (0.20)	0.65 (0.25)

First, I analyzed data from students who worked with the *conceptually oriented tutors*. I tested whether there were statistically significant pre/post learning gains and I compared the learning gains between students working individually and students working collaboratively. I did so separately (with separate HLMs) for gains on the conceptual test items and gains on procedural test items. For the conceptual test items, a significant effect between pre and posttests was found with posttest having a higher score, $t(74) = -9.29$, $p < .001$, $r = .73$, while no significant effect for individual/collaborative learning, $t(70) = -1.25$, $p = .22$, $r = .15$, nor interaction, $t(74) = 1.47$, $p = .15$, $r = .17$, was found (see Figure 3.2.1). For the procedural test items, a significant effect between pre and posttests was found with posttest having a higher score, $t(74) = -6.80$, $p < .001$, $r = .62$, while no significant effect for individual/collaborative learning, $t(70) = 0.35$, $p = .72$, $r = .04$, nor interaction, $t(74) = 0.39$, $p = .70$, $r = .05$, was found (see Figure 3.2.1). Thus, although there was learning from pretest to posttest on both conceptual and procedural test items across social planes, there was no difference in learning between students working individually and students working collaboratively. To investigate whether there was a difference in the time it took students to complete the posttest, I ran a t-test. No significant difference was found for the time it took students to complete the posttest between the students working individually and students working collaboratively, $t(74) = -1.16$, $p = .25$.

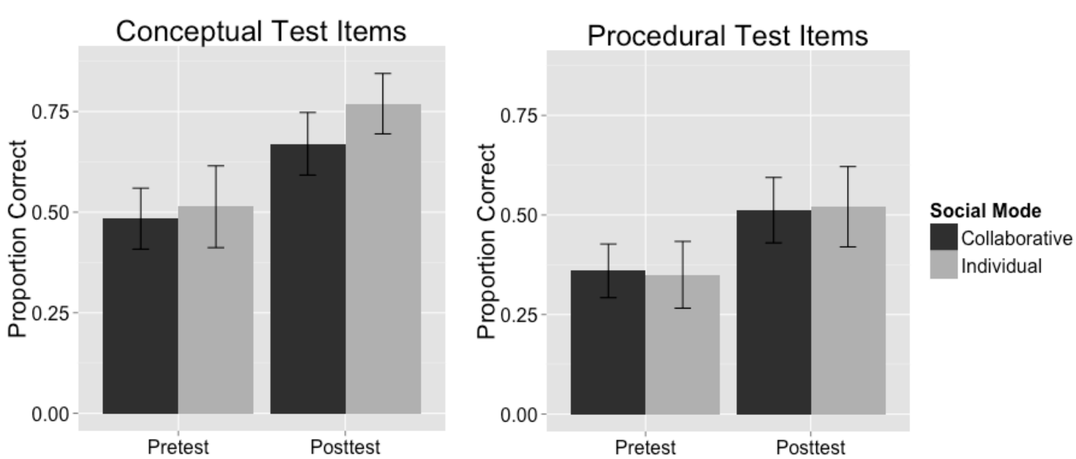

Figure 3.2.1. Learning gains on the conceptually oriented tutors. Conceptual test items on the left and procedural test items on the right. Collaborative students are black and individual students are light gray.

Second, I analyzed data from students who worked with the *procedurally oriented tutors*. I tested whether there were statistically significant pre/post learning gains and I compared the learning gains between students working individually and collaboratively. I did so separately (with separate HLMs) for gains on the conceptual test items and gains on procedural test items. For the conceptual test items, a significant effect between pre and posttests was found with posttest having a higher score, $t(68) = -4.49$, $p < .001$, $r = .48$, while no significant effect for individual/collaborative learning, $t(64) = 0.68$, $p = .5$, $r = .08$, nor interaction, $t(68) = -0.56$, $p = .58$, $r = .07$, was found (see Figure 3.2.2). For the procedural test items, a significant effect between pre and posttests was found with posttest having a higher score, $t(68) = -8.40$, $p < .001$, $r = .71$, while no significant effect for individual/collaborative learning, $t(64) = 0.04$, $p = .97$, $r = .005$, nor interaction, $t(68) = -0.57$, $p = .57$, $r = .07$, was found (see Figure 3.2.2). Similar to what I found with the conceptually oriented tutor, there was learning from pretest to posttest with the procedurally oriented tutor, on both conceptual and procedural test items, across social planes, but there was no difference in learning between students working individually and students working collaboratively. Also, no significant difference was found for the time it took students to complete the posttest between the students working individually and students working collaboratively, $t(68) = -0.49$, $p = .62$.

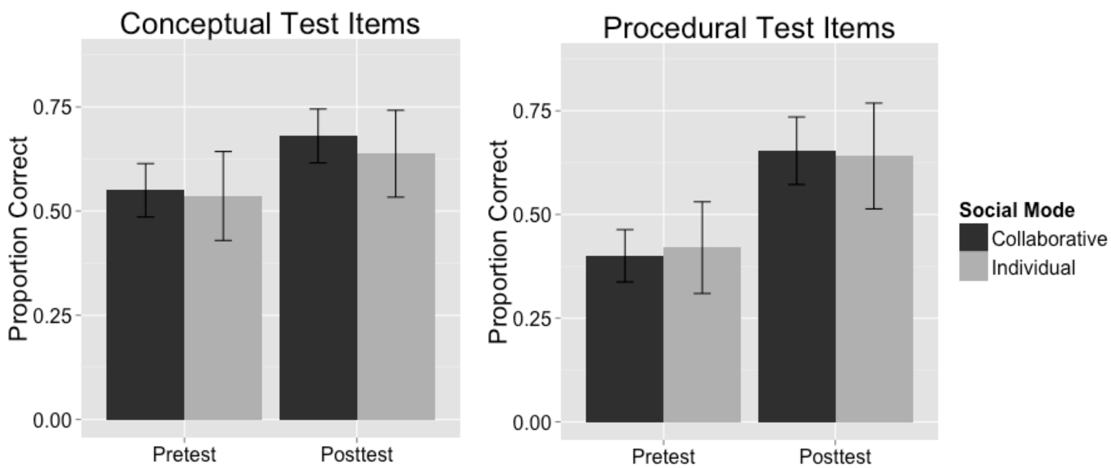

Figure 3.2.2. Learning gains on the procedurally oriented tutors. Conceptual test items on the left and procedural test items on the right. Collaborative students are black and individual students are light gray.

3.2.3.2 Time on ITS

Table 3.2.2. Mean time and problems completed on the ITS for each condition and standard deviations

Tutor Materials	Social plane	Time in Minutes: M (SD)	Problems Completed: M (SD)
Conceptually-oriented	Collaborative	74.23 (13.13)	43.21 (12.27)
	Individual	84.16 (18.11)	45.24 (14.50)
Procedurally-oriented	Collaborative	71.17 (14.41)	43.15 (10.31)
	Individual	84.11 (20.68)	45.30 (12.65)

To test the hypothesis, that the students working collaboratively, would take longer on the tutor to complete the problems, I ran two t-tests. Because the students working collaboratively would have the same amount of time as their partner, I compared the dyads to the students working individually for both the conceptually oriented and procedurally oriented conditions. The reported p-values were adjusted for multiple comparisons using the Bonferroni correction. For the study, ample time was given to students to work with the fractions CITS with the expectation that all students would complete all of problems for the assigned units. Using two t-tests, we found no difference between students working individually or collaboratively in the number of problems completed for the conceptually oriented tutors, $t(59) = -0.57$, $p = .57$, or the procedurally oriented tutors, $t(55) = -0.70$, $p = .49$, (see Table 3.2.2). However, because the number of problems was fixed, students could work at their own pace and would finish the tutors at different times. Using two t-tests, there was a significant difference between students working individually/collaboratively on the time spent on the tutor for the conceptually oriented tutors, $t(59) = -2.32$, $p < .05$, $r = .29$, and the procedurally oriented tutors, $t(55) = -2.71$, $p < .05$, $r = .34$, where, surprisingly, students working collaboratively spent less time on the ITS (see Table 3.2.2). The students working collaboratively were able to complete the same number of problems as the students working individually but in less time.

To investigate if the difference in time may have been due to the students in the collaborative conditions encountering fewer errors, which can take time to correct, or asking for more hints, I ran t-tests comparing the total errors, encountered, initial errors, which indicate the number of steps that where not correct, and the number of hints requested between the two social planes. For the conceptually oriented condition, there were no significant differences between the total number of errors, $t(59) = 1.81$, $p = .45$, initial errors, $t(59) = 0.39$, $p = 1.00$, and hints requested, $t(59) = 1.31$, $p = 1.00$, for social planes. Within the procedurally oriented condition there were also no significant differences found between the total number of errors, $t(55) = 0.49$, $p = 1.00$, initial errors, $t(55) = 1.29$, $p = 1.00$, and hints requested, $t(59) = -0.57$, $p = 1.00$, for social planes. These results indicate that for both the conceptually and procedurally oriented conditions, there was no difference in the errors and hints between students working collaboratively and individually.

3.2.4 Discussion

The results of Experiment 2 showed significant learning gains for students working collaboratively with both the procedurally oriented and conceptually oriented tutors. There was no difference in the learning gains of students working collaboratively versus students working individually. However, students working collaboratively completed the same number of tutor problems in less time on the tutor. These results confirm my hypothesis that young learners can be successfully supported in learning through the use of a CITS and indicate that a CITS is a viable option to use in the classroom.

Consistent with Experiment 1 (Olsen et al., 2014a), the results did not support my hypothesis that students working on conceptually oriented tasks would benefit more from collaboration and students working on procedurally oriented tasks would benefit more from working individually. However, in the current study, I found evidence that collaborative learning with an ITS can be more efficient than learning individually with an ITS. Within the study, all students solved the same number of problems (i.e. had the same amount of practice), but the students working in the collaborative condition spent less time on the tutor. This result was surprising; I expected to find the opposite as I had with Experiment 1 (Lou et al., 2001). Collaboration may increase the time spent on each problem if students are discussing the solution, which is time that would not be spent in the individual condition. To try to resolve the discrepancy between Experiments 1 and 2, I analyzed the differences in errors between conditions. Through discussion, the students in the collaborative condition may be able to avoid more errors that take time to resolve. However, I did not find evidence of lower errors in the collaborative condition and instead found that the students working collaboratively and individually made the same number of errors and requested the same number of hints. The efficiency may also come in that the students are dividing the steps between group members. They are then able to finish more steps faster by overlapping the different tasks. To investigate this question, future work would need to analyze the learning that happened within the tutor and how it may have changed over time. By analyzing the process data, we could better understand what actions the students were taking with the tutor and where the efficiency gains were made. Changes in behavior over time may be an indication of where collaborative and individual learning may be most beneficial, especially if we see students moving away from more collaborative behaviors and towards cooperative behaviors.

While the collaborating students learned as much as their classmates who worked individually with regard to domain knowledge, they may have had more of an opportunity to develop their math reasoning skills and social skills by working with a partner. In a collaborative setting, students need to be able to construct their arguments well enough for their partner to understand their reasoning and are given the opportunity to ask questions (Chi & Wylie, 2014). This process provides them with the opportunity to develop their math reasoning and to critique the reasoning of others. A limitation of this study is that we did not assess social skills or mathematical reasoning skills for the students, which is where we would expect students collaborating to benefit beyond those working individually, as Rummel and Spada (2005) found that students who had an opportunity to collaborate had better knowledge about collaboration skills. However, if the efficiency in problem solving is coming through the division of labor, these explanation benefits may be limited.

3.3 Summary and Discussion

Before being able to investigate if collaborative and individual learning have complementary strengths, first the question if a collaborative ITS could successfully support student learning for elementary school students needed to be addressed, as the students were younger than have typically been supported with a collaborative ITS (Baghaei & Mitrovic, 2005; Diziol et al., 2010; Harsley et al., 2016; Lesgold et al., 1992; Suebnukarn & Haddaway, 2004; Tchounikine et al., 2010; Walker et al., 2006). Across Experiments 1 and 2, I found positive results with the students having learning gains in the individual conditions comparable to those students working in the collaborative conditions. These results indicate that a collaborative ITS is a viable option for elementary school learning, especially as these results were supported in a classroom setting. This finding is important since, within current standards, it is not just required for students to be able to complete the steps to solve a problem, but they have to be able to understand and explain why the procedure works (Common Core State Standard Initiatives, 2017). By being able to use a collaborative ITS with younger students, we can provide more individualized support for students while still having them engage in a learning process that supports the giving and receiving of explanations (Hausmann et al. 2004). However, learning to provide explanations is not the only skill required and it is important to understand when the strengths of different social planes would be beneficial.

Experiments 1 and 2 aimed to address if collaborative and individual learning have complementary strengths in terms of conceptual and procedural knowledge through both a pull-out study, in which the environment was more controlled, as well as a classroom study, where the environment would be more realistic. Within these experiments, the students were all working on the fractions CITS that was developed to support both collaborative and individual learning activities. In both experiments, the results did not support my hypothesis or past research that students working on conceptually oriented tasks would benefit more from collaboration and students working on procedurally oriented tasks would benefit more from working individually (Diziol et al., 2009; Mullins et al., 2011). However, learning with an ITS individually has been shown to be very successful, especially within mathematics (Ritter et al., 2007; Rau et al., 2012). Collaboration adds an extra layer of complexity that might be expected to inhibit the learning process, even within an ITS. However, the effect sizes do support that the conceptually and procedurally oriented tutors were supporting the their respective knowledge types. In Experiment 2, the students working on the conceptually oriented tutors had large effects size for learning gains on the conceptual test items, while the students working on the procedurally oriented tutors had large effect sizes for the procedural test items compared to the conceptual test items.

Complementary strengths may not have been found if the alignment of collaborative and individual learning with conceptually and procedurally oriented tasks was at too large of a grain size. As observed in the process analysis of Experiment 1, errors may be an opportunity where collaboration would be beneficial (Ohlsson, 1996). When students are confident in their answers, there may not be much for them to discuss. When they then make an error, the error provides them with the opportunity to correct their mental model, where it can then be beneficial to have another viewpoint (Webb, 2013). When addressing misconceptions, it may then be more beneficial for students to be collaborating, but otherwise be working individually to build fluency. Misconceptions can occur in both conceptually and procedurally oriented problems. By aligning the social modes at the problem level, I may have been examining the wrong grain size for the complementary strengths.

Experiments 1 and 2 make contributions to the field by demonstrating that collaborative ITS can be used to successfully support learning with elementary school students and furthering the investigation into the different strengths of collaborative and individual learning. In Experiments 1 and 2, the learning gains for students collaborating were as high as those working individually. This finding adds to the body of literature that has shown collaborative ITSs to be successful with older students. Although elementary school students have a different set of social skills, it is still possible to support their learning in a collaborative environment that is primarily led by the group instead of the teacher. Additionally, the experiments add to the literature on the strengths of collaborative and individual learning. Although they did not support the results of previous experiments (Diziol et al., 2009; Mullins et al., 2011), they provided evidence that problem type may not be the appropriate alignment for social plane. Process analyses around errors suggest that misconceptions and errors may be a fruitful direction for future work.

4 Combining Collaborative and Individual Learning in a Classroom

Although I did not find evidence for complementary strengths between collaborative and individual learning in Experiments 1 and 2, that does not mean that the two social planes together are not better than either alone. For example, Rittle-Johnson et al. (2001) claim that both conceptual and procedural knowledge are important for learning and may interrelate. When the students only receive practice on one type of knowledge, as they did in Experiments 1 and 2, then they miss the benefits of the other knowledge. Students would then benefit more when they get to practice both types of knowledge. Additionally, when the social planes are beneficially aligned with the problem types, the benefits may be magnified. Students may also just find benefit in getting to switch between the two social planes.

Additionally, collaborative and individual learning may support different learning processes that can impact the learning process and knowledge construction (Koedinger, Corbett, & Perfetti, 2012) and these processes may be more effective when a student gets to engage in both. Collaborative learning supports students in giving and receiving of explanations and co-constructing knowledge (Hausmann, Chi, & Roy, 2004), which may help students develop a deeper conceptual understanding (Teasley, 1995). In addition, discussions that happen during collaboration can potentially support the students' social goals (e.g., responsibility goals, popularity goals) and make them feel more connected to their group members, which can increase their motivation for the activity (Rogat, Linnenbrink-Garcia, & DiDonato, 2013) and increase the desire to continue working on the task. Specifically, situational interest in the task, which is interest that arises due to a response to the factors in the environment (Linnenbrink-Garcia et al., 2010), can increase when a task involves collaboration. On the other hand, for problem-solving practice, individual learning may be more beneficial than collaborative learning. Working individually may allow students to get more practice in the same amount of time and develop fluency (Mullins et al., 2011) since students are not sharing tasks with a partner and do not necessarily have to pause to explain their actions. By allowing students to engage in both of these learning processes instead of just one, students may have additional learning gains. It remains an open question if a combination of collaborative and individual learning is better than either alone and how to best support this combination.

If collaborative and individual learning are beneficial for different types of knowledge constructions, then a combination of collaborative and individual learning may be more beneficial than either alone. Previous work within CSCL has combined social planes within learning activities using integrative scripts (Dillenbourg, 2004) that prescribe different social planes for different phases of a learning activity (Dillenbourg, 2004; Diziol, Rummel, Spada, & McLaren, 2007). For example, integrative CSCL scripts based on the Jigsaw method have people work individually to gain expertise in an area before working in expert groups and then mixed expert groups to share that expertise (Aronson, 1978). Although these scripts use a combination of collaborative and individual learning, they are often only compared to individual only interventions and not to collaborative only interventions when their effectiveness is investigated. It can be difficult to find these combinations in the literature because in pervious work they have often been referred to as the collaborative condition without distinguishing that students also have a chance to work individually. In recent work by Celepkolu, Wiggins, Boyer, & McMullen (2017), they compared students working on paired programming to students who had individual time to assess the problem before working collaboratively. Although they found that the mixed condition was better than just the paired programming, the conditions did not have the same number of phase, as the students in the collaborative condition did not have a chance to discuss the assignment in pairs before beginning the programming portion. In my work, the students in each condition have the opportunity to do the same tasks. By orchestrating a combination of collaborative and individual learning that plays to the strengths of each social plane, we may be able to more effectively support learning. However, it is also possible that switching between social planes adds overhead to the learning process, which could have a negative impact on the student performance that outweighs the benefits of a combination, even if this combination is aligned to their particular strengths. Hence, it is important to understand whether combining individual and collaborative learning, in a way that aligns with their respective strengths, is more effective than individual or collaborative learning alone.

For Experiment 3, I investigated the open question of whether a combination of collaborative and individual learning is more efficient for student learning than either alone. In the study, all of the students worked on both conceptual and procedural knowledge through erroneous example problems and procedural problem sets respectively. Although complementary strengths were not supported in Experiment 1 and 2, it is important to understand how the collaborative and individual social planes might support each other when students have the opportunity to engage in both compared to only one.

4.1 Research Questions and Hypotheses

As stated, previous research has found mixed results around the effectiveness of collaborative learning (Lou et al., 2001). These mixed results may be due to how the collaboration and individual learning is being aligned with the learning activities and how the collaborative and individual learning phases are being combined, if at all, in the integrative script. Collaborative learning may be beneficial by supporting students in giving and receiving explanations as well as the opportunity to co-construct knowledge with their partner (Hausmann, Chi, & Roy, 2004). In addition, discussions that happen during collaboration can potentially support the students' social goals (e.g., responsibility goals, popularity goals) and make them feel more connected to their group members, which can increase their motivation and interest for the activity (Rogat, Linnenbrink-Garcia, & DiDonato, 2013) and increase the desire to continue working on the task. Specifically, situational interest in the task, which is interest that arises due to a response to the factors in the environment (Linnenbrink-Garcia et al., 2010; Schraw, Flowerday, & Lehman, 2001), can increase when a task involves collaboration. Situational interest is of particular importance because educators can have some influence over the environment and tasks within the classroom (Mitchell, 1993). On the other hand, for problem-solving practice, individual learning may be more beneficial than collaborative learning. Working individually may allow students to get more practice in the same amount of time and develop fluency (Mullins et al., 2011) since students are not sharing tasks with a partner (when students are collaborating, they may divide the tasks to finish faster but get less practice) and do not necessarily have to pause to explain their actions. In light of these different learning processes, collaborative and individual learning may complement each other when combined.

To design a mixed collaborative/individual condition, I created learning activities that, based on theoretical grounds such as those discussed above, would appear to play to the strengths of the given social plane; specifically, I used erroneous example problems for collaborative learning and tutored problem solving for individual learning. Within research on example-based learning, both worked examples and erroneous examples have been shown to be successful for supporting learning (McLaren, et al., 2012; Renkl, 2005; Tsovaltzi et al. 2010). In addition, prior research shows that when students study worked examples collaboratively, they tend to avoid shallow processing, ask for fewer hints, and spend more time on explanations than when working individually (Hausmann, Nokes, VanLehn, & van de Sande, 2009; Hausmann, van de Sande, & VanLehn, 2008a; Hausmann, van de Sande, & VanLehn, 2008b). Further, erroneous examples can help to foster reflection and more fruitful explanations (Isotani et al, 2011; Siegler, 1995; Tsovaltzi et al., 2009). When students are able to collaborate around erroneous examples, they may benefit from engaging in sense making with their partner, fostered both through the erroneous examples and the collaborative learning. On the other hand, for tutored problem solving, tutors often support student learning through step-by-step support. This step-by-step support focuses the attention of the student on one step at a time, which can lead to students entering an answer as soon as it is known instead of having a discussion around the problem (Mullins et al., 2011). When students are working individually, they do not have to divide tasks with another student, or stop often to discuss a problem step, which likely allows each student to get more practice with the problem-solving skills. In turn, more practice with the problems may allow the students to build more fluency and procedural knowledge (Anderson, 1983). Additionally, students have a chance to self-explain without another student stepping in (Chi, Chiu, & LaVancher, 1994). When students are able to work individually around the tutored problem solving, they may benefit from the faster-paced practice that is fostered from both the step-by-step nature of the problems and the individual learning.

In Experiment 3, my main hypothesis centered on the effectiveness of combining collaborative and individual social planes to support learning. Specifically, I investigated the combination of students working collaboratively on erroneous example problems and individually on procedurally oriented problems compared to students either working collaboratively or individually on both problem types. I hypothesized that the students that have a combination of collaborative and individual social planes (i.e., mixed condition) will have higher learning gains than students who only work collaboratively or individually (H1). Because the process that the students engage in when learning plays a role in the learning outcomes, I additionally investigated process variables, including student interest in the task, problems completed, hints, and errors, that could provide insight into how the conditions differed. When students are working individually, they will complete more problems. I hypothesized that students working individually on the erroneous example problems would complete more problems than those working collaboratively (i.e., mixed and collaborative conditions) and those working individually on the tutored problem solving (i.e., mixed and individual conditions) would complete more problems than those working individually as they were be spending less time on explanations (H2) (Hausmann et al., 2008b). While working with the fractions CITS, additionally I hypothesized that students who have a chance to collaborate will make fewer errors (H3) and request fewer hints (H4) (Hausmann et al., 2008a; Hausmann et al., 2008b). For the mixed condition, the low error rate and hint requests will be maintained even for the procedurally oriented problem types, as the students will have benefited from the collaborative social plane during the erroneous example problems. For the situational interest in the fractions CITS, I hypothesized that students who have a chance to work collaboratively (i.e., mixed and collaborative conditions) will have more situational interest in the activity than students that only work individually (H5) (Linnenbrink-Garcia et al., 2010). Together, these process analyses could provide insights into how the different students performed while working with the tutor.

4.2 Methods

4.2.1 Experimental Design and Procedure

The quasi-experimental study was conducted in a classroom setting with 382 4^{th} and 5^{th} grade students between 18 classrooms (7 fourth grade and 11 fifth grade), 12 math teachers, and five school districts. The study took place during the students' regular class periods. All students worked with the fractions CITS described above. For Experiment 3, students were assigned the erroneous example problems and procedurally oriented problem types for the equivalent fractions, least common denominator, and comparing fractions units. At the class level, students were randomly assigned to one of three conditions: mixed, collaborative, or individual. Seven classes were assigned to the mixed condition, 6 classes to the collaborative only condition, and 5 classes to the individual only condition. In the mixed condition, the students worked collaboratively on the erroneous example problems and individually on the tutored problem-solving activities to align with the strengths of the social planes. In the other conditions, students either worked collaboratively on both types of problems or individually on both types of problems.

In all three conditions, the erroneous example problems for a unit came before the procedural problems to allow the students to address errors before getting more instruction through the procedural problems sets (Renkl & Atkinson, 2003). Students in all conditions completed one unit each day; they switched from the erroneous example problems to the tutored problem-solving activities half way through class. Within each class, all of the students were instructed to switch problem sets at the same time. Because the time-on-task was constant for all conditions within each unit, each student finished a different number of problems. Within each class, teachers paired their students based on who would work well together and had similar math abilities to avoid extreme differences that could hinder collaboration.

Students worked with the same partner as much as possible and only changed partners due to absenteeism. If a student's partner was absent in the collaborative conditions, the student would be paired with another student working in the same condition for the remainder of the study. When students started with a different partner from the day before, they would begin on the problem set at the place of the student who had made less progress. When students were collaborating, they each sat at their own computer. The students were instructed to sit next to each other and were able to communicate through speech. This speech was recorded for each student individually using a tablet.

The study ran across five class periods of 45 minutes each. On the first day, the students took the pretest individually. At the beginning of the second day, the students took a short tutorial either individually or in groups (aligning with their social plane for the erroneous example problems) that gave some instruction on how to interact with the tutor. The students then worked with the tutor for the next three days in their condition. On the fifth day, the students took a posttest individually and answered a short survey to gauge their situational interest when working with the tutors.

4.2.2 Dependent Measures

For Experiment 3, I collected pretest and posttest measures, tutor log data, and situational interest measures. For the pretest and posttest measures, I assessed students' fractions knowledge at two different time points using two equivalent test forms in counterbalanced fashion. The tests targeted isomorphic problems for both the erroneous and procedurally oriented problem types and were administered on the computer. The tests also had transfer problems for naming, making, adding, and subtracting fractions. Each test had 15 questions, seven erroneous example, six problem solving, and two fractions explanations questions. For each question on the test, the students were able to get a point for each step completed correctly. On the tests there were 81 possible points for the 13 erroneous example and procedural knowledge questions. Within the results, all test scores are reported as a percentage of the total possible points. Examples of the test items can be found in Appendices 2 and 3.

To assess the students' situational interest in the tutoring activity, we had the students answer a brief survey before completing the posttest. The questions were adapted from the Linnenbrink-Garcia et al. (2010) situational interest scale. The scale consists of three separate factors: trigger, maintained feeling, and maintained value. Situational interest can consist of both the attentional as well as the affective reaction to a situation (Mitchell, 1993) and can then be divided into two forms: triggered and maintained. The triggered situational interest refers to the initiated interest that is associated with the environment (Linnenbrink et al., 2010). On the other hand, the maintained situational interest is the connection that the students make with the material or domain and the realization of its importance. The learning environment can impact the maintained situational interest by allowing the students to make a connection with the knowledge presented (Mitchell, 1993). The maintained situational interest provides the link between the triggered situational interest and personal interest, which is interest in a topic than endures over time (Hidi & Renninger, 2006; Schraw & Lehman, 2001). Maintained situational interest can then take a form that is similar to individual interest with both feeling and value components (Linnenbrink et al., 2010). The maintained feeling focuses on the enjoyment that the student has had while the value focuses on the perceived meaningfulness of the topic. The situational interest survey consisted of 12 questions, four within each factor. I adapted the questions from asking about the math teacher and math classroom to asking about the time spent on the fractions CITS. Each question was presented to the student on a Likert scale that ranged from one to seven. Allowing the score for each factor to range from 4 to 28. I have reported the percentage of the total available score for each of the three factors. The situational interest questions can be found in Appendix 4.

During the tutoring session, I also collected log data from the students. As with Experiments 1 and 2, the log data contained information around the students' transactions with the tutor, including the number of problems that the students completed, the errors, and the hint requests. Because some students were changing social planes between the different problem types, I compared the log data variables within the problem types rather than using an overall count. In other words, from the log data I computed the completed problems, number or errors, and hints requests individually for both the erroneous example problems and the tutored problem solving. For each unit and problem type, there were a total of eight problems for the students to complete. So for both problem types, the students could complete a range from 0 to 24 problems across the three units. For the errors and hints, there was no limit to the number of errors that could be made or the number of times a student could request a hint (although there were only three distinct hints for each step). For both the errors and hints, I calculated the average across the problems completed for each student.

4.3 Results

Out of the 382 students who participated in the study, 75 students were excluded from the analyses because of absenteeism during parts of the study, thus leaving us with a final set of 307 students. Out of the 307 students, 104 were in the collaborative only condition, 83 in the individual only condition, and 120 in the mixed condition. There was no significant difference between conditions with respect to the number of students excluded, $F(379,2) = 0.59$, $p = .56$. There was, however, a significant difference in the pretest scores across conditions, $F(2, 304) = 9.4$, $p < .05$. In post hoc analysis using a Bonferroni correction, I found that the collaborative condition was significantly lower than the other two conditions.

4.3.1 Learning Gains

To investigate whether students learned using my tutors and if there was a difference in learning between the students in the different conditions (H1), I used a multilevel approach to take into account differences between school districts and the repeated measures of the pretest and posttest. I used a hierarchical linear model (HLM) with student at the first level and school district at the second level. At level 1, I modeled the pretest and posttest scores along with the student's grade (4^{th} or 5^{th}) and condition, and at level 2, I accounted for differences that could be attributed to the school district. For the different variables, I chose pretest for the test baseline, mixed condition for the condition baseline, and 4^{th} grade for the grade baseline. For each variable, the model includes a term for each comparison between the baseline and other levels of the variable. I did not include dyads as a level because of the added complexity of some students working with no partner (i.e. individuals), some students having one partner, and some students having two partners because of absenteeism. I am aware of non-independence issues such as common fate and reciprocal influence within dyads that may have impacted my results (Cress, 2008). I measured the effect size with Pearson's correlation coefficient (r) where 0.1 is considered a small effect size, 0.3 a medium effect size, and 0.5 a large effect size.

Table 4.3.1. Percent Correct: means (SD) for test items at pretest/posttest

Condition	**Pretest**			**Posttest**		
Grade	4th	5th	Condition Mean	4th	5th	Condition Mean
Collaborative	0.22 (0.12)	0.36 (0.26)	0.30 (0.23)	0.46 (0.23)	0.66 (0.24)	0.59 (0.26)
Individual	0.28 (0.15)	0.55 (0.24)	0.42 (0.24)	0.49 (0.21)	0.74 (0.20)	0.62 (0.24)
Mixed	0.31 (0.17)	0.53 (0.23)	0.43 (0.23)	0.69 (0.17)	0.68 (0.24)	0.69 (0.21)
Grade Mean	0.27 (0.16)	0.47 (0.26)		0.57 (0.22)	0.69 (0.23)	

For the learning gains analysis (See Table 4.3.1), there was a significant difference between pretest and posttest scores, $t(301) = 12.56$, $p < .05$, $r = .59$, with the posttest scores being higher across all conditions (see Figure 4.3.1). For the main effects of condition, there was a significant difference between collaborative and mixed, $t(297) = -3.12$, $p < .05$, $r = .18$, and a marginally significant difference between individual only and mixed, $t(297) = -1.83$, $p = .07$, $r = .11$, with mixed condition having higher test scores than the other conditions across test times. There was a significant interaction between pretest/posttest and collaborative/mixed conditions, $t(301) = -2.78$, $p < .05$, $r = .16$, and a significant interaction between pretest/posttest and individual/mixed conditions, $t(301) = -3.56$, $p < .05$, $r = .20$, with the learning gain slope being higher for the mixed conditions than the other conditions, supporting my hypothesis that the mixed condition would be more effective for learning.

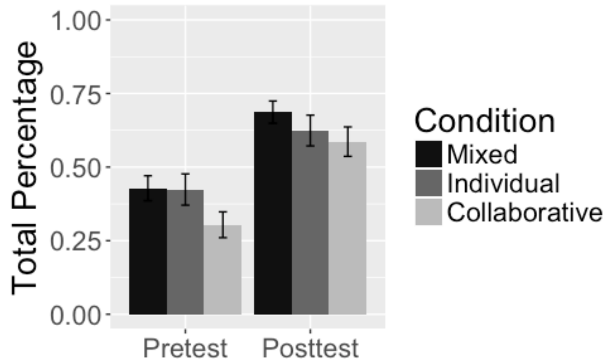

Figure 4.3.1. Test score percentage at pretest and posttest by condition.

For the student's grade level (i.e., 4th v. 5th grade), there was a significant main effect of grade, $t(297) = 2.93$, $p < .05$, $r = .17$, with the 5th graders having higher test scores than the 4th grade students across test times (see Figure 2.4.2). Surprisingly, there was a significant interaction between grade and pretest and posttest, $t(301) = -5.53$, $p < .05$, $r = .3$, indicating that the 4th graders had higher learning gains than the 5th graders. There was not a significant interaction between grade and individual/mixed conditions or collaborative/mixed conditions, $t(297) = 0.90$, $p = .37$ and $t(297) = 0.80$, $p = .42$ (see Figure 4.3.2) as these differences were captured in the higher order interaction.

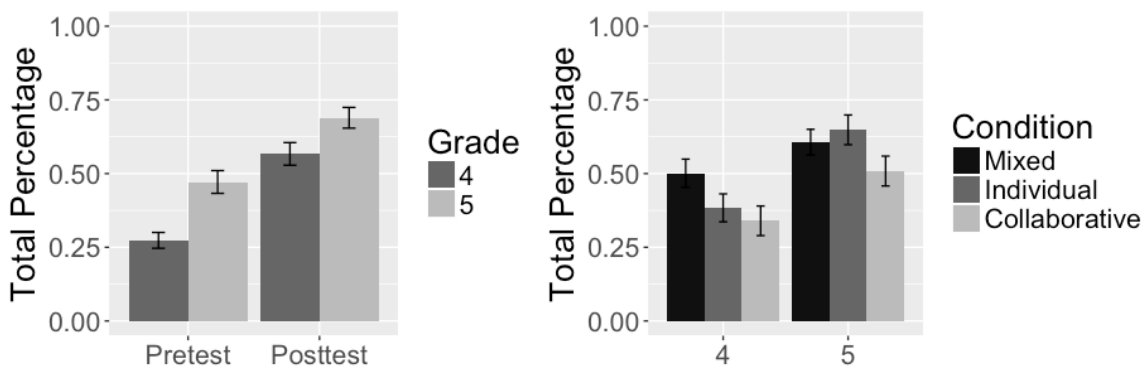

Figure 4.3.2. (Left) Test score percentage for pretest and posttest by grade and (Right) test score percentage for grade by condition.

For the three way interactions, there were a significant interactions for both the pretest/posttest, grade, and collaborative/mixed conditions, $t(301) = 4.57$, $p < .05$, $r = .25$, and the pretest/posttest, grade, and individual/mixed conditions, $t(301) = 3.19$, $p < .05$, $r = .18$, with the slope differences between the mixed conditions and the other conditions being more pronounced for the 4th grade students than the 5th grade students (see Figure 4.3.3). These interactions indicated that the mixed condition, compared to the other conditions, was more beneficial in terms of learning gains of 4th grade students than those of 5th grade students.

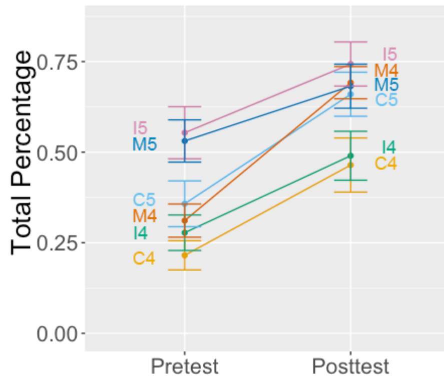

Figure 4.3.3. The students worked either collaboratively and individually (M), only collaboratively (C), or only individually (I) with the mixed condition having higher learning gains than the other conditions. This effect was more pronounced in the 4th grade students than the 5th grade students.

4.3.2 Problems Completed

To test the hypothesis that students working individually will complete more problems than students working collaboratively (H2), I ran two HLMs to compare the number of problems completed. Because students were working in different social planes for the different problem types, I compared between conditions within each problem type separately. When students were working in dyads, they would complete the same number of problems as their partner. To prevent inflating the sample size, I compared student dyads to students working individually appropriately depending upon condition (See Table 4.3.2). For the HLM analysis, I had student/dyad at the first level and school district at the second level. At level 1, I modeled grade, and condition, and at level 2, I accounted for random differences that could be attributed to the school district.

Table 4.3.2. Mean number of problems (SD) completed for all conditions.

Condition	**Erroneous Example Problems**		**Procedural Problems**	
Grade	4th	5th	4th	5th
Collaborative	10.62 (3.89)	11.94 (5.15)	9.24 (4.52)	15.31 (5.95)
Individual	16.38 (5.54)	22.25 (2.88)	16.00 (5.01)	18.89 (5.56)
Mixed	12.97 (5.34)	14.79 (5.14)	17.14 (6.58)	16.61 (5.90)

For the erroneous example problems (see Figure 4.3.4), there was a main effect of condition with a marginally significant difference between the mixed and individual conditions, $t(96.35) = 1.89$, $p = .06$, $r = .19$, with the individual condition completing more problems and a significant difference between the mixed and collaborative conditions, $t(118.82) = -2.13$, $p < .05$, $r = .19$, with the mixed condition completing more problems. There was no significant main effect of grade, $t(103.79) = 0.47$, $p = 64$. For the interactions between grade and condition, there was a significant interaction between grade and mixed/individual conditions, $t(154.48) = 3.65$, $p < .05$, $r = .28$, with there being a greater difference in problems completed between grades in the individual condition compared to the mixed condition. There was not a significant interaction between grade and mixed/collaborative conditions, $t(70.56) = 0.48$, $p = .63$.

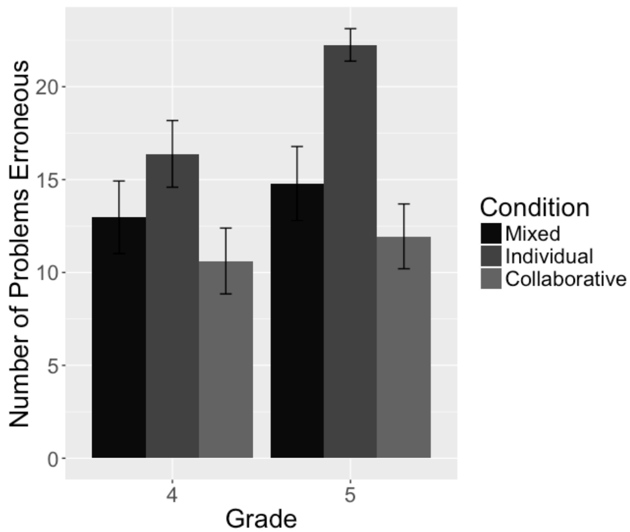

Figure 4.3.4. Number of erroneous example problems completed by grade and condition.

For the procedural problems (see Figure 4.3.5), there was not a significant difference between the mixed and individual conditions for a main effect, $t(193) = -0.35$, $p = .73$. However, there was a significant difference between the mixed and collaborative conditions with the mixed condition completing more procedural problems, $t(193) = -4.47$, $p < .05$, $r = .31$. There was no significant main effect of grade, $t(193) = -0.04$, $p = .97$ and there was no significant interaction between grade and the mixed/individual conditions, $t(193) = 1.50$, $p = .13$. In contrast, there was a significant interaction between grade and the mixed/collaborative conditions, $t(193) = 2.82$, $p < .05$, $r = .20$, with there being a greater difference between grades within the collaborative condition.

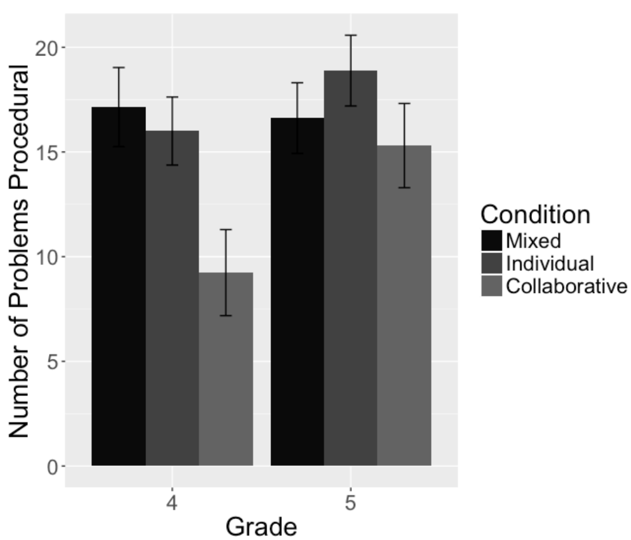

Figure 4.3.5. Number of procedural problems completed by grade and condition.

4.3.3 Errors and Hint Requests

As with the number of problems completed, the analysis for the errors and hints were done separately for the erroneous example problems and procedural problems so that dyads could be compared to students working individually to avoid inflated values. Because there were differences in the number of problems completed between the conditions, for both hints and errors, I averaged the numbers requested and made across the number of problems completed. For my analysis, I then used a measure of hints per problem and errors per problem. Again, the hints and errors were compared across conditions and grades using an HLM to account for the random differences in school district.

Table 4.3.3. Mean errors per problem (SD) for all conditions.

Condition	**Erroneous Example Problems**		**Procedural Problems**	
Grade	4th	5th	4th	5th
Collaborative	7.72 (4.14)	4.57 (2.19)	19.94 (23.69)	7.29 (8.69)
Individual	5.51 (2.79)	3.46 (1.93)	9.75 (6.69)	5.95 (6.16)
Mixed	4.48 (2.04)	4.54 (1.99)	3.57 (4.36)	5.49 (7.35)

To investigate the hypothesis that students who have an opportunity to collaborate (i.e., mixed and collaborative) will make fewer errors (H3) when either working collaboratively or individually compared to students that only work individually (see Table 4.3.3), I ran two HLMs for the erroneous example problem types and the procedural problem types. For the erroneous problem type, there was not a significant main effect for the mixed and individual conditions, $t(30.15) = 1.69$, $p = .10$, $r = .29$ (See Figure 4.3.6). There was a significant effect between the mixed and collaborative conditions, $t(46.77) = 4.57$, $p < .05$, $r = .56$, with the collaborative condition making more errors per problem. There was no significant main effect of grade, $t(20.55) = 0.09$, $p = .93$. For the interactions, there was a significant interaction between grade and the mixed and individual conditions, $t(35.52) = -2.46$, $p < .05$, $r = .38$. and a significant interaction between grade and mixed and collaborative conditions, $t(16.05) = -3.36$, $p < .05$, $r = .64$, with student errors increasing from the mixed condition to the other conditions in the 4th grade but not in the 5th grade.

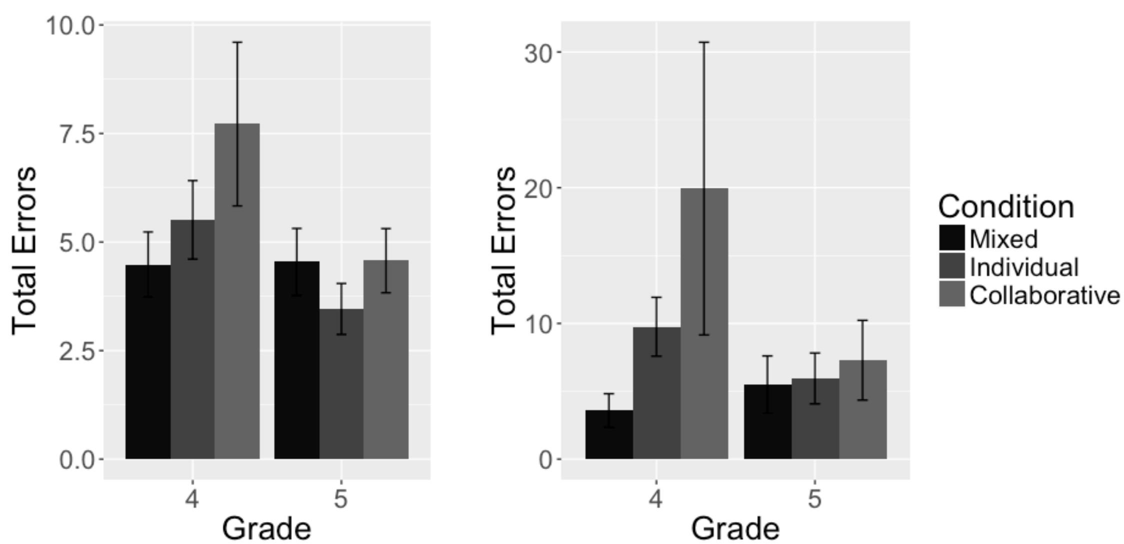

Figure 4.3.6. Errors per problem made by grade and conditions for (Left) erroneous example problems and (Right) procedural problems.

For the procedural problems types, there was a significant main effect for condition between the mixed and individual conditions, $t(154.49) = 2.81$, $p < .05$, $r = .22$, and the mixed and collaborative conditions, , $t(180.11) = 6.30$, $p < .05$, $r = .42$, with the mixed condition making fewer errors in both cases (See Figure 4.3.6). There was a significant main effect of grade, $t(92.08) = 2.02$, $p < .05$, $r = .21$, with the 5th grade students making fewer errors. There was not a significant interaction between grade and the mixed and individual conditions, $t(182.06) = -1.61$, $p = .11$. There was a significant interaction between grade and the mixed and collaborative conditions, $t(110.87) = -4.13$, $p < .05$, $r = .37$, with student errors increasing for the 4th grad students from the mixed to other conditions but for the 5th grade students remaining comparable across conditions.

Table 4.3.4. Mean hints per problem requested (SD) for all conditions.

Condition	**Erroneous Example Problems**		**Procedural Problems**	
Grade	4th	5th	4th	5th
Collaborative	6.10 (7.07)	2.32 (3.72)	3.22 (3.91)	0.39 (0.64)
Individual	4.30 (4.25)	1.17 (1.96)	6.19 (6.35)	1.74 (4.09)
Mixed	2.23 (4.39)	2.52 (3.49)	1.20 (2.56)	1.47 (3.49)

In addition to analyzing student performance through error rates, I also analyzed the request for hints. To investigate the hypothesis that students who have an opportunity to collaborate (i.e., mixed and collaborative) will request fewer hints per problem (H4) when either working collaboratively or individually compared to students that only work individually (see Table 4.3.4), I ran two HLMs for the erroneous example problem types and the procedural problem types. For the erroneous example problems, there was a significant main effect of condition between the mixed and individual conditions, $t(98.79) = 2.01$, $p < .05$, $r = .20$, and the mixed and collaborative conditions, $t(121.11) = 3.30$, $p < .05$, $r = .29$, with the mixed condition requesting fewer hints in both cases (See Figure 4.3.7). There was not a significant main effect of grade, $t(106.41) = 1.45$, $p = .15$. However, there were significant interactions between grade and mixed/individual conditions and mixed/collaborative conditions, $t(156.34) = -2.36$, $p < .05$, $r = .19$ and $t(72.84) = -2.66$, $p < .05$, $r = .30$ respectively, with the individual and collaborative conditions requesting more hints in the 4th grade compared to the mixed condition than in the 5th grade.

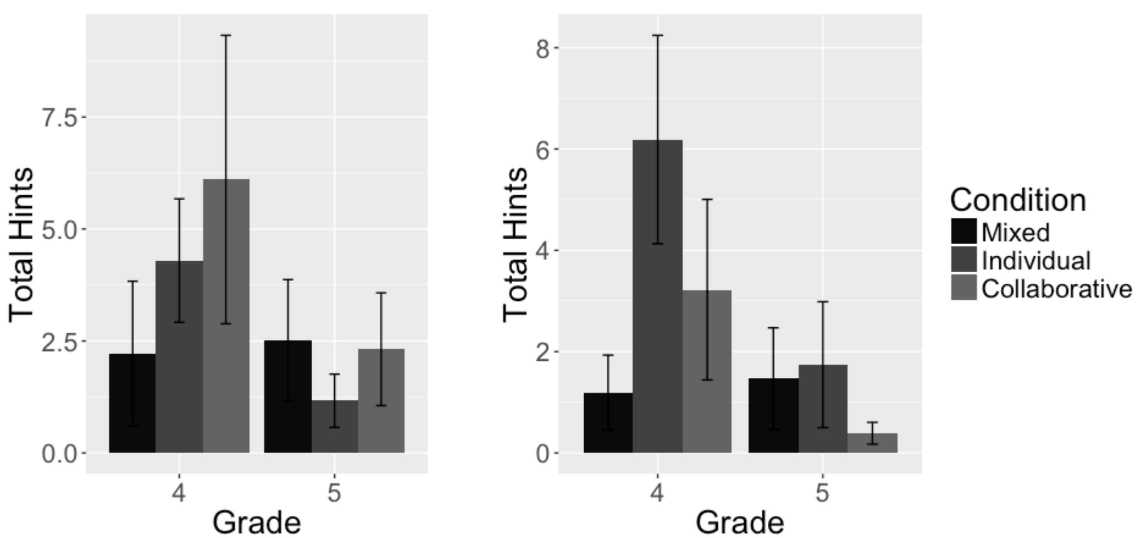

Figure 4.3.7. Hints requested per problem by grade and conditions for (Left) erroneous example problems and (Right) procedural problems.

For the procedural problem types, there was a significant main effect of condition between the mixed and individual and between the mixed and collaborative, $t(143.59) = 5.51$, $p < .05$, $r = .42$ and $t(171.29) = 2.18$, $p < .05$, $r = .16$, respectively, with the individual condition requesting more hints than the mixed condition (See Figure 4.3.7). There was not a significant effect for grade, $t(81.46) = 1.19$, $p = .24$. For the interactions, there was a significant interaction between grade and mixed and individual conditions and a significant interaction between grade and the mixed and collaborative conditions, $t(168.76) = -3.80$, $p < .05$, $r = .28$ and $t(100.44) = -2.38$, $p < .05$, $r = .23$ respectively. Again, the 4th grade mixed condition was much lower than the other 4th grade conditions while the collaborative condition within the 5th grade was lower than the other conditions.

4.3.4 Situational Interest

Table 4.3.5. The situational interest mean scores (SD) for trigger, maintained feeling, maintained value for each of the different conditions.

Condition	**Trigger**		**Maintained Feeling**		**Maintained Value**	
Grade	4th	5th	4th	5th	4th	5th
Collaborative	0.65 (0.22)	0.75 (0.20)	0.65 (0.26)	0.73 (0.21)	0.74 (0.21)	0.82 (0.19)
Individual	0.61 (0.19)	0.50 (0.20)	0.62 (0.22)	0.49 (0.22)	0.75 (0.17)	0.62 (0.23)
Mixed	0.75 (0.17)	0.69 (0.20)	0.74 (0.21)	0.70 (0.24)	0.86 (0.14)	0.79 (0.18)

To investigate the impact that working with a partner may have had on the student's situational interest in the tutoring activity (H5), I conducted a MANOVA with the trigger, maintained feeling, and maintained value as dependent variables and condition and grade as independent variables. There was a significant effect of condition on the three situational interest factors, $F(6, 600) = 7.69$, $p < .05$. There was not a significant main effect of grade on the three situation interest factors, $F(3, 299) = 0.89$, $p = .45$, but there was a significant interaction between grade and condition for the three situational interest factors, $F(6, 600) = 7.69$, $p < .05$.

Given the significance of the MANOVA analysis, I conducted a follow-up using three HLMs, one for each dependent measure, with student at the first level and school district at the second level (see Table 4.3.5). At level 1, I modeled the situational interest scores, grade, and condition, and at level 2, I accounted for random differences that could be attributed to the school district. For trigger situational interest, there was a significant difference between the mixed and individual conditions, $t(229.99) = -2.64$, $p < .05$, $r = .17$, with the mixed condition having a higher interest score but there was not a significant difference between the mixed and collaborative conditions, $t(225.02) = -1.58$, $p = .12$. There was no main effect for grade, $t(151.38) = -0.96$, $p = .34$, or any interactions between grade and conditions, $t(292.32) = -0.30$, $p = .77$ (individual/mixed) and $t(126.27) = 1.62$, $p = .11$ (collaborative/mixed).

For the maintained feeling situational interest factor, I found a main effect between mixed and individual conditions, $t(186.92) = -2.07$, $p < .05$, $r = .15$ (see table 2.4.2). As with the trigger situational interest, there was no significant main effect between mixed and collaborative conditions, $t(180.84) = -1.36$, $p = .18$, and no main effect of grade, $t(104.61) = -0.60$, $p = .55$. There was also no significant interaction between the conditions and grade, $t(276.65) = -0.80$, $p = .43$ (mixed/individual) and $t(91.20) = 1.19$, $p = .24$ (mixed/collaborative).

The maintained value situational interest measure did not follow the same pattern of results at the other factors (see Table 2.4.2). For the maintained value situational interest, there were significant main effects for both mixed and individual conditions and mixed and collaborative conditions, $t(167.01) = -2.87$, $p < .05$, $r = .22$ and $t(160.75) = -2.85$, $p < .05$, $r = .22$ respectively, with the students in the mixed condition reporting a higher maintained value. There was a marginally significant main effect for grade, $t(87.56) = -1.71$, $p = .09$, $r = .18$, with 4th grade students reporting a higher interest. For the interactions, there was not a significant interaction between grade and the mixed and individual conditions, $t(264.38) = -0.41$, $p = .68$, and a significant interaction between grade and mixed and collaborative conditions, $t(75.35) = 2.45$, $p < .05$, $r = .27$. These results indicate that the students who had an opportunity to work with a partner found the fractions CITS more immediately interesting than students only working individually and that this interest may have been extended to the domain as well with the maintained situational interest measures.

4.3.5 Discussion

In Experiment 3, I found that students across all conditions and grade levels learned from working with a tutoring system that supported both studying erroneous example problems and problem-solving practice. Thus, the results demonstrate the effectiveness of the instructional conditions. More interestingly, the results confirmed my hypothesis (H1) that a combination of collaborative and individual learning is more beneficial than either alone, as was found across the 4th and 5th grades. Through a combination of collaborative and individual learning, we are able to better support student learning. I did find that this result was more pronounced with the 4th grade than the 5th grade students. These results resemble those from other research where the age of the students had an impact on the effectiveness of the learning intervention (Mazziotti, Loibl, & Rummel, 2015). This difference may indicate that the given combination of individual and collaborative learning is particularly effective early in the learning process when students may need more support targeted at the skills they are trying to acquire. The 5th grade students may have already learned correct procedural knowledge, so the support from a partner would not be as beneficial. It may also be that the 5th grade students had higher pretest scores so could not have as high of learning gains. However, at posttest, the students were still not at ceiling. Below, I explore why the mixed condition had higher learning gains for the 4th grade students than the 5th grade students by analyzing my process analyses. In addition, the 5th grade students in the collaborative condition had higher learning gains than the other 5th grade conditions. However, the difference may be an effect of differences on the pretest. The 5th grade collaborative condition did not have significantly different posttest scores than the other 5th grade students.

To help explain the differences in the 4th and 5th grade results in the mixed condition, I looked at the student's situational interest while working on the task. When students are more interested in a task, they are willing to put more time and effort into completing that task (Rogat et al., 2013). From the literature, and as I had hypothesized (H5), I would expect to find that the students who have a chance to collaborate would have higher interest in the task. The results support the notion that a collaborative setting can be more motivating for students and that it can be so even when an individual component is added for part of the time in that the students in both the collaborative and mixed conditions expressed higher interest in the immediate task and their feelings towards the domain (i.e., maintained feeling) than the students working individually. These results supported my hypothesis, but there were not any differences between the 4th and 5th grade students. Additionally, I found that the students in the mixed condition had a higher reported situational interest on the maintained value factor indicating that the mixed condition may impact how the students value fractions more in the short term, which can lead to a maintained personal interest (Hidi & Renninger, 2006; Schraw & Lehman, 2001). However, because the interest measure was only administered at the end of the experiment, it may be that the students in the mixed condition already had a greater interest in the domain, which influenced their learning. Also, although the higher value was only in the mixed condition, I did not find any differences between the grades. Allowing students to collaborate on tasks thus might be one way to both motivate students and to create a beneficial learning environment that could lead to a personal interest in the domain, but the interest in the task does not help to explain the differences between the grades in the mixed condition.

For the mixed condition, there may have been efficiencies in the students working in the two social planes that had a stronger effect on the 4th grade students compared to the 5th grade students. To understand the efficiencies in problem solving, I analyzed the number of problems that students completed. I had hypothesized that the students working individually would get through more problems than the students working collaboratively as there would be less discussion and time spent explaining answers (H2). In other words, the students in the mixed condition would complete the same number of problems as the students in the collaborative condition (and fewer than the individual condition) for erroneous example problems, but they would complete the same number of problems as the students in the individual condition (and more than the collaborative condition) for the procedurally oriented problems. I found partial support for this hypothesis in the procedural problem types where the students in the mixed and individual conditions (both working individually) did not have a difference in the number of problems completed, but the students in the mixed condition did complete more problems than the students in the collaborative condition. However, for the mixed and collaborative conditions, there was an interaction with the 5^{th} grade collaborative students completing an equivalent number of problems as the 5^{th} grade mixed students, which implies that the mixed and collaborative condition main effects may have been confined to the 4^{th} grade students, aligning with my main findings. This finding may support the fact that the 5^{th} grade students had already been taught the procedures and may have spent less time explaining and sharing answers than the 4^{th} grade students. However, for the erroneous example problems, I did not find support for my hypothesis. For the main effect of condition, the difference between the mixed condition and the individual condition was only marginally significant, when it was predicted to be significant, and the difference between the mixed condition and the collaborative condition was significant, despite both sets of students collaborating on the problem sets. Although there was not a significant difference between the mixed and individual conditions, the finding may have been isolated to the 4^{th} graders as suggested by the interaction between grade and the mixed and individual conditions, where there is a much larger difference between the two conditions within 5^{th} grade. These results align with the learning gain results where the mixed condition may have then been more beneficial for the 4^{th} graders and suggest that there may have been some benefit to working in the mixed condition as the students completed more problems than their social plane counterparts for the erroneous example problems and the same in the procedural problems.

Besides efficiency, the mixed condition may have been more effective, especially for the 4^{th} grade students, if they were able to apply good habits learned from working with a partner to their individual sessions where they had fewer interruptions. To investigate this question, I analyzed the requested hints and errors made by the students averaged across the number of problems they completed. Previous research found that students working collaboratively asked for fewer hints and made fewer errors than students working individually (Hausmann et al., 2009; Hausmann et al., 2008a; Hausmann et al., 2008b). Therefore, I hypothesized that students collaborating would ask for fewer hints and making fewer errors than students working individually, except in the case of the mixed condition where the students would carry over their practices from working collaboratively when working individually (H3, H4). For the procedural problem types, there was a difference between the grades with the 5^{th} graders making both fewer errors and requesting fewer hints across the conditions compared to the 4^{th} grades except when compared to the 4^{th} graders in the mixed condition (as seen by the interactions). This finding again might be explained by the fact that the students may have already been familiar with the procedures associated with the units covered. The 4^{th} grade students in the mixed condition still maintained a low error rate and asked for few hints despite working individually on the procedural problem types, supporting my hypothesis that the error and hint rates would be maintained when working individually (H3, H4). This difference is especially apparent when comparing the hints requested by the 4^{th} grade students in the individual condition and the 4^{th} grade students in the mixed condition. Although the hint and error rates show that the students in the mixed condition maintain low errors and hints even when they begin to work individually, which may suggest that the students are taking knowledge from their collaborative sessions and applying it to their individual sessions, because the low hints and errors are not also maintained in the collaborative condition, as I predicted in my hypotheses, it is unclear if the order of the social planes had an impact on student learning. However, similar to the learning gain results, the hint and error results do show that the 4^{th} grade, mixed condition students did have tutor behaviors much closer to the 5^{th} grades students than the other 4^{th} grade students. The process analyses from the procedural problem types along with pretest scores would suggest that the 5^{th} grade students may have already had an understanding of the material beyond what the 4^{th} grade students had allowing the 5^{th} grade students to make fewer mistakes and need less support from the system and perhaps their partner. On the other hand, the mixed condition may have been able to appropriately support the 4^{th} grade students where needed by having a partner available when more sense making was necessary, such as with the erroneous example problems. Students could then take this knowledge and apply it to the procedural problems without having to negotiate and share steps with a partner.

In Experiment 3, I supported student learning through the use of erroneous example problems and tutored problem solving. I chose these activity types because the strengths of collaborative and individual learning had related strengths to the learning activities so that a combination may have built upon itself. Specifically, this combination may have been effective because it allowed the students to address misconceptions with a partner and thus develop a deeper understanding. After addressing misconceptions, the students then had an opportunity to build fluency with individual problem solving. This alignment of the learning activities with the hypothesized strengths of the social planes may have enhanced the support to the students more than either could provide alone. On the other hand, the combination by itself, regardless of the tasks, may have been beneficial to students by providing them with more variety in activities. In my analysis, I found the mixed condition to be more effective for 4th grade students than the 5th grade students. Through secondary analysis of process data, I found similar patterns in student hints and errors and the number of problems completed. In these variables, the 4th grade students in the mixed condition performed much more closely to the 5th grade students than the other 4th grade students. However, although my results support that this combination of collaborative and individual learning with the learning tasks was more effective than either social plane alone, it is still an open question under what circumstances a combined collaborative and individual condition would be more effective than either alone and what an effective combination entails. These results do open up a broader line of inquiry of research in CSCL that focuses on the question of how collaborative and individual learning can most effectively be combined when students enter a lesson at different learning states as happens within a class. To be able to find what combinations of collaborative and individual learning can be effective for learning, additional research is needed. Additionally, it would be beneficial to have future analysis into the dialogues between the students to see how the support from the partners was different between conditions and how the support may have impacted the effectiveness the conditions.

4.4 Summary

Experiment 3 provides evidence that collaborative and individual learning can be combined within the classroom, specifically when using an ITS. It contributes to the existing literature by comparing a combination of social planes to either alone and examining the different strengths of collaborative and individual learning, which so far has been rare. Although it is unclear about why the mixed condition in Experiment 3 was more effective for 4th grade than 5th grade students, it provides evidence for moving the field forward in the exploration of this combined space. Experiment 3 provided just one potential way of combining social planes to support learning. For Experiment 3, all students had the same alignment of social plane with problem type.

However, students do not all work at the same pace and need the same support. In Experiment 3, to allow students to work in pairs and switch between individual and collaborative data, the students needed to move through the activity as a class. During these fixed phases, students did not always have the opportunity to work on a problem set long enough to master the skills being addressed in the problem. In addition, absentee students can quickly fall behind. The use of this system prevented students from progressing at their own pace in the tutor and engaging in the activity as intended when absent. Collaborative and individual learning combinations could be combined to more flexibly adapt the social plane to student needs. One benefit of ITSs is that we are able to track student learning on specific skills (Van Lehn, 2006). By better tracking individual learning within both collaborative and individual environments, we may be able to better adapt the social plane in which a student is working to their current needs, which would add fluidity between social planes that is currently not supported in the classroom because of the added complexity to the orchestration of the activities. This fluidity between social planes can develop by allowing students to work at their own pace and switch to the next activity when done, which may be aligned with a different social plane, leading to students being in different states at the same time or by adapting the social plane the student is working in within the same activity to their actions, such as pairing students when a misconception reached. To implement activities that include these fluid transitions in the classroom, first, better orchestration for these changes are needed.

Additionally, in Experiments 1 and 2, I encountered several challenges when it came to pairing students in real-time in the classroom. Although all pairs were made ahead of time, when students were absent, I needed to create new pairs, which was a frequent occurrence. In Experiment 2, on average, at least one student was absent in a class for 3.67 of the five days, which means that over 70% of the time, teachers would need to change pairings of students due to absentees. In Experiment 3, on average, at least one student was absent in a class for 3.94 of the five days, which means that over 79% of the time, teachers would need to change pairings of students due to absentees and need support for the orchestration. These numbers do not count students were only there for part of class because they either came late or left early. In these instances, students again had to find a new group. Systems that are supporting multi-day activities that entail both collaborative and individual learning need to have the flexibility to work within the real constraints of a classroom while adapting to student characteristics to productively support learning. In future chapters, I will address initial work to support the orchestration of activities that allow for this fluidity between social planes that can support future research to fully explore the space of combing collaborative and individual learning within the classroom.

5 Collaborative and Individual Learning Framework

In Chapter 4, I presented research that began to explore how collaborative and individual learning could be combined to be more effective than either social plane alone. However, this question is far from answered. There is currently very limited research that explores how we can most effectively take advantage of multiple social planes. Different phases of an activity within integrative scripts, which combine different social planes in a single learning activity, are intended to complement each other to support the learning of the domain material. Although there are many examples of integrative scripts, such as Jigsaw (Aronson, 1978) and Think-Pair-Share (Johnson & Johnson, 1999), the components of these scripts have rarely been deconstructed to provide a better understanding of how collaborative and individual learning can best be combined. Within my research, the results indicate the need for a more nuanced understanding of when collaborative and individual social planes are beneficial for student learning. There may be aspects of the learning environment, student needs, or content that make one of the social planes more beneficial than the other because of the different learning processes that they elicit. How these social planes can be effectively combined is still an open question. In this chapter, I will introduce a framework that outlines the design space for a combined collaborative and individual learning environment. By developing a framework that outlines dimensions for how to combine individual and collaborative learning, researchers can better explore the space of how collaborative and individual learning can be combined and understand how current integrative systems fit into this space.

Such a framework is not just useful theoretically; it also has practical value, in that it can guide the design of a versatile, flexible orchestration tool for integrative activities. As discussed in Chapter 4, to explore more complex combinations of collaborative and individual learning, better orchestration support (i.e., planning and real-time classroom management support of the activity) is needed for researchers to design and implement these learning activities in the classroom. When designing and implementing a learning activity that has both collaborative and individual learning phases, the different uses of the social planes can lead to different orchestration needs in the technology. However, to be able to effectively explore different designs, it does not make sense to redesign an orchestration system for each new combination. To make a new orchestration system for each new classroom scenario would be time consuming and would make it difficult to compare different types of learning designs. This framework can help to define the dimensions that would need to be considered within an orchestration system and the range of activity designs that would have to be supported in the real-time orchestration of an activity in the classroom.

When designing the framework, it is important to consider how the different elements can be arranged to be beneficial classifiers. When supporting tasks in the classroom, it can be useful to consider what needs to be done to support the activity in three different stages (i.e., pre-active, inter-active, post-active). For example, Kaendler, Wiedmann, Rummel, & Spada (2015) developed the implementing collaborative learning in the classroom (ICLC) framework to address the competencies that teachers need across implementation stages (i.e., pre-active, inter-active, post-active) to support collaborative learning. Before the activity, the teacher needs to have the planning competency. During the planning, the teacher needs to design the activity so that it will have a maximum chance of success and benefit for the students by developing the macro-script for the activity (Dillenbourg & Tchounikine, 2007). When designing an activity, it is then important for the teacher to choose a design where there is enough support for it to be able to be carried out within their class. During the activity, the teacher needs to have the monitoring, supporting, and consolidating competencies. During the class, the teacher needs to be able to recognize where students need support and to lend support to the students, which can either be through their help, a system, or other students. The teachers then need to be able to ensure that the students have made learning gains and progress on the task. Finally, after the learning process, the teachers need to reflect back on the activity. In terms of orchestration, the support often only spans the planning and real-time stages (Prieto et al., 2011) with the reflection on the last activity being used to plan the next. Although the stages of the activity are useful to consider to understand when the majority of the decision-making needs to be done for an activity, the stages by themselves do not consider the type of support that is needed for an activity to be successful.

Instead of only considering the stages of an activity, it can be important to consider how that support is provided. Supporting teachers in managing classroom activities is not a new idea and support tools for collaborative learning have been shown to be very successful (Soller, Martinez, Jermann, & Muehlenbrock, 2005). Collaboration learning support often is often approached through either structuring or regulating the activity (Jermann, Soller, & Lesgold, 2004). The structuring of the activity occurs before the interaction begins while the regulation of the activity happens in real-time. Tools are developed to support the structuring of the activity during the planning phase when the teacher is designing the macro-script and the structure of the activity. On the other hand, when the tools are developed to support the regulation of the activity, the tool is primarily used during the activity to diagnose and guide the activity when it does not align with the desired state (Soller et al., 2005). During the regulation, there may be changes to the original planned activity to have students reach the desired state. In these different approaches, the tool plays a very different role. Although all activity planning requires some structuring, it is vital to consider what activity designs would require a tool that supports regulation. By classifying different design elements in terms of the amount and type of support that they require during the different stages of the process, we can develop a better understanding of the complexity of different designs and how they would compare in terms of the types of support required to be able to orchestrate them in the classroom.

This chapter aims to address what dimensions need to be considered when designing a combined collaborative and individual learning environment. These are the same dimensions that need to be flexibly supported within an orchestration system design meant to support collaborative and individual learning in the classroom. Since the combination of collaborative and individual learning is still a fairly new area of research, the framework is based upon theory in related fields and practical classroom constraints. I will first present the challenges of orchestrating collaborative and individual learning with three different scenarios that highlight a range of ways of combining collaborative and individual learning activities and illustrate how a single orchestration tool could be developed to support the management needs of each design. Second, I will present my framework for the design dimensions for a collaborative and individual activity that can both be used as a guide for designing orchestration tools that support multiple social planes as well as an analytical lens on current learning designs.

5.1 Challenges of Orchestrating Collaborative and Individual Learning

When designing a learning activity that combines collaborative and individual learning, different designs require different levels of orchestration complexity. This complexity is often related to how much freedom the students have within the activity to progress at their own pace and for the activity to be adapted to individual needs. When an activity is planned, and executed, uniformly across all students in a class, the management of the task is much easier to monitor. However, there may be some loss of effectiveness of learning, as each student may not be getting the support that they need when they need it. To be able to support the use of collaborative and individual learning in the classroom as well as continue to investigate how collaborative and individual learning can best be combined, it is important that we have the tools to support the orchestration for a multitude of collaborative and individual learning designs. In this section, I present three activity designs using collaborative and individual learning to illustrate the range of designs and the range of orchestration needs that correspond with these designs that need to be addressed.

First, activities can be designed to have most of the decisions made during planning and for the students to move through the activity in sync, which requires less monitoring during the activity. In previous research, having students' progress in sync is the most common type of design (Mullins et al., 2011; Olsen et al., 2016; Olsen et al., 2017). As an example of this type of design, I will use Experiment

3, where the students learned in an environment that combined collaborative and individual learning in a fractions ITS. In this study, there was a condition where students worked collaboratively on erroneous example problems and individually on tutored problem solving. The order was set so that all students collaborated before working individually and the entire class transitioned between the activities half way through the class period. At the beginning of the study, students were assigned to groups and only were assigned a new partner in the case of absenteeism. In this activity, the majority of the support was needed in the planning of the task, while the management that is needed during the task is minimal. The time needed to be tracked so that students could transition, but the time could be tracked for the entire class instead of individually for each student. The most significant orchestration challenges are around pairing students at the beginning of class when students are absent and then supporting the students in transitioning between social planes.

Second, activities can be designed so that the majority of decisions are made during planning, but students are not working in sync and can progress at their own pace. A slightly more complex set of designs allow for the students to be in different phases at the same time. As an example, from Experiment 3, I found that the mixed condition was more productive for the 4th grade students than the 5th. In this case, it may be beneficial to have the students who scored lower at pretest collaborate on the erroneous example problems while the students who score higher at pretest work individually on both sets of problems. Some students are working collaboratively first while others are working individually first depending upon the student, but the teacher would still know who is working in what social plane before the activity begins. Instead of giving the students a set amount of time to work on each problem set, the students would be given the time they needed to finish each problem set and would transition once the task was complete. Finally, so that they would not have to be waiting for a partner, I could allow the students to be paired based upon the order that they complete the current phase that they are working on to allow students to begin the next phase faster. Within this example, it is much harder to monitor the state of the classroom, as the students would be transitioning between phases at different times. Some students would be working collaboratively while others are working individually, which was not the case in the first example. To orchestrate the activity, students need to be frequently monitored to support transitions and to assign partners. The transition also takes more time to manage as it is happening across a larger window for all of the students. It is an orchestration challenge for the teacher to monitor the classroom and reliably understand what phase each student is in quickly.

Finally, activities can be designed to allow for transitions between social planes within a phase that are not preplanned by adapting to student actions. In the previous two examples, although the students may have been working out of sync, they were sticking to a pre-structured plan. By allowing for adaptation to happen in real-time, students may deviate from the original plan when it will be beneficial for their learning. I know of no work in which students transition between social planes adaptively based on student actions. An example of this adaptation would be to have students work individually until a student makes a string of errors on a skill that can be identified as a misconception. The student would then be paired with a partner in real-time who had previously overcome the same misconception. The pairing would happen without the students changing phases – they would still be working on the same task – which is unique from the previous example. In the design when the students are working collaboratively and individually is being adapted to student the misconceptions the students are making. For this design to be successful, a teacher would need to identify a student that is struggling, find them a suitable partner, and have those students begin collaborating, which does not leave the teacher with much time to be helping students. An orchestration tool would be able to provide real-time support to the students by monitoring their activities and suggesting suitable groups when it is necessary, which would allow the information to be directly communicated to the students what they needed to do next instead of the teacher having to keep track of all of the tasks.

In this section, I illustrated three of many ways to combine collaborative and individual learning. As shown in the three examples, learning designs can range from relying on more up front planning and having students work in sync to adapting to the students in real-time to allow for students to by out of sync both between and within phases. Depending on the learning design, the orchestration support that is needed differs. The orchestration can entail more simple tasks such as keeping track of time to more complex tasks, such as tracking student learning and actions to be able to adapt to their needs. Although the examples provide a glimpse at the range of combined collaborative and individual learning designs, my framework provides a lens for analyzing existing designs and can help to define the range of designs an orchestration tool would need to support to make the investigation of combined collaborative and individual learning more accessible. Before developing tools to support the research of combined and individual collaborative learning, it is first important to understand the breadth of the space.

5.2 Framework

This framework presents an outline for dimensions that should be considered when designing a combined collaborative and individual activity for use in the classroom. When designing a lesson, it can be beneficial to break it down into different phases to be able to deliberately plan each part of the lesson. Within my framework, I define a phase of the learning activity as the planned alignment of social plane with a sequence of tasks. When there is a planned transition between social planes, there is a transition between phases. However, when social plane is being adapted to student actions, as in the third example above, the students would still be working on the same tasks, just in a different social plane than originally intend so would be in the same phase. Within a phase, there may be multiple tasks for the students to complete. My framework for designing combined collaborative and individual phases (see Table 5.2.1) consists of four dimensions: the social plane students are currently working in, the order of the social planes, the transitions between social planes, and group formation. These dimensions reflect the areas that need to be taken into consideration when developing a combined collaborative and individual learning environment that are supported by both theoretical and practical learning concerns in the classroom. Although the framework consists of four different dimensions, the dimensions are not independent from one another. A decision in one dimension can have in impact on what the design options are within another dimension.

Table 5.2.1. Framework for designing a combined collaborative and individual learning environment

Dimension	Structuring		Regulating
	Class Level	Student Level	
Social Plane	• Fixed social plane across phases • Matched with tasks	• Set based upon student characteristics	• Adapt within the phase to student actions
Order	• Collaboration First • Individual First	• Set based upon student characteristics	
Transitions	• Synchronous	• Asynchronous	
Group Formation	• Fixed groups across phases • Rotating groups across phases • Set based upon knowledge	• Just-in-time • Student choice	

For the dimensions, a decision can either be made during the planning process when the task is being structured, or can have an unplanned adapt to what is happening real-time in the classroom by regulating the activity. These different stages align with the two approaches discussed by Soller et al. (2005). For the orchestration, when decisions are made during the structuring phase, the support cannot end there but needs to be able to support the task in real-time as well. Within the structuring stage, each of the four dimensions can either be designed to be consistent across the class (left column in Table 5.2.1) or set based on the specific student needs (right column in Table 5.2.1). For the structuring stage, these variables for each dimension are chosen ahead of time but may still involve real-time tracking during the activity to support the choice with the student level choices requiring more classroom support. On the other hand, the regulating stage, as with the descripting in Soller et al. (2005), involves not just carrying out the pre-defined task but monitoring the current student state and being able to adapt when needed. Within the regulating stage, there is only one variable type within the column: adapt within the phase to student actions. However, 'student actions' is a placeholder for any student data within the classroom (e.g., misconceptions, strategies, motivation) that could be tracked and the social plane could be adapted to. Since this adaptation in one dimension would cause a change in the other dimensions, there is no distinction made across the four dimensions. These different stages also align well with the first two stages presented in the ICLC framework (Kaendler et al., 2015). Within the structuring phase, the teacher would still be expected to use their planning competency (and perhaps their reflecting competency if it helps them to plan the next lesson), while during the regulation phase, the teachers would be expected to use their monitoring, supporting, and consolidating competencies. Although the teacher remains an integral part of both of these stages, support from an orchestration tool is necessary to allow for the flexibility of both planning and executing different learning designs.

For each of the dimensions, I present different design options that can be set within the structuring phase and adapted within the regulation phase. Although there is little research around the use of adaptation for choosing when students work collaboratively and individually, adapting to students has been shown to be successful in both individual settings (Aleven, McLaughlin, Glenn, & Koedinger, 2017) and collaborative settings (Tsovaltzi et al., 2010). In the following sections, I present these design options for each of the dimensions.

5.2.1 Structuring

5.2.1.1 Social Plane

A significant decision in designing a combined collaborative and individual activity is deciding what tasks should be done collaboratively and what should be done individually. Selecting the social plane is an important part of the activity design because it can determine how productive a phase will be for a student and what type of processes the student will engage in during the phase. By planning an activity beforehand, there is then a macro-script for the students to follow. This script can help to prevent confusion about what task is to be completed next. When planning what social plane students will be working in, it can either be the same for the entire class or dependent upon the students. For the social plane, it can be fixed across the phases, matched with the tasks, or set based upon student characteristics.

One of the first decisions to make for the social planes is if the students will work in a single social plane for the entire activity or if they will transition between social planes. On certain activities, it may be best for the students to work only individually or only collaboratively (i.e., *fixed social plane across phases*). Switching between social planes can add an overhead cost, which can decrease the amount of time that students have to actually work on the activity. Although fixed social planes are not an interesting case in terms of integrating social planes, it can be an important condition for researchers.

Instead of having students work in the same social plane the entire time, what is often common in the classroom is to have the *social plane matched with a task* (see Table 5.2.1). It may be that certain social planes are more beneficial when paired with certain tasks. For example, Mullins et al. (2011) found that students working collaboratively had higher learning gains on conceptual knowledge when working on conceptually oriented tasks than students working individually. Complementarily, students working individually had higher learning gains on procedural knowledge when working on procedurally oriented tasks than students working collaboratively. This study demonstrates one way in which the social planes may be better paired with certain types of tasks to have an impact on learning. However, the study is just one example and how the collaborative and individual phases should be used is still an open question that may vary depending upon task content, student attributes, student knowledge, or variety of social plane.

The social plane can also be assigned to students *based upon student characteristics* rather than being a class variable. For example, students often have a preference for working individually or in a group. It may be useful to account for the preferences that students have to work individually or collaboratively because it can play a role in how well the student will work in that environment and can impact their motivation. By assigning students to the social plane of their preference, students will feel like they have more control over their learning environment and have a higher interest (Schraw, Flowerday, & Reisetter, 1998).

The student's prior knowledge is another student characteristic that could be taken into consideration when assigning the social plane that a student will work in. Different knowledge types can develop in an iterative fashion. For example, conceptual and procedural knowledge do not develop independently (Rittle-Johnson et al., 2001). The development of one can depend on the development of the other, and depending on a student's current prior knowledge, it may be more beneficial for them to be either working individually or procedurally. If a student does not understand the concepts needed for an activity, then the co-construction with a group may be more beneficial than working individually (Azmitia & Montgomery, 1993). By aligning the learning goals of the task with the student's prior knowledge when the student starts the task, what social plane the student works in can be better paired for each individual student.

When designing an activity that integrates multiple social planes, there is more to consider than just the tasks that the students will be engaged in. It is also important to consider what learning processes that the students should engage in during these tasks. Often in classrooms, social plane alignment is done at the class level where all students are working in the same social plane for the same tasks. However, with more support for the management of the activity, the social plane and task alignment could become more specialized towards the needs of individual students.

5.2.1.2 Order

For collaborative and individual activities, order of the phases within an activity can impact how the phases interact with one another and how beneficial that particular phase will then be. As with choosing the social plane, the ordering of the phases can either be consistent across the entire class or can be determined for individual students. The ordering of the phases can be determined based upon dependencies between different tasks during the activity. However, if there are not any dependencies, the ordering may be dependent upon how the different learning processes within the social planes would interact with one another or classroom constraints. For the ordering, students can either work individually first, collaboratively first, or have it set based upon students characteristics.

The majority of integrative scripts have the *collaboration phases follow the individual phases* to allow students to do individual prep work to be better prepared for the collaboration phase and to have something to contribute. For example, in the Arguegraph script, students first work individually on a problem set and are then paired with a partner based upon their responses (Dillenbourg & Tchounikine 2007). When a collaboration phase follows an individual phase, the individual work can provide students with material to discuss during the collaborative session.

In contrast, *collaboration phases less often precede individual phases*. By having students collaborate before working individually, the collaborative phase can help students to make deeper connections that they use later when working individually (Hausmann et al., 2009). For example, if students first work through worked examples together, they may develop a deeper understanding that they can then apply to an individual phase of problem solving to build fluency as I had done in Experiment 3. Productive failure provides another example of students working collaboratively first (Kapur, 2014). However, in this case, the students often transition to a whole class setting rather than individual work.

Although the ordering of the collaborative and individual phases can be decided independent of the task that they are paired with, more often the order of the social planes is dependent upon the alignment with the learning tasks. For example, if students are collaborating on worked examples and working independently on problem-solving, which would allow students to make deep connections on the worked examples and practice fluency on the problem-solving, then research would suggest that the worked examples should proceed the problem-solving for more productive learning (Renkl & Atkinson, 2003). Because of the pairing of the task and social plane, the ordering of the collaborative and individual phases would then already be decided.

Like with the social planes, the ordering can also be determined on a student-by-student basis by being *based upon student characteristics*. For example, during the structuring stage, the order of phases can also be set depending upon the student's prior knowledge. If a student already has an understanding of the domain and the procedures within the domain, it may be more productive for the student to be working individually first and later working collaboratively on challenging material.

Although the order of the task often feels like it is already set based upon the planned activity, research would suggest that the ordering is something that should be given more consideration. For example, often we think to teach students the material directly before having them practice individually. However, the research on productive failure would suggest that we should actually engage students in the material in the opposite order (Kapur, 2014). Within the ordering dimension, it is then important to not just consider the tasks that the students are engaging in but how the social plane that they are working within may impact the task.

5.2.1.3 Transitions

Closely related to the ordering of the phases are the transitions that take place between the social planes. The transitions are when students switch from working in one social plane to another. When these transitions are planned, as with the other dimensions, they can either be synchronous or asynchronous for students in the class.

Transitions *synchronous* have all students in the class change to the next phase of the activity at the same time, regardless of their progress in the previous phase or when they may have finished that phase. This type of transition is what is most often implemented in integrative scripts (Dillenbourg & Tchounikine 2007) and provides teachers with more control over the class. Without support in the classroom, it is time consuming for a teacher to track when each student is done and move them onto the next phase, especially if the students need to form groups at this point. By having students all transition at the same time, they can reduce the amount of time when they have to be managing the class rather than interacting with the students to support their learning.

However, with support, *asynchronous* transitions would be able to happen independently for students/groups once the students finish the previous phase. For example, in intelligent tutoring systems, students may be assigned a fixed sequence of problems to complete or they may be assigned a problem set that relies on mastery learning, where students must obtain a certain level of performance before progressing (VanLehn, 2006). In either of these cases, students will be working at different paces and progress to the next phase at different times. By allowing students to transition based upon their own progress, students can spend more time on the activities that are challenging form them and will have less downtime if a task is easier for them. However, because students are working at different paces, it can become more difficult for the teacher alone to track all of the students and the time more of their time would be spent just managing the transition without orchestration support.

Although planning the transitions in the learning activity appears to be very straight forward, the transition dimension is one that has to have the most flexible support within the classroom. Even when the transitions are designed to be after a certain amount of time, the phase may take longer than expected or there may have been an unexpected interruption. More positively, the students may have gotten through the task more efficiently than expected. In all of these cases, it is necessary to have flexibility within the classroom to adapt these transition points.

5.2.1.4 Group Formation

Last, group formation relates to the timing of when groups are formed and does not include group composition (e.g., heterogeneous, homogenous). Although group composition is an important factor in collaborative learning, it is not included in this framework because it does not necessarily change the management of the activity. Instead group composition is important to consider in all of the group formation designs presented in this section (Lin, Huang, & Cheng, 2010). Group formation is important because it can impact how students interact with their partners and can have a significant impact on the management of the activity. Groups can be made during the structuring stage and set to be consistent across the phases, rotate across the phases, align based on student knowledge or groups can be made in real time when individual students are ready for a partner.

Often groups are formed before the activity begins in the structuring stage. In the classroom, students often have a *fixed partner* for a given time allowing students to be able to get to know their partner and to develop a rapport. Collaborating students with better rapport between them tend to have increased learning gains (Azmitia & Montgomery, 1993). When students have a fixed partner across time, the students are often paired together independent of the task that they are working on.

Partner pairing can also be based on phase so that the partner either is *rotating for each phase* or so that the students are assigned *based on their prior knowledge* of the domain that was measured through previous work or a pretest for the domain. This pairing by phase, opposed to a set pair for the entire activity, allows for more flexibility to account for specific skills and knowledge needed for the phase. When students are paired by phase they also switch partners more often giving them an opportunity to work with multiple partners, which can provide them with different collaborative experiences.

Instead of having partner's set during the structuring phase, the teacher can choose to have partners set in real-time when a partner is needed. For *just-in-time* grouping, students do not have pre-assigned partners, but instead are given the first available partner when they need one. One form of just-in-time grouping is to allow *students to choose* their partners. By pairing students with the first available partner, students do not have to wait as long after finishing a phase for their partner to finish. Also, by nature of students finishing around the same time, it can be assumed that the students would be around the same knowledge level given their pace. However, pairing students just-in-time without support can be very time consuming for the teacher. Around the transition period, they would need to keep track of the students as they finish and find them a partner, which is time that they are not supporting student learning. Alternatively, the students could find a partner when they have completed their task. However, when students are allowed to choose their group, they will often wait for their friends, which may not always be the best academic choice for them, even if you just look at the time that they spend waiting.

Assigning groups can be challenging for a teacher when done during planning because they need to keep in mind the different constraints for the groups and can become even more challenging in real-time when they are occupied by other tasks. An orchestration tool can help support teachers by allowing them to provide their constraints to the system and then the system can provide suggested groups allowing the orchestration system to support group formation in real-time as well or when new groups are needed unexpectedly, as is the case for absenteeism.

5.2.2 Regulating

It is important for all activities to be planned in advance. However, that does not mean that the implementation of the activity cannot deviate from the plan. Based upon student actions, motivation, and classroom constraints, there may be a need to change the way that students are interacting during the activity. In this case, the regulating stage comes into play. Although not all activities need to be regulated, it can be beneficial for student learning if we are able to adapt the activity to their current needs. Adaptations can range from small, like re-arranging groups based upon absenteeism, to having students work in a different social plane based upon tracked interpreted student actions. When regulating the activity, often all of the dimensions are adapted at the same time. In Table 5.2.1, there is only one row because when one dimension is adapted to, all of the other dimensions tend to change as well. In addition, it is not yet well defined what we can use as indicators to adapt the social plane to. In this case, I used 'student actions' as a broad term to capture a range of indicators that future research will define. In this section, I will provide several examples of ways that the dimensions can be adapted to student actions.

There is a wide range of student actions that can be adapted to, such as help/hint abuse, guess and check strategies, and quick, consecutive correct actions. Although adapting the social plane to student actions has not been done, to the best of my knowledge, by adapting the social plane, students may be able to engage in different learning processes when they are most beneficial. For example, depending on a student's misconceptions as indicated by their errors, it may be beneficial for a student to work with a group on a task rather than individually (Ohlsson, 1996). Tracking errors for misconceptions is one example of student actions that can be adapted to in real-time. By adapting to student actions, the system may be able to better align the collaborative and individual learning with when it will be most beneficial for the individual students.

When the use of social planes is adapted, the order that the students encounter the different social planes may also be affected. Depending upon the student's actions during the session, the ordering of social planes in the session may change to better align with the student's current needs. Although student needs have been tracked and adapted to for students working individually (Aleven et al., 2017), I am not aware of any studies that have adapted social plane. By adapting social plane, the students in any given class will be more likely to be working collaboratively and individually at different times, which increases the difficulty of classroom management if the teacher must keep track of the order for all students.

When the use of collaborative and individual learning is adapted to student needs in real-time, a transition between the social planes will always be involved. Like the other dimensions, the transitions can be adapted to student actions that take place real-time. Often when the other dimensions are adapted to student actions, the transitions will also be adapting to these same student actions since the adaptation of the other dimensions causes switching between the collaborative and individual social planes within the phase. Like with social plane and ordering, a transition can occur when a student encounters a misconception. Instead of having the student continue to work independently, the student could be transitioned to working with a partner. Another way that transitions can be adapted to student actions is through student motivation. Discussions that happen during collaborations can potentially support the students' social goals and make them feel more connected to their group members, which can increase their motivation for the activity (Linnenbrink-Garcia et al., 2010). However, these same social goals can also derail the students so that they engage in more off-task behavior. Depending on the student's current state of motivation and behavior, it may be beneficial to switch students from working collaboratively or individually.

Additionally, in a classroom, often the planned exercise has to be adapted to what is currently happening and the transitions need to be adaptable. For example, if a student's partner has completed a task but the student still has four questions left to complete, then a balance needs to be found for when the student should switch tasks, which may be before they finish their first task. Another example is when students are taking longer to finish a task than expected. Teachers will often give them more time than was originally planned before switching. In both of these instances, the timing of the transition is being adapted to classroom events. The transitions are much more dependent on the circumstances of the classroom than the other dimensions. There is a limited amount of time in a classroom, which can influence the design of a learning activity (Dillenbourg et al., 2011) as the activity cannot often spill over into the next period. As the transitions become more adaptive, the activity can be more aligned with the needs of the students, but the orchestration can become more difficult.

Finally, students can also be paired based upon student actions, as with the other dimensions. For example, if a student were assigned to work in a group to help address a misconception, then they would need to be assigned to a group in real-time within the phase. Like just-in-time pairing, this group is not a pre-planned group. In this case, a partner could be chosen that would be most beneficial to the student for helping to address the misconceptions. Groups can also change in real time based upon classroom constraints. Sometimes students are unexpectedly absent or have to go home sick. In these instances, the groups would need to be formed on the fly.

Because social planes have often been used in a fixed manner in previous work (Dillenbourg & Tchounikine, 2007), current orchestration tools often are designed to support only synchronous class support rather than being adapted for individuals (Manathunga, Hernández-Leo, Caicedo, Ibarra, Martinez-Pabon, & Ramirez-Gonzalez, 2015; Wang, Tchounikine, & Quignard, 2015a). By allowing for more adaptation to student needs, more monitoring of students is needed and it can become more difficult for teachers to adapt to real-time constraints since each student could be in a different state. For an orchestration tool to meet these needs, it must be adaptable so it can match what support a teacher needs in the classroom based upon the activity the students are engaged in. An orchestration tool can help support the teacher by being able to track the state of the student and suggest changes when they are needed to help lower the cognitive load for the teacher. In developing an orchestration tool, it is important to allow flexibility for change within each of the planned phases.

5.3 Summary and Discussion

In this chapter, I present a novel framework that captures the design space for combined collaborative and individual learning activities. This framework provides a lens through which to analyze the space of combined collaborative and individual learning and can inform the direction of future research. The framework consists of four dimensions (social plane, ordering, transitions, and group formation) that provide a basis with which to compare and develop combined collaborative and individual learning environments. For each of the dimensions, the different design choices were divided into what would be decided before the activity in the structuring stage and in real-time in the regulating stage, which align with suggested collaboration support (Soller et al., 2005). During the structuring stage, the different design choices are divided by if it would regulate the activity for the entire class in the same way or if the original activity plan differs between students. The regulating stage takes this one step further by adapting to student needs in real-time. In chapter 6, I presented a set of models that provide an initial view of how individual learning can be tracked when students are collaborating. By expanding on these models, we can begin to develop indicators of when students should be transitioned between different social planes.

Additionally, the framework defines the research space for combined collaborative and individual that may be of interest for further investigation. To effectively research this space, better orchestration support is needed for designs that require high cognitive load. As illustrated through the three learning design examples, support for different types of designs can vary. Within some designs much more of the support is needed during planning while in other designs it is needed during real-time (although no design has no real-time support) to be able to support teacher competencies (Kaendler et al., 2015). For a learning activity to be successful in the classroom, it is important to be able to have enough support for the orchestration of the activity. Often orchestration tools have been developed to support a specific activity (Manathunga et al., 2015; Martinez-Maldonado, et al., 2013; Martinez-Maldonado, Clayphan, & Kay, 2015; Wang et al., 2015a). These tools do not allow for activities to be adapted to specific classroom needs and cultures. By providing orchestration tools that are flexible in the support that is provided depending upon how the activity is being designed for the classroom, we will be better able to provide the correct support when it is needed. Therefore, having support for this orchestration is a prerequisite to being able to investigate the different combinations of social planes, and to be able to compare different designs, it would be necessary for an orchestration tool to support a range of learning designs instead of being designed for a specific situation. Without the support, too much load is put on the teacher during the activity for them to be able to have the activity run as it was designed.

The framework presents a design space that should be considered when developing an orchestration system to support researchers in investigating combined collaborative and individual learning. The framework does not provide recommendations on how these activities should be supported in the tool to be effective in the classroom. For these recommendations it is important to look at what has been currently learned from previous research of orchestration (Dillenbourg, 2009; Dillenbourg & Jermann, 2010; Dillenbourg et al., 2011; Prieto et al., 2011). Additionally, it is important to understand specifically how a tool that addresses multiple design scenarios, would be perceived by a teacher and how the new designs that are currently not supported could be used within the classroom. Within the classroom, there is already an existing ecosystem of both teachers and students. It is important to understand where the responsibilities lie between the students, teachers, and any system that is developed to provide support so that it balances reducing the cognitive load and still allowing for teacher autonomy. These needs makes it important for future work to include teachers within the design process so that any designed tools could match the needs of researchers as well as classrooms, which are the goals that I address in Chapter 7.

6 Modeling Individual Learning in a Collaborative Environment

In the previous chapter, we saw that the design space for combining collaborative and individual learning includes many opportunities to adapt the use of the social plane to the needs of the individual student. Currently, there is not much research in this area and it is still an open question of what features of the learning space can be adapted to. In individual learning, learning environments have been adapted to prior knowledge, strategies, motivation, metacognition, and learning styles (Aleven, McLaughlin, Glenn, & Koedinger, 2017). However, it is not known to which, if any, of these characteristics social plane may be effectively adapted. Before adapting to student needs, we first need to be able to understand the learning processes as students work in individual and collaborative learning environments and how these may influence their learning.

There has been a substantial amount of prior work in analyzing collaborative learning processes. This research covers many research questions and aspects of collaboration including analyzing collaborative processes to better understand learning and social influence (Janssen & Bodemer, 2013; Stahl, Koschmann, & Suthers, 2006), detecting and classifying collaboration skills (Suthers & Chu, 2012; Xu, Murray, Woolf, & Smith, 2013), change in communication and processes that happen over time (Mercer, 2008; Reimann, 2009), group dynamics and how we can recognize them and intervene (Martinez-Maldonado, Yacef, & Kay, 2013; McNely, Gestwicki, Hill, Parli-Horne, & Johnson, 2012; Perera, Kay, Koprinska, Yacef, & Zaïane, 2009), and detecting collaboration patterns within dialogue and its influence on learning and retention (D'Mello, Olney, & Person, 2010; Wen, Yang, & Rosé, 2014; Wise & Chiu, 2011). Previous research has developed assessments for individual's attitudes towards collaborative learning (Johnson & Norem-Hebeisen, 1979). There has also been some work on assessing the collaborative skills of individuals (Hesse et al., 2015; Rummel & Spada, 2005).

Most of the work in CSCL, however, does not attempt to assess individual domain-level learning as students collaboratively solve problems. Although domain-level learning is not always the goal in having students collaborate, collaboration can be used as a tool to support student learning within a domain. Without understanding how this tool impacts learning, it cannot be used effectively. Often learning gains are assessed using posttest metrics that do not take into account the learning processes as they occur during the collaboration. Griffin and Care (2013; 2015) have expressed the need to be able to assess collaboration as part of a set of 21st century skills and have begun to develop methodologies for doing this assessment. In addition, research has begun to show correlations of these learning processes with individual outcomes (Hao, Liu, von Davier, & Kyllonen, 2015). However, very little work on assessing the individual learner within a collaborative setting attempts to predict domain-level task performance through modeling, which could allow the learning environment to adapt to the students as the learning is occurring for more benefit to the students, as presented in the framework in the previous chapter. The closest research is work by Nye et al. (2014), who predict performance of students based on their conversations with an intelligent agent (rather than problem-solving activity), and work by Rafferty, Davenport, and Brunskill (2013), who predict posttest scores based on actions of collaborating students, but without distinguishing between the learning of individual students within each dyad.

By contrast, much research in the fields of educational data mining (EDM) and ITSs has focused on modeling and predicting individual learning, as it results from learning activities carried out individually. Widely used models are Bayesian Knowledge Tracing (Corbett & Anderson, 1995), AFM (Cen et al., 2007; Pavlik et al., 2009), and Knowledge Decomposition Model (Zhang, Mostow, & Beck, 2007). Subsequent research has adapted and extended the standard versions of these models to better predict and understand individual learning, such as by treating correct and incorrect attempts differently (i.e., as potentially causing different amounts of learning) (Pavlik et al., 2009), by weighing recent performances more heavily (Galyardt & Goldin, 2015), or by allowing for different learning rates for predetermined groups of students (Liu & Koedinger, 2015). These individual models are not only used to assess student learning, but they are also used in running tutoring systems to adapt to individual students' learning, for example to help students attain mastery on a set of targeted skills with just the right amount of practice (Corbett et al., 2000).

In this chapter, I will describe a set of models that I developed from adapting well-established statistical models that take into account features of the collaboration. Using the log data from the experiments presented in Chapter 3, I test these models to see what features, if any, improve the model fit for students working collaboratively or individually. These models provide an initial foundation for predicting individual learning within a collaborative and individual environment that can be used to more accurately adapt the social plane in which a student is working. By being able to predict student learning based upon features of the environment, such as whether the student is working with a partner or not, we may be able to better understand when the collaboration and individual learning are being productive and adapt the social plane accordingly.

6.1 Additive Factors Model

The work presented in the current article presents new versions of the AFM applied to collaborative learning scenarios. The AFM (Cen et al., 2007; Spada & McGaw, 1985) is a logistic model that has been used and studied widely by the EDM community. It derives from basic models used in Item Response Theory (Wilson & De Boeck, 2004). It is a form of a growth model that tracks, over time, the learning of a set of knowledge components (KCs). A KC is a unit of cognitive structure that can be inferred from the performance on a related task (Koedinger, Corbett, & Perfetti, 2012). The KC is often related to a skill that the student is attempting to acquire and based upon the student's current knowledge can differ in grain size. Application of AFM requires a KC model, which is a mapping of the steps in practice tasks for knowledge components.

To assess students' individual learning as it occurs during collaborative learning scenarios, I could apply the standard AFM to data from collaborative learning sessions. However, given that collaboration can have a substantial influence on student learning, models of student learning that account for effects of working collaboratively are likely to be more accurate than models that do not. Surprisingly little work has addressed this possibility. Some research has used hidden Markov models to distinguish between effective and ineffective collaboration patterns (Bergner, Walker, & Ogan, 2017); however, for this work, the students were in a peer tutoring setting as opposed to being engaged in joint problem solving. Within my research, I extended AFMs – similar to the approach applied by Pavlik et al. (2009) and Zhang et al. (2009), who extended individual models to select practice adaptively and include transfer effects adaptively – to include features that are unique to collaboration such as having a partner to help on certain problem-solving steps and helping/observing a partner work on steps, or a partner's previous knowledge. I modified the standard AFM to investigate if accounting for features of the collaboration lead to a better model fit. For these investigations, I used tutor log data from Experiments 1 and 2, described above. I hypothesized that models including collaborative features would provide a better fit with the data compared to the standard AFM (H1). Additionally, if the model provided a better fit, I investigated if there was an overall pattern in the difference between the learning rates when students were working collaboratively compared to individually. I hypothesized that learning rates estimated using the extended models for individual and collaborative activities show a tendency for one method of learning to be more beneficial and show the benefits of helping others to solve problems (H2).

6.1.1 Methods

6.1.1.1 Experimental Context

The models were run on the tutor log data collected during Experiments 1 and 2 (see Chapters 3 and 4 for the description of the experimental design). Experiment 1 used problem sets focused on equivalent fractions while Experiment 2 used problem sets from seven fractions units. Another difference between the experiments was the way that the collaboration was supported. In Experiment 1, the students were supported through well-defined roles that had a clear divide for each step in the problem. These roles created opportunities for each partner to be the driver and helper in a clearly distinguished manor. In Experiment 2, the collaboration support did not provide the same clear divide for each step. Although each student had their role to play, they each contributed to each step. In Experiment 2, there was no divide between a student's own opportunities and their partner's opportunities as their was in Experiment 1. In both data sets, the students either worked on conceptually or procedurally oriented problems. Students either worked collaboratively or individually on the assigned problem sets. Using this tutoring system, students worked collaboratively in a synchronous, networked way. They sat at their own computer and had a shared (though differentiated) view of the problem state.

6.1.1.2 Data Sets

My data sets capture all interactions that students had with the tutoring software. They follow a standard approach to log data from an intelligent tutoring system. The data sets capture each student's performance (correct or incorrect on first attempt) on the *steps* of the tutor problems (i.e., separate elements within a tutor problem that require student input, as seen in Figure 1 and 2). In my data, each step within a tutor problem is mapped onto a knowledge component (Koedinger et al., 2012), according to the tutor's underlying knowledge component model, which provides a detailed decomposition of the knowledge to be learned Thus, I can view the data as comprised of sequences of *opportunities* to apply each knowledge component, as is common in the field of educational data mining (e.g., Aleven & Koedinger, 2013). Although there are multiple steps in a problem, the underlying knowledge components are assumed to be functionally independent (Koedinger et al., 2012) – practice with a given knowledge component is assumed to improve the student's probability of correct performance only for that particular knowledge component, not for others. My data logs contain detailed records of both individual and collaborative sessions, which is not standard.

In general, knowledge component models can be created and refined through cognitive task analysis and/or mining of log data from earlier system versions. I took the first route in creating the knowledge component model for the fractions tutor. That is, I analyzed all tutor problems to identify underlying knowledge components related to the fractions units. The knowledge components were the same between the individual and collaborative conditions, but there was no overlap in the knowledge components between the conceptual and procedural steps. For Experiment 1, the conceptual knowledge breaks down into 16 knowledge components while for the procedural knowledge, there were 15 knowledge components, with no overlap between these two sets of knowledge components. In total, the data set contained 84.7 total students hours, with 2,912 data points (instances of a step within a tutor problem) for the conceptually oriented tutor condition and 4,206 data points for the procedurally oriented tutor condition, for a total of 7,118 total step instances that were used in the models. Each are labeled with a knowledge component, according to the tutor's knowledge component model. For Experiment 2, the conceptually oriented knowledge had 30 knowledge components while for the procedurally oriented knowledge, there were 26 knowledge components. The dataset contained 46,320 total step instances, with 23,221 data points for the conceptually oriented tutor and 23,099 data points for the procedurally oriented tutor, where each was labeled with a knowledge component. For purposes of modeling collaborative learning, I added additional attributes, namely, whether the step was carried out individually or collaboratively, the number of prior opportunities the student has had to help/observe a partner practice (in the helper role) the knowledge component in the given step, and the impact of the partner's prior knowledge on learning.

6.1.1.3 Analysis Methods

I fitted all models, described below, with the tutor log data. I did so separately with data sets from the procedurally oriented tutor problems and data from the conceptually oriented tutor problems. This separation enables me to investigate if the collaborative features that were added to the models have different effects for these two types of knowledge (i.e., to test my hypothesis about the model fits). Because students were assigned to either work on procedurally or conceptually oriented problems, there was no overlap of the students in the two data sets (nor, as mentioned, was there overlap in the knowledge components in the data sets). All of the models were implemented in R using package lme4 (Bates, Maechler, Bolker, & Walker, 2015). Given we have a binary outcome measure (1 if the student got the step correct and 0 if the student got the step incorrect), I used a generalized linear mixed model, the glmer function in the lme4 package. The glmer function makes the assumption that the residual error and the random effects in the model all have a mean of 0. There is also an assumption of normality for the random effects. Within the lme4 package, the glmer function uses maximum likelihood for fitting the model with Laplace Approximation. For all of the models, the number of parameters was calculated as the number of fixed effects and the number of variances and co-variances for the random effects.

I compared the goodness of fit of the models across the two data sets using the deviance, the Akaike information criterion (AIC), and the Bayesian information criterion (BIC). The relative deviance reflects the model fit without taking into account the complexity of the model. The AIC reflects the model fit while taking into account the complexity of the model; it imposes a penalty based on the number of parameters. Similar to the AIC, the BIC takes into account the model complexity when determining the fit but with a harsher penalty for added parameters. In addition, I used a chi-square likelihood-ratio test for fit comparison for the nested models. Also, I used a t-test to compare the collaborative and individual learning rates for the knowledge components and to compare the partner opportunity learning rates to 0.

6.1.2 Models

In this section I review my baseline model, the standard AFM, and present the novel models I created by adding collaborative features to the standard AFM. Within Experiment 1, I compared the baseline (standard AFM), AFM with Condition, and AFM with partner opportunities. With the Experiment 2 data, I compared the baseline, AFM with Condition, and AFM with partner pretest measures.

6.1.2.1 Baseline Model: Standard Additive Factors Model

The standard AFM (Cen et al., 2007; see Formula 1 below) is a generalized mixed model that captures the log-odds that a given student correctly solves a given problem step as a function of three estimated parameters: the student's initial proficiency, the ease of the knowledge components involved in the step, and the learning rates for those knowledge components.

$$ln \frac{p_{ij}}{1-p_{ij}} = \theta_i + \sum_k Q_{kj}(\beta_k + \gamma_k N_{ijk}) \quad (1)$$

p_{ij} is the probability that student i gets step instance j right, θ_i represents the initial proficiency of student i, β_k is the ease of knowledge component k, and γ_k is the learning rate of this knowledge component. All three are modeled as random effects to reduce the likelihood of over-fitting the data in this model and subsequent models (Wilson & DeBoeck, 2004). The students in my data set are a sample of the larger population of interest, as are the knowledge components in my data set. The Q_{kj} term represents the mapping between steps in the tutor problems and knowledge components with $Q_{kj} = 1$ if step instance j involves knowledge component k and $Q_{kj} = 0$ otherwise. N_{ijk} represents the number of opportunities student i has had to apply knowledge component k prior to step j, the current step. Although in a standard AFM, the learning rate is restricted to be greater than or equal to zero, this restriction was not enforced in my models to allow for students learning the wrong information from their partner. With a positive learning rate parameter, AFM predicts a gradual increase of expected performance over successive practice opportunities, with smaller returns of later practice, asymptoting at perfect performance. AFM's fundamental assumptions are that different students start with different initial competencies and then learn the same amount from each practice opportunity for any given knowledge component. AFM assumes further that knowledge components differ both in their initial ease and in the amount of learning that occurs on each opportunity.

6.1.2.2 Additive Factors Model with Individual and Collaborative Learning (Condition)

Next, I address adding features that reflect possible mechanisms of learning collaboratively to the models. For starters, I focus only on the learning that occurs on a student's *own* opportunities, that is, the opportunities for which the student is responsible for entering the answer. On these opportunities, students may learn different amounts (per opportunity) when they are working individually versus collaboratively. Compared to working individually, a student working collaboratively may get more learning out of a step they solved because of fruitful discussion with the partner, but could conceivably also learn less than when solving the step alone, with tutor help only, for example if the partner simply tells them the answer and the student does not reflect on the answer.

$$ln\frac{p_{ij}}{1-p_{ij}} = \theta_i + \sum_k Q_{kj}(\beta_k + \gamma_{kc}N_{ijkc}) \qquad (2)$$

I modified the standard AFM so that, for any given knowledge component, the model has a separate learning rate parameter based on condition (individual versus collaborative). In Formula 2, the index *c* represents the condition (collaborative or individual). Further, each knowledge component has two separate learning rates, γ_{kc}, one for each condition, modeled as random effects. This split makes it possible to capture a difference in the individual learning that might occur between individual and collaborative steps (on the steps that a student is responsible for solving). The models include separate counts of prior knowledge component opportunities (N_{ijkc}) encountered while working collaboratively versus individually. This count includes only the student's own opportunities, not the partner opportunities.

6.1.2.3 Additive Factors Model with Partner Opportunities

Within collaborative learning, students may also learn from opportunities their partner is responsible for solving. On the partner's steps the student is watching and possibly providing advice, feedback, and explanations, which may help not only the partner learn, but also the student who is giving the advice, feedback, and explanations. Thus, I modeled the learning that occurs not only on a student's own opportunities (as modeled in Formulas 1 and 2) but also on their partner's opportunities. Similar to how Zhang et el. (2007) modeled how word learning benefits from seeing words with identical stems, I assume that the learning that occurs when watching and/or helping a partner is possibly different from that which occurs when *doing* steps.

$$ln\frac{p_{ij}}{1-p_{ij}} = \theta_i + \sum_k Q_{kj}(\beta_k + \gamma_k N_{ijk} + \rho_k N_{pjk}) \qquad (3)$$

I extended the standard AFM to include the learning that may happen with a partner's opportunity (see Formula 3). I added a new knowledge component-specific parameter, ρ_k, to capture the rate of the learning that could happen on a partner's opportunities, modeled as random effects. $\rho_k N_{pjk}$ represents the learning from a partner's opportunities on knowledge component *k.* Also, N_{pjk} is the number of such opportunities prior to the current step. The *c* (condition index) was not included in the partner's opportunities because students who work individually do not have any partner opportunities to observe.

6.1.2.4 Additive Factors Model with Condition and Partner Opportunities

I also tested a model that combines the collaborative features of the previous two models to capture how these two ways of possibly benefitting from collaboration might balance and account for different aspects of individual learning by collaborative problem solving. This model (Formula 4) takes into account any differences in learning rates that may occur for a student's own opportunities between individual and collaborative learning (in Formula 2). Also, it includes the learning that may occur on a partner's opportunities while working collaboratively (in Formula 3).

$$ln\frac{p_{ij}}{1-p_{ij}} = \theta_i + \sum_k Q_{kj}(\beta_k + \gamma_{kc}N_{ijkc} + \rho_k N_{pjk}) \quad (4)$$

6.1.2.5 Additive Factors Models with Partner Pretest Measures

The standard AFM model accounts for a student's initial proficiency; however, when a student is working with a partner, the partner's pretest score may be as important to accurately predict learning. To better understand how a student's partner's knowledge may impact the prediction of a student's learning, I analyzed four different variations of measuring partner knowledge: partner pretest scores, absolute difference between partner pretest scores, and two different directional differences between partner pretest scores, which accounted for whether the student's partner had a higher or lower test score than the student. For all of the variations, the scores were put into groups that were then used in the models to better understand the overall trends of influence of a partner's knowledge. Because a student's partner could change during the sessions because of absenteeism, the values were assigned at the step level rather than the student level. For the partner pretest scores, I put the scores into three groups, high, regular, and low, in which the cut-off for high was one standard deviation above the mean pretest score and the cut-off for low was one standard deviation below the mean pretest score. Formula 5 shows the extended AFM with Partner Pretest Scores, in which ω_{ijp} captures the initial partner pretest score and S_{ijp} takes on the value of 1 when student i on step j is part of group p, 0 otherwise. The effect that the partner's knowledge has on learning rate is captured by δ_p and can only take one of three values.

$$ln\frac{p_{ij}}{1-p_{ij}} = \theta_i + \omega_{ijp} + \sum_k Q_{kj}(\beta_k + \gamma_k N_{ijk} + \delta_p S_{ijp} N_{ijk}) \quad (5)$$

The next three variations, instead of using only the partner pretest score, use the difference between the student's pretest score and their partner's pretest score. For the absolute difference, there were three classifications: students in homogeneous dyads (similar pretest scores), students in heterogeneous dyads (non-similar pretest), and students working individually. Dyads were classified as being heterogeneous if the difference between the two students' pretest scores was greater than .1 or less than -.1. Formula 6 shows the extended AFM with Absolute Difference, in which ω_{ija} captures the partner pretest score and S_{ija} takes on the value of 1 when student i on step j is part of group a, 0 otherwise. The effect that the partner's knowledge has on learning rate is captured by δ_a and can only take one of three values.

$$ln\frac{p_{ij}}{1-p_{ij}} = \theta_i + \omega_{ija} + \sum_k Q_{kj}(\beta_k + \gamma_k N_{ijk} + \delta_a S_{ija} N_{ijk}) \quad (6)$$

For the directional difference, there were four groups including if the scores were homogeneous, low heterogeneous, high heterogeneous, or if the student worked individually. The scores were classified as being high heterogeneous if the difference between the scores was greater than .1 with the partner's score being higher. The scores were classified as being low heterogeneous if the difference between the scores was less than -.1 with the partner's score being the lower score. Formula 7 shows the extended AFM with Directional Difference, in which ω_{ijd} captures the partner pretest score and S_{ijd} takes on the value of 1 when student i on step j is part of group d, 0 otherwise. The effect that the partner's knowledge has on learning rate is captured by δ_d and can only take one of four values.

$$ln\frac{p_{ij}}{1-p_{ij}} = \theta_i + \omega_{ijd} + \sum_k Q_{kj}(\beta_k + \gamma_k N_{ijk} + \delta_d S_{ijd} N_{ijk}) \quad (7)$$

For the multiple levels directional difference, there were six groups: homogeneous, very low heterogeneous, low heterogeneous, very high heterogeneous, high heterogeneous, or individual. The scores were classified similar as the directional difference but with additional groups to distinguish the differences in the scores that had a higher difference. The very high heterogeneous group was greater than .3, the high heterogeneous group was greater than .1, the very low heterogeneous group was less than -.3, and the low heterogeneous group was less than -.1. Formula 8 shows the extended AFM with Levels Directional Difference, in which ω_{ijg} captures the partner pretest score and S_{ijg} takes on the value of 1 when student i on step j is part of group g, 0 otherwise. The effect that the partner's knowledge has on learning rate is captured by δ_g and can only take one of six values.

$$ln\frac{p_{ij}}{1-p_{ij}} = \theta_i + \omega_{ijg} + \sum_k Q_{kj}(\beta_k + \gamma_k N_{ijk} + \delta_g S_{ijg} N_{ijk}) \quad (8)$$

Based on the performance of the models that capture the different ways to measure the partner's pretest score, I combine these models with the model that captures condition for models that account for both collaborative features (i.e., AFM with Condition and Partner Pretest Score and AFM with Condition and Levels Directional Difference).

6.1.3 Results

I present results of applying the models presented above to my data sets, addressing my hypotheses stated above. For each of the different hypotheses, I present the results from both Experiments 1 and 2 separately.

6.1.3.1 Effect of Collaborative Features (H1)

Table 6.1.1. Goodness of fit for all Experiment 1 models along with number of parameters (NP). The asterisks indicate the model with the best performance for the given criterion.

Model Name	Deviance	AIC	BIC	NP
Standard AFM Comparison for Conceptually Oriented Problems				
Standard AFM	2996.1	3006.1	3036.0*	5
AFM with Condition	2983.9	2999.9*	3047.7	8
AFM with Partner Opportunities	2988.4	3004.4	3052.2	8
AFM with Condition and Partner Opportunities	2983.8*	3005.8	3071.5	11
Standard AFM Comparison for Procedurally Oriented Problems				
Standard AFM	4254.9	4264.9	4296.7	5
AFM with Condition	4221.0	4237.0*	4287.8*	8
AFM with Partner Opportunities	4228.1	4244.1	4294.9	8
AFM with Condition and Partner Opportunities	4220.9*	4242.9	4312.7	11

To test if adding collaborative features to the baseline AFM improves the goodness of fit (hypothesis H1) in Experiment 1, I compared the goodness of fit of the models with collaborative features against the baseline model, separately for the conceptual and procedural data sets. For the conceptually oriented problems, all of the models with collaborative features had lower AICs, than the standard AFM. The AFM with Condition was found to have the best fit in terms of AIC. On the other hand, the Standard AFM had the best BIC (see Table 6.1.1). When comparing the model fits (see Table 6.1.2), the models that include Condition are a significantly better fit than the baseline, while the model that only includes Partner Opportunities is not a significantly better fit. Finally, the model that has both collaborative features does not fit better than a model with just one feature.

Table 6.1.2. Experiment 1 Model comparison using a chi-square likelihood-ratio test. The model with the better fit is bolded.

Model Comparison	**Chi-Squared**	**P-value**
Standard AFM Variations for Conceptually Oriented Problems		
Standard AFM v. **AFM with Condition**	$\chi^2(3) = 12.2$	< .05
Standard AFM v. AFM with Partner Opp.	$\chi^2(3) = 7.7$	= .05
Standard AFM v. **AFM with Condition and Partner Opp.**	$\chi^2(6) = 12.8$	< .05
AFM with Condition v. AFM with Condition and Partner Opp.	$\chi^2(3) = 0.5$	= .91
AFM with Partner Opp. v. AFM with Condition and Partner Opp.	$\chi^2(3) = 5.1$	= .17
Standard AFM Variations for Procedurally Oriented Problems		
Standard AFM v. **AFM with Condition**	$\chi^2(3) = 33.9$	< .05
Standard AFM v. **AFM with Partner Opp.**	$\chi^2(3) = 26.8$	< .05
Standard AFM v. **AFM with Condition and Partner Opp.**	$\chi^2(6) = 34.0$	< .05
AFM with Condition v. AFM with Condition and Partner Opp.	$\chi^2(3) = 0.09$	= .99
AFM with Partner Opp. v. AFM with Condition and Partner Opp.	$\chi^2(3) = 7.2$	= .07

For the procedurally oriented problems, compared to the Standard AFM, the AFM with Condition was found to have the best fit in terms of AIC and BIC (see Table 3.1.1). All of the models with collaborative features had lower AICs compared to the baseline model (H1). When comparing the model fits (see Table 6.1.2), all models with collaborative features are a significantly better fit than the standard AFM. The model with both collaborative features is not a significantly better fit than a model with one feature.

Table 6.1.3. Goodness of fit for all Experiment 2 models along with number of parameters (NP). The asterisks indicate the model with the best performance for the given criterion.

Model Name	**Deviance**	**AIC**	**BIC**	**NP**
Standard AFM Comparison for Conceptually Oriented Problems				
Standard AFM	17539.3	17549.3	17589.1	5
AFM with Condition	17462.3	17478.3	17542.0*	8
AFM with Partner Pretest Score	17518.6	17534.6	17598.2	8
AFM with Absolute Difference	17537.3	17553.3	17616.9	8
AFM with Directional Difference	17522.4	17538.4	17602.1	8
AFM with Levels Directional Difference	17520.9	17536.9	17600.6	8
AFM with Condition and Partner Pretest Score	17444.1*	17466.1*	17553.6	11
AFM with Condition and Levels Directional Difference	17445.3	17467.3	17554.8	11
Standard AFM Comparison for Procedurally Oriented Problems				
Standard AFM	15982.6	15992.6	16032.0	5
AFM with Condition	15885.5	15901.5*	15964.5*	8
AFM with Partner Pretest Score	15978.0	15994.0	16057.1	8
AFM with Absolute Difference	15978.4	15994.4	16057.4	8
AFM with Directional Difference	15977.5	15993.5	16056.5	8
AFM with Levels Directional Difference	15975.9	15991.9	16054.9	8
AFM with Condition and Partner Pretest Score	15885.5	15907.5	15994.2	11
AFM with Condition and Levels Directional Difference	15884.6*	15906.6	15993.3	11

For Experiment 2, the conceptual models that included the collaborative features were all a better fit than the baseline model except for the AFM with the absolute difference, which only included the differences in the student's and the partner's scores without considering the direction of those differences (see Table 6.1.4). In addition, Table 3.1.3 shows that all of the models had a better (lower) deviance and most of the models had a better AIC. All of the models that included the different learning rates for collaborative and individual work also had a lower BIC than the baseline. The models with two features, AFM with Condition and Partner Pretest Score and AFM with Condition and Levels Directional Difference, were also compared to the models that had one shared feature using the chi-square likelihood-ratio test. For the AFM with Condition and Partner Pretest Score, the fit was significantly better than for the models with just one of the parameters, $\chi^2(3) = 18.3$, $p < .05$ (AFM with Condition) and $\chi^2(3) = 74.5$, $p < .050$ (AFM with Partner Pretest Score). For the AFM with Condition and Levels Directional Difference, the fit was significantly better than the models with just one of the parameters, $\chi^2(3) = 17.0$, $p < .05$ (AFM with Condition) and $\chi^2(3) = 75.6$, $p < .05$ (AFM with Levels Directional Difference). Overall, although the AFM with Condition has the best fit according to BIC, the AFM with Condition and Partner Pretest Score has the best fit according to deviance and AIC while also statistically being a better fit than AFM with Condition.

Table 6.1.4. Experiment 2 Model comparisons using a chi-square likelihood-ratio test. The model with the better fit is bolded.

Model Comparison	**Chi-Squared**	**P-value**
Standard AFM Variations for Conceptually Oriented Problems		
Standard AFM v. **AFM with Condition**	$\chi^2(3) = 77.0$	< .05
Standard AFM v. **AFM with Partner Pretest Score**	$\chi^2(3) = 20.8$	< .05
Standard AFM v. AFM with Absolute Difference	$\chi^2(3) = 2.1$	= .56
Standard AFM v. **AFM with Directional Difference**	$\chi^2(3) = 16.9$	< .05
Standard AFM v. **AFM with Levels Directional Difference**	$\chi^2(3) = 18.4$	< .05
Standard AFM v. **AFM with Condition and Partner Pretest Score**	$\chi^2(6) = 95.2$	< .05
Std. AFM v. **AFM with Condition and Levels Directional Difference**	$\chi^2(6) = 94.0$	< .05
Standard AFM Variations for Procedurally Oriented Problems		
Standard AFM v. **AFM with Condition**	$\chi^2(3) = 97.1$	< .05
Standard AFM v. AFM with Partner Pretest Score	$\chi^2(3) = 4.6$	= .20
Standard AFM v. AFM with Absolute Difference	$\chi^2(3) = 4.2$	= .24
Standard AFM v. AFM with Directional Difference	$\chi^2(3) = 5.2$	= .16
Standard AFM v. AFM with Levels Directional Difference	$\chi^2(3) = 6.8$	= .08
Standard AFM v. **AFM with Condition and Partner Pretest Score**	$\chi^2(6) = 97.1$	< .05
Std. AFM v. **AFM with Condition and Levels Directional Difference**	$\chi^2(6) = 98.1$	< .05

For the procedural dataset (see Table 6.1.4), very different results were found than for the conceptual dataset. Table 3.1.3 shows that the models that include the different slopes for collaborative and individual work (i.e., Condition) had a better fit than the baseline with lower deviance, AICs, and BICs. However, the models with only the partner pretest score measures were not a better fit than the baseline with higher AICs and BICs. The exception is the AFM with Levels Directional Difference, which was marginally statistically significant better fit than the baseline and had a lower deviance and AIC but not a lower BIC. The models with two features, AFM with Condition and Partner Pretest Score and AFM with Condition and Levels Directional Difference, were also compared to the models that had one shared feature using the chi-square likelihood-ratio test. For the AFM with Condition and Partner Pretest Score, the model was a not a significantly better fit than AFM with Condition, $\chi^2(3) = 0.0004$, $p = 1$, and was a significantly better fit than AFM with Partner Pretest Score, $\chi^2(3) = 92.5$, $p < .05$. This same pattern was followed for the AFM with Condition and Levels Directional Difference, $\chi^2(3) = 0.94$, $p = .80$ (AFM with Condition) and $\chi^2(3) = 91.3$, $p < .05$ (AFM with Levels Directional Difference). Overall, the AFM with Condition has the best fit according to AIC and BIC, while not being statistically different than the models with two collaborative features but being less complex.

6.1.3.2 Comparison of Learning Rates (H2)

Finally, I test hypotheses that there are overall trends in the differences in learning rates between individual and collaborative steps and that the learning rate for partner opportunities is greater than 0. Testing these hypotheses illustrates how AFM models that include collaborative features can provide insight into how collaboration might affect individual students' learning outcomes.

Table 6.1.5. For AFM with Condition in Experiment 1, the means and SD for the learning rates (left) and the variance and St.Dev. attributed to the random effects (right).

Model Name	Mean	Std. Dev.	Variance	Std. Dev.
AFM with Condition for Conceptually Oriented Problems				
Collaborative Learning Rates	0.19	0.13	0.06	0.25
Individual Learning Rates	0.16	0.12	0.05	0.23
AFM with Condition for Procedurally Oriented Problems				
Collaborative Learning Rates	0.21	0.15	0.09	0.29
Individual Learning Rates	0.11	0.10	0.03	0.17

I report the analyses for the models that included a single collaborative feature since these were the best fitting models for Experiment 1. For conceptually oriented problems, there was no significant difference between the collaborative and individual learning rates (see Table 6.1.5), $t(15) = 1.48$, $p = .17$ for AFM with Condition. I found that the learning rates on partner opportunities were significantly greater than 0 (see Table 6.1.6), $t(15) = 2.06$, $p < .05$, $d = 1.06$ (AFM with Partner Opportunities). For the procedurally oriented problems, the collaborative learning rates (estimated using AFM with Condition) were significantly higher than the individual learning rates (see Table 3.1.5), $t(14) = 6.18$, $p < .05$, $d = 0.78$. The learning rates on partner opportunities were significantly greater than 0, $t(14) = 2.82$, $p < .05$, $d = 1.5$ (see Table 6.1.6).

Table 6.1.6. For AFM with Partner Opportunities in Experiment 1, the means and SD for the learning rates (left) and the variance and St.Dev. attributed to the random effects (right).

Model Name	Mean	Std. Dev.	Variance	Std. Dev.
AFM with Partner Opportunities for Conceptually Oriented Problems				
Partner Opportunities Learning Rates	0.04	0.08	0.01	0.10
AFM with Partner Opportunities for Procedurally Oriented Problems				
Partner Opportunities Learning Rates	0.04	0.06	0.01	0.10

For the analysis of the learning rates for Experiment 2, I used a t-test to compare the learning rates for the knowledge components between students working collaboratively and students working individually. For AFM with Condition for the conceptually oriented tutors, there was no statistical difference in the learning rates between collaborative ($M = 0.03$, $SD = 0.06$) and individual learning ($M = 0.05$, $SD = 0.09$), $t(14) = 1.55$, $p = .14$. For AFM with Condition for the procedurally oriented tutors, there was no statistical difference in the learning rates between collaborative ($M = 0.02$, $SD = 0.002$) and individual learning ($M = 0.01$, $SD = 0.03$), $t(14) = 0.57$, $p = .58$.

6.1.4 Discussion

Across two different studies, I tested two hypotheses. First, I showed that models with collaborative features have better fits to collaborative data than models without (hypothesis H1). I tested this effect separately for activities aimed at helping students acquire conceptual knowledge and procedural knowledge, to leave open the possibility that collaboration might have a different effect depending on the nature of the knowledge to be learned. For the log data from Experiment 1, on conceptually oriented activities, I found that all models with collaborative features had a better fit than the baseline models in terms of AIC, supporting my hypothesis H1. The best-fitting model added the feature Condition (working individually versus collaboratively). This model was a better fit than the baseline model according to AIC and chi-square likelihood-ratio tests. The BIC results, which indicate a greater goodness of fit for the baseline models, raise some doubt regarding this conclusion. However, AIC is a better indicator than BIC when using the model for future prediction, as we do in this work, so it is appropriate to attach more weight to this indicator (Dziak, Coffman, Lanza, & Li, 2012).

These same results were replicated in Experiment 2, where the models with the added collaboration features were also a better fit than the baseline model. In this case, the AFM with Condition and Partner Pretest Score had the best fit to the data in terms of the AIC with the AFM with Condition being a close second. For the models that included a form of the partner's pretest score, all of the models were a better fit than the standard AFM except for the AFM with Absolute Differences. All of the other models had some indication of the level of proficiency of the partner either overall or in relation to the student, while the AFM with Absolute Differences only had an indication if the partner's knowledge was at a similar level to the students. It seems that including a measure of the partner's knowledge alone is not enough, but instead it is important to understand how that knowledge may have an impact on the student. These results indicate that by including a gauge of the partner's knowledge, we are able to more accurately predict a student's performance while collaborating on conceptually oriented knowledge.

For students working on procedurally oriented problems, in Experiment 1, I found that all of the models with collaborative features performed better than the baseline model in terms of AIC, supporting hypothesis H1. Compared to the standard AFM, the model with separate learning rates for individual and collaborative opportunities (Condition) did better in terms of AIC and BIC. The results provide evidence that adding collaborative features, such as opportunities to work with a partner and to provide help to a partner, to models of individual procedural knowledge acquisition improve the fit of the models. The AIC and chi-square likelihood-ratio test results both support this conclusion.

Again, the results were replicated with the Experiment 2 data in terms of the AFM with Condition confirming H1. By replicating this result on a dataset that has no clear divide between steps that the student and their partner are responsible for (Experiment 2 versus Experiment 1), I provide support that distinguishing between collaborative and individual learning rates can improve the predicted performance although the students are not splitting the tutor opportunities with their partner and instead are engaged the same amount on each step. Unlike the findings for the conceptually oriented knowledge, for procedurally oriented knowledge, I did not find any benefit to adding a variation of the partner's pretest score to the standard AFM. These results indicate that a partner's prior knowledge may only have an impact on a student's learning when focusing on conceptually oriented knowledge, which may be due to the type of talk that occurs around conceptual and procedural knowledge although other explanations cannot be ruled out. For the conceptually oriented problems, prior knowledge may have more of an impact on the problem understanding while for the procedurally oriented problems, the prior knowledge does not help the students with the procedures as much. To better understand this difference, future work on statistically modeling effects of collaboration would need to include, in the models, features of the environment typically outside of the log data, such as the dialogue to better understand how and what knowledge is being shared.

Second, to test the utility of the models for gaining insight into possible mechanisms of collaborative learning, I compared the learning rates estimated with these models, between students working individually and students working collaboratively for both Experiments 1 and 2 (H2). I also tested whether helping a partner leads to learning gains with the AFM with Partner Opportunities. I found that the learning rates were higher for collaborative than for individual learning in Experiment 1, although only for procedurally oriented problems. This result partially supports hypothesis H2 in that I found higher learning gains for the procedurally oriented problems. In Experiment 2, I did not find a significant difference between the collaborative and individual learning rates for either the conceptually oriented dataset or the procedurally oriented dataset, which did not replicate the findings from Experiment 1. Across the two experiments, it did not seem that either learning condition was overall more beneficial for learning in the sense that students get more out of a collaborative opportunity than an individual opportunity. Perhaps the effect of collaboration depends on the specific knowledge component, beyond whether the knowledge component is conceptual or procedural in nature. Although I did not find any replicated differences between learning rates, the more accurately the model predicts student performance, as the AFM with Condition does compared to the standard AFM, the more likely it is that instruction that adapts to student difference, based on this model, is effective.

I also found that the learning rates on partner opportunities were significantly greater than zero for both the conceptually oriented and procedurally oriented problems, supporting hypothesis H2. These findings suggest that helping a partner can have a positive effect on learning and that working collaboratively, especially on procedurally oriented problems, helps students get more out of a single opportunity. Although this result supports my hypothesis, I am particularly surprised because in Experiment 2, models with the partner's pretest knowledge were not better fits for the data as would be expected if discussing the solution with your partner was more beneficial than just observing them solve the problem, which may indicate that when students are working collaboratively on procedurally oriented tasks, they learn more from watching their partners perform the procedures than through discussion, as in vicarious learning (Chi, Roy, & Hausmann, 2008). It then may be beneficial for these types of problems to have assigned roles as was done in Experiment 1 compared to Experiment 2. These findings illustrate how my statistical models of individual learning from collaborative activities can shed some light on when and how collaborative learning is effective. Thus, these models can be a valuable tool for research in CSCL.

Regarding possible extensions to this work, additional collaboration features may improve the model fit further, such as features related to dialogue, which may be strong indicators of the quality of the collaboration outside of anything recorded in the tutor log data and may have a strong influence on individual learning. A limitation of this work is that there is no comparison of the conceptual and procedural datasets. Any differences between the models that I found could be due to where the students currently are in the learning process and the impact that it has on how they collaborate. For future work, students would work on both types of knowledge. My models can be applied to these scenarios, such as the data from Experiment 3, without modification; they are not restricted to data sets in which students work either collaboratively or individually only. By applying the models to combined conditions, they provide a starting point for predicting learning across social planes, which could be used to adapt to student needs as discussed in my framework in Chapter 5. In addition, the models could be applied to situations where students come to the collaboration with different mastery of knowledge components to see how students learn the knowledge components from their partner. Still, my current models provide a basis for integrating collaborative features into an AFM. These collaborative features provide a better prediction for the student learning during the tutor that takes into account how the students will be working. By using these models, we can refine our knowledge component models used in ITSs to better individualize to these collaborative environments where the changes that are needed may be different than those that are needed to support individual ITSs.

6.2 Summary

By modeling individual learning within a collaborative environment, we can aim to both better understand how different features of collaboration influence learning as well as to better predict learning so we can adapt to student needs. My research presents new statistical models that predict individual learning from collaborative learning activities. Prior research in computer-supported collaborative learning has not, to the best of my knowledge, created statistical models to measure the gradual knowledge growth by individual students during collaborative problem-solving practice, which I do by differentiating learning with a partner from learning alone as well as learning by observing a partner. By contrast, the research fields of ITSs and EDM have focused on the modeling of individual learning, but exclusively from individual activities (Corbett & Anderson, 1995; Cen et al., 2007).

My models contribute to the field by demonstrating the value of including collaborative features in a statistical model for individual learning and provide insights into the possible mechanisms of collaborative learning. For both experiments, there was evidence of the importance of having different learning rates for students working individually and collaboratively. However, there did not seem to be an overall trend that one type of social plane was better than the other. These findings support my pretest/posttest learning results from Experiments 1 and 2 and indicate that when collaborative and individual learning are beneficial may be more nuanced. By investigating how different features fit into a statistical model that predicts individual learning, we can develop a better understanding of what features within a learning session have an influence on that learning. These results can be used to better support learning gain data as a way of assessing the learning as the students perform the task. Although I investigated my new AFM versions in an intelligent tutoring system, they are not restricted to this context. The models only require a log of student actions labeled with knowledge components and success criterion allowing the models to be applied to a wide range of data sets collected in a computer supported collaborative setting.

In addition, the AFMs with the added parameters could, in the future, provide a foundation for creating a form of individualized mastery learning within systems for computer-supported collaborative learning. That is, the improved models could be used to assess when individual students have reached mastery while collaborating within a given unit of instruction. The system could then, for example, promote students to the next unit when all collaborators within a given dyad or team have reached mastery. The models could also be expanded to assess when individual or collaborative work is not being as productive as expected and be able to recommend when students switch social planes. By being able to predict individual learning in both individual and collaborative environments, these models would be able to smoothly track student learning throughout a lesson even as they move through different social planes. This may be beneficial to learning, as one social plane did not appear to be more beneficial than another across the conceptual and procedural problem types. By predicting individual learning across social planes, we can allow for more flexibility in how we adapt learning environments, particularly when students work individually and collaboratively, to student needs as I addressed in my framework.

7 Orchestrating Collaborative and Individual Learning

Based upon challenges encountered in my own studies as well as the need for orchestration support to research more complex designs, as part of my research, I designed an orchestration prototype to support researchers in investigating combined collaborative and individual learning scenarios in the classroom. Through my own studies, I encountered challenges to orchestrating the collaboration across multiple days. When students were absent, new pairs needed to be both communicated to the students as well as to the system creating double the work to complete one task. It can also take up time. As new pairs are being made in the system, the teacher or researcher, whoever is doing the pairing, is not available to help students. Additionally, the students cannot begin the task until the new pairings have been communicated to the system. Other researchers have also dealt with similar orchestration issues. By having students start at a fixed point at the beginning of each class, then new pairs can be made more easily (Walker, Rummel, & Koedinger, 2009). Researchers have also shared that they have made new pairs for all students at the beginning of each session to avoid the issue of students being absent (Walker, Rummel, & Koedinger, 2011). Finally, by working with student groups greater than two or only having the intervention occur over one session, researchers have limited the impact of absenteeism on the study (Celepkolu et al., 2017; Martinez-Maldonado, Yacef, Kay, Al-Qaraghuli, & Kharrufa, 2011; Rodriquez, Price, & Boyer, 2017; Walker, Rummel, & Koedinger, 2014). None of these solutions directly address how we can easily support students collaborating for multiple days in a row with the same partner and instead provide work-arounds, as often occurs in research. For studies to take place in the classroom without having to develop artificial learning scenarios, such as having a new partner each day, more orchestration support is needed for researchers that can support real classroom challenges but in a way that would not be disruptive to current classrooms by taking into account the teachers' values. In addition, to investigate this theoretical question of how to effectively design these learning scenarios, as presented in my framework, the orchestration support also needs to account for the theoretical questions that researchers may have.

When designing a system to support research within the classroom, it is easy to ignore how that system will fit into the current classroom culture and be used by the teacher (Dillenbourg, 2013). However, for an intervention to be adopted long term into the classroom and to be ecologically valid, current teacher practices and values need to be considered during development. Part of considering the classroom culture is how the learning activity will be orchestrated within the classroom and how the different responsibilities will be distributed. When different social planes are involved within the activity, the cognitive load is increased for the teacher (Van Leeuwen et al., 2015b). In the classroom, multiple groups need to be monitored at the same time to be able to provide them with support. On top of that, support needs to be given as students transition between social planes. When student transitions are not synchronous, this management can take over any time that would be spent supporting the students' learning. Orchestration tools can help to support the management of the activity so that more time can be spent on the learning activity rather than management.

Across the literature, the definition of orchestration has been debated. In the widest definition, orchestration entails the design of the learning activity, the adaption and planning of the activity for a specific class, and the real-time management of that activity (Dellatola & Daradoumis, 2014; Kollar & Fischer, 2013; Prieto et al., 2011). Orchestration has also been narrowly defined as the real-time management of an activity within the constrained environment of the classroom (Dillenbourg, 2013; Tchounikine, 2013). Although what stages of lesson development and execution are included in the orchestration definition has been debated, there is often a set of commonalities that are included across different orchestration systems. Prieto et al. (2011) define five different aspects of orchestration as adaptation, regulation, awareness, planning, and role of the teacher. These aspects are important themes when considering the support that an orchestration tool provides to the learning experience during either the planning or real-time management in which both intrinsic constraints (e.g., student characteristics, domain content) and extrinsic constraints (e.g., time, discipline, extraneous events) need to be accounted for (Dellatola & Daradoumis, 2014; Dillenbourg, 2013; Prieto et al., 2011). Within my own work, I am including both the planning and the real-time regulation of the learning environment in my definition since without a well thought-out lesson, there would not be much to regulate.

As seen in Chapter 5, there are multiple ways to design a learning activity that combines both collaborative and individual learning. To be able to explore this space effectively, we need to be able to have tools that can support the orchestration of the many different learning design combinations. I aim to explore what would be needed in a research tool so that it does not only take into account these different dimensions but in a way that would meet the needs of the teacher within the classroom. As mentioned, it is not enough to only support a research agenda if the tools developed could not realistically be integrated into the classroom. It is important to develop the tools in a teacher-centric manner so that they are accessible to all teachers and fit into the classroom culture (Dillenbourg, 2009; Dillenbourg & Jermann, 2010; Dillenbourg et al., 2011). To specifically address classroom culture, I focus on the transition moments that happen between social planes. Currently in the classroom, the transitions often happen at a set time point. However, to allow more adaptability of social plane to student needs, we need to allow for more fluidity within the transitions between social planes allowing for not all students would be working in the same social plane at the same time. Students may transition because they finish their task at a different time. They may also transition if there is something that would be beneficial from one social plane that they are not getting in the other. A learning design that has high fluidity between social planes can be difficult implement because of the amount of monitoring that it would take during the class period making it is important to provide support for these crucial transition moments.

In this chapter, I review current orchestration tools along with the types of support that they provide in the classroom. Then, I describe two classroom pilot studies that I conducted and the lessons learned that led to a change in the way that I orchestrated the use of the collaborative and individual ITSs in the classroom. Third, I present a set of co-design sessions that I conducted with a set of teachers to develop a better understanding of where orchestration support would be most beneficial and what its responsibilities would be to best support teachers while supporting the needs of the researcher. Fourth, I present a prototype of an orchestration system that integrates the needs of the teachers and researchers in supporting combined collaborative and individual learning designs, and I validate the effectiveness of the design to examine how it satisfies the needs of the researcher and teacher. Finally, I present future directions for this research.

7.1 Related Work

7.1.1 Current Orchestration Support

Within the CSCL literature, multiple orchestration tools have been developed to support the management of activities within the classroom. The majority of these tools focus either on supporting the monitoring of the activity so that teachers can more effectively adapt to current classroom conditions or to integrate existing technology seamlessly to reduce the amount of time and cognitive load that is spent during the activity. Although the different systems are all developed with different specific goals in mind, all of the systems, for the most part, remain aggregators of information for the teacher to make all crucial decisions rather than providing a tool that provides support for multiple designs to be explored.

One primary way to support teachers in orchestrating a classroom activity is by providing tools for the teacher to more efficiently monitor the activity so that they can then orchestrate the activity as they see fit (Alavi & Dillenbourg, 2012; Looi & Song, 2013; Martinez-Maldonado, Clayphan, & Kay, 2015; Raca & Dillenbourg, 2013; Mercier, 2016; VanLehn, Cheema, Wetzel, & Pead, 2016; Wang, Tchounikine, & Quignard, 2015a). The monitoring of the activity can take different forms depending upon the goals of the activity and can range from simple one-dimensional information to dashboards that contain information from multiple sources. For example, Raca and Dillenbourg (2013) use a set of three to four cameras that allows them to capture and report on classroom attention during a lecture. The attention information can be presented to the teacher both after class as a type of reflection as well as during class as a real-time indicator. However, it is left up to the teacher on how to act. Along those same lines, Alavi and Dillenbourg (2012) developed Lantern as a way to support recitation sessions when small groups are getting help from a teaching assistant (TA). In this case, the students can use the Lantern to mark when they need support from the TA. The students can change the color that the Lantern displays to mark the problem that they are currently working on. The number of LEDs indicates how long the students have been working on the problem and the speed of the blinking, how long the students have been waiting for help. Again, it is up to the TA to orchestrate the support that is given to the students and the Lantern just provides an awareness tool.

Orchestration systems have also provided support to teachers through aggregating information around the learning activity into a dashboard to allow the teachers to monitor multiple aspects of the activity at once (Looi & Song, 2013; Martinez-Maldonado et al., 2015; Mercier, 2016; Wang et al., 2015a). Dashboards within orchestration tools can provide much of the same information as a learning dashboard but is meant to provide teachers with information that allows them to manage and adapt the learning lesson to the student needs rather than only providing students social or cognitive support. For example, Martinez-Maldonado et al. (2015) developed and tested MTDashboard that provided the teacher with information both on the progress of the task as well as the group progress information. They used a 2 by 3 design to actually test different types of dashboard information with the teachers either having the activity progress information or not, and either having group information displayed as participation of group members, solution size for group, or text information about number of solutions. This information allows the teacher to see when a phase of the activity has gone longer than expected as well as to see the group states in that current phase to decide if students are ready for the next phase, Other dashboard orchestration systems often have just a subset of this information but allows the teacher to go more in depth. Looi and Song (2013) provide a dashboard for teachers in their GroupScribbles tool that allows them to monitor individual student participation and to monitor the group task performance. Wang et al. (2015a) provide support through both quantitative data about the progress of the student as well as qualitative data through student dictation and can click in for further information allowing the teacher to help the students while keeping an eye on the overall progress of the class. The dashboard developed by Mercier (2016) has a similar goal in that it provides the teacher with a live update of student answers that are marked in color based upon correctness allowing the teacher to focus on students that need help but also to adjust the difficulty and address misconceptions at as a whole class when needed.

To be able to do swift transitions between social planes, other orchestration systems have focused on streamlining the workflow within the classroom (Cuendet, Bonnard, Kaplan, & Dillenbourg, 2011; Håklev, Faucon, Hadzilacos, & Dillenbourg, 2017; Manathunga et al., 2015; Martinez-Maldonado et al., 2013; Munoz-Cristobal et al., 2013; Munoz-Cristobal et al., 2015; Phiri, Meinel, & Suleman, 2016; Prieto et al., 2014). These systems may do integration through augmenting the physical space with technology, interconnecting existing technology, or providing a workbench in which multiple platforms can live within one space. When augmenting the classroom with technology, the purpose of the orchestration tool is to be able to complement and enhance what is already being done. For example, Munoz-Cristobal et al. (2013; 2015) developed GLUEPS-AR that uses adapters to allow virtual artifacts to be accessed from both virtual and physical spaces. This system is not intended to change the flow of the activity in the classroom, but instead to enhance what is already being done in the classroom by integrating technology that allows interactions to happen in different ways and spaces. However, Cuendet et al. (2011) developed a paper interface that is enhanced through the use of Tinkerlamp (Zufferey, Jermann, & Dillenbourg, 2008) that allows the activity to flow through the different social planes smoother by supporting the transition of information from one phase to the next.

Another way of streamlining the workflow is through the use of a centralized workbench. This centralized workbench provides a space for the teacher to develop a learning activity that may span multiple different tools. It can allow the instructor a way to author different parts of the activity in ways that they are familiar but then to execute the activity seamlessly. Centralized workbenches often have the goal of reducing the time and cognitive load needed to execute an activity in real-time. For example, Phiri et al. (2016) developed an orchestration workbench that they then tested in a flipped classroom design.

The orchestration tool allowed the instructor to set configuration details linking different resources that would be used in class to the lesson. The workbench then allows these resources to be easily accessible and in one place, reducing the amount of time needed to transition. Prieto et al. (2014) developed a similar system, GLUE!-PS, which allows teachers to author parts of the lesson in individual tools but can then semi-automatically deploy the learning designs and still allow the teacher to make changes to the design in real-time as needed allowing the teacher to use tools that they are familiar with but can still centralize the running of the activity to one place. Along these same lines, Håklev et al. (2017) have been working on the development of orchestration graphs to be implemented in a MOOC environment. The orchestration graphs provide a structured view of the learning activity where the teacher can integrate different types of tasks, which have before been supported through plugins and widgets, where the output of one can be fed into the input of the next. The orchestration graph can then allow the teacher to manage the learning activity in real-time and to intervene when the community may not be performing as expected.

Similar to workbenches, the last set of systems focuses on connecting different technology but this time the devices (e.g., tablets, tabletops) within the classroom (Manathunga et al., 2015; Martinez-Maldonado et al., 2013). By connecting the devices that are often shared as a class (e.g., whiteboards) to devices often used by groups (e.g., tabletops) to devices often used by individuals (e.g., tablets) there can be a better flow of information between both the teacher and students as well as between the different social planes. For example, Manathunga et al. (2015) propose integrating smart devices and wearable devices to support the orchestration of the activity. Through these devices students can receive notifications or orchestration signals and teachers can post to a shared board modify the activity flow allowing the system to adapt to classroom changes, such as absenteeism fluidly and to prevent confusion with students by being able to update their instructions. Martinez-Maldonado et al. (2013) take a different approach in using an orchestration server, learning analytics engine, and interconnection layer to connect different learning technologies allowing the teacher to monitor the student's progress in an activity even as they may switch between the different types of technologies that they are currently engaged with.

Current orchestration tools support a range of student activities across a range of different technologies. However, many of these tools and activities still approach the learning activity at a class level and do not support students switching phases asynchronously. In the monitoring tools, the expectation seems to be that all students are currently in the same phase of the activity. In VanLehn et al.'s (2016) FACT project, the system allows for some flexibility for students to be working out of sync, but mostly addresses the case for students that started the activity late. The assumption is that most students in class will still be moving at the same pace. In the integration of the technology, there is the same expectation that students will all be going through the activity at the same pace although this is not the case in real classrooms. Many of the systems do allow for flexibility to adapt the activity in real-time, but the adaptation still often happens at the whole class level, partially because it would be very difficult for the teacher to monitor and adapt for each group individually. For researchers to investigate how these fluid transitions within different combined collaborative and individual learning designs impact learning, there needs to be support for the orchestration of these designs within the classroom. My work attempts to address this gap by supporting the orchestration of fluid transitions between social planes in a way that will support researchers in their investigations but meet teacher needs in the context of the classroom. Students do not all finish the same work at the same time and can use different types of support at different times. Although it is important to provide teachers with the ability to intervene and have control over the activity (Dillenbourg & Jermann, 2010), teachers cannot do everything at once. An orchestration system can provide the support to allow students to be in different social states at the same time either through advancing through the activity at different rates or through getting different social support within a phase. An activity that allows fluidity between social planes would only be possible with more automated orchestration support from a system, which is not provided in the current systems.

7.1.2 Orchestration Lessons and Design

Although there has been disagreement across the field around the definition of classroom orchestration, there have been several attempts to summarize and provide design recommendations around what orchestrable technology entails. These recommendations focus on the usability of technology at the classroom level opposed to personal or group use. Orchestration is the third level of usability after personal usability and group usability – how well the technology supports group interactions (Dillenbourg et al., 2011). Classroom orchestration is concerned about the design and use of the technology to match the needs of the classroom that are not factors at the other levels of usability. At the classroom level, it is important to account for constraints around the curriculum, assessments, time, sustainability, space, and discipline that may seem irrelevant when designing the usability for the individual students or groups (Dillenbourg et al., 2011). To have educational systems work outside of the lab and within a real world classroom, these constraints must be accounted for, as they cannot be easily controlled. By supporting classroom orchestration as well as student goals and interactions, a learning system is more likely to be successful within the classroom long-term. The different factors and design recommendations compiled for classroom orchestration tend to fall into three main groupings. Each of these groupings illustrates a central theme that is key to orchestration.

The first theme addresses the importance of planning the activity so that it aligns with the needs of the classroom. Part of the definition of orchestration includes the planning of the learning activity (Prieto et al., 2011). By planning the activity, there is a structure for the activity to follow in real-time. During planning, it is important to consider the integration of the different social planes, the sequencing of the tasks, and the continuity and workflow between the tasks (Dillenbourg, 2009; Dillenbourg & Jermann, 2010). During the planning, it is also important to consider the space and resources that are available within the class. However, the activity cannot just be planned within a vacuum. It is also important to consider the alignment and synergy of the activity with the learning goals (Prieto et al., 2011). Within the classroom, there is a curriculum that must be taught within a given amount of time, and the curriculum is aimed at teaching certain skills that will later be assessed. These curriculum, assessment, and time constraints are then vitally important to consider when designing a learning activity for it to be adopted into a classroom (Dillenbourg & Jermann, 2010; Dillenbourg et al., 2011). Orchestration tools can take these constraints into account by allowing the learning activity to be designed by the teacher opposed to only having preset tasks.

The second theme addresses the importance of knowing the state of the students during the learning activity and being able to adapt when necessary. Much of the existing orchestration technology addresses the real-time execution of the learning activities within the classroom. For an activity to run smoothly, there needs to be awareness of the classroom, regulation and management of the activity, and flexibility to adapt when it is necessary (Prieto et al., 2011, Dillenbourg, 2013). Within the classroom, there can be multiple things that do not go as planned. For example, all of the students may not be there that day or students may be taking longer on a phase of the activity than planned. In this case, it is important to have awareness of the classroom and to have enough flexibility within the activity to be able to change it as needed (Dillenbourg, 2009; Dillenbourg, 2013; Dillenbourg & Jermann, 2010). Teachers are not just responsible though for the cognitive learning of the students but are also responsible for the discipline and emotional state of the students. It is important to have enough flexibility in the system for the teachers to react to these student needs as well. During the class, teachers want to support their students in learning; however, for learning to even happen the activity still needs to be managed and there needs to be enough awareness and flexibility for the activity to adapt.

The final theme of recommendations addresses the role of the teacher in the orchestration and the sustainability of the activity in the classroom. The teacher is responsible for the classroom and the learning activity that the students engage in. Different activities can create different amounts of cognitive load and it is important to consider what the role of the teacher is during the activity and where support can be provided as well as if the activity design is practical for the classroom (Prieto et al., 2011). For the orchestration, Dillenbourg and Jermann (2010) recommend that the teachers are the drivers and have control of the activity (Dillenbourg, 2013). The support provided should be teacher-centric (Dillenbourg, 2009). However, this does not mean that support cannot be provided to the teacher for the activity. Teachers do not need to make all decisions in the classroom as long as they are able to have control over the decisions that are made. Additionally, not all teachers come with the same experience and it is important for the tools that are used to support them to then be designed for all and to be minimalistic so that they do not over engineer features that are already well supported in the classroom (Dillenbourg & Jermann, 2010). It is important to consider the design of the orchestration support tools in terms of what will be sustainable in the classroom (Dillenbourg et al., 2011). If a tool is too complicated or only designed for the needs of a single lesson, then it will not be worth the teacher's time to learn the tool.

These three themes around orchestration recommendations provide guidelines when designing an orchestration system. However, they do not address specific design decisions for an orchestration system or how to integrate the values of the different users. In my orchestration system, I aim to provide support for a range of transitions between social planes, specifically fluid transitions, which are currently difficult to manage in the classroom. This support will allow for a wide range of combined collaborative and individual learning scenarios to be orchestrated with one tool that can support both researchers and teachers in using these learning designs in the classroom. Within my work, I will first provide examples of where I have encountered classroom orchestration challenges during pilot studies and how the design of my learning activities were changed to better address these challenges. Next, I will present a series of co-design sessions that provide insights into how to integrate the values of teachers and researchers to develop a tool that can be easily assimilated into the classroom. These insights contribute to the current orchestration tool guidelines by providing more concrete suggestions related to the needs of the teacher. Finally, I present a validation of an orchestration prototype to address the role of the teacher within the orchestration system as well as the ability to both plan and adapt to the classroom needs in a way that can support research within the classroom.

7.2 Discovering Challenging Orchestration Moments

Between Experiments 1 and 2 (see Table 2.1.1), I ran two different classroom pilots to develop a sense for the orchestration challenges to using collaborative tutors within a real classroom. Although I had used the collaborative tutoring system with students in Experiment 1, it was in a pull-out design and was in much more of a controlled environment. There were never more than two students (one dyad) working with the system at a time. Also, if a student were absent that day, then the pair would be rescheduled for another day. Within the pull-out design, the students could easily be monitored since there was a one to one ratio of experimenters to students. Although the system worked well for the pull-out design, it would not necessarily be addressing all of the constraints that are inherent to a whole class.

The pilots were intended to investigate three questions regarding classroom orchestration: 1) how is the tutor used in a less structured classroom setting, 2) how does the orchestration work when more than one student is using the tutor at the same time, and 3) what are the challenges, if any, of pairing students across multiple sessions. In the classroom, there is often not a one to one ratio between the instructors (i.e., teachers or researchers) and the students. In this case, the students tend to have much more freedom in how they interact with both the system and their partner because there is not someone constantly observing them, which may lead to students not always following the activity plan as intended. Additionally, there is not an instructor to provide personal assistance to each student. The system needs to be able to support changes made to the system efficiently so that all of the time is not consumed on helping a single student. Finally, in Experiment 1, the students only participated for a single session. The process of pairing across multiple sessions may need to be different than the process for pairing students for a single session. Below I present the qualitative results from both classroom pilot 1 and 2 as they pertain to the orchestration of the CITS. I then present the design changes made to the system to better support the orchestration of the CITS based upon these results. Together these pilot studies demonstrate the need to adhere to the design guidelines presented above and provide early prototypes for classroom orchestration functionality with an ITS. In these pilot studies, the research was the primary user of the system. However, in a typical classroom, the teacher could also act as the user.

7.2.1 Classroom Pilot 1

Classroom Pilot 1 was my first attempt at using CITS within a real classroom. The previous pilots and studies had either taken place in the lab or in schools in a pull-out design. In Classroom Pilot 1, I wanted to take the setup from Experiment 1 but apply it to a classroom setting.

7.2.1.1 Methods

Sixty-four 4th and 5th grade students participated in Classroom Pilot 1 from one school, an all girls' school, and four classes. The study ran across four days for each class with 45-minute sessions each day. Each teacher paired the students participating in the study based on students who would work well together and had similar math abilities. Student pairs were randomly assigned to work in one of four conditions: collaborative conceptual, collaborative procedural, individual conceptual, and individual procedural. There were students who were working either collaboratively or individually in the same classroom and students remained in their same condition for the length of the study. Students only switched partners if their partner was absent that day.

On the first day, the students worked independently with the tutor to become acquainted with the technology. On the second day the students took a pretest and began working in their condition when completed, which continued on the third day. On the fourth day, the students completed a posttest. The students all worked with CITS problems that were designed for Experiment 1 with students either engaging with the conceptually oriented or the procedurally oriented problems. The students also used the same pretest and posttest that were designed for Experiment 1 (see Section 2.2.2.2). As with Experiment 1, students who were paired together worked at their own computer and did not sit next to each other in the classroom. The students communicated through Google Hangouts, which was software that was already available at the school.

7.2.1.2 Results

To test if the tutor was successful in the classroom setting, I first analyzed the pretest and posttest results using repeated measures ANOVAs. Because of student absenteeism, in the analysis there were 19 students in the collaborative conceptual condition, 13 students in the individual conceptual condition, 17 students in the collaborative procedural condition, and 13 students in the individual procedural condition. As with Experiment 1, I ran the analyses separately for the students working on the conceptually and procedurally oriented problems since the problem types could not be directly compared. For the conceptually oriented condition, there was a significant learning gain between pretest and posttest, $F(1, 30) = 5.63$, $p < .05$, for the conceptual test items. There was no significant difference between students working individually and collaboratively and there was not a significant interaction. For the procedural test items, neither the pretest and posttest gains nor the condition had a significant effect. There was a marginally significant interaction, $F(1,30) = 3.45$, $p = .07$. For the procedurally oriented problems, a similar pattern emerged. For the conceptual test items, there was a marginally significant pretest and posttest learning gain, $F(1,28) = .3.13$, $p = .09$. There was not a significant effect of condition or a significant interaction. For the procedural test items there was a significant pretest and posttest learning gain, $F(1,28) = 5.45$, $p < .05$. There was not a significant effect of condition or a significant interaction.

Although the pretest and posttest data show some indication that the tutors could be used successfully in the classroom, the observations that emerged from the study were much more telling about the use of the tutor in the classroom. I observed that when students perceive an option in activities, such as working collaboratively or individually, they had a preference for one activity over another. It was not important to them that they engaged in their preference the entire time, but they did want to have an opportunity at some point. Within a single classroom, I had students working both individually and collaboratively but without the opportunity to ever work in the other social plane. Because the students did not have an opportunity to experience both social planes, some students were less motivated because they could observe their classmates in the desired state.

Second, I observed that students collaborating have an easier time communicating with their partner when sitting next to each other. In the classroom, the students that were partnered were not necessarily sitting next to each other and were just communicating through Google Hangouts. When students had trouble expressing their understanding over Google Hangouts, they would often stand up and walk across the room to talk to their partner allowing them to use the visuals on the tutor screen through gestures as part of the conversation and provided grounding. The students would also be able to see their partner's face as they provided an explanation to provide a better grounding for if the explanation was making sense, which allowed them develop a deeper understanding with their partner.

7.2.1.3 Design Changes and Discussion

In Classroom Pilot 1, I found that the tutoring system could be successfully used in the classroom. Even using the tutors for a short time period, there were signs of learning. However, there were still complications in the orchestration of the activity that caused it to not go as smoothly as anticipated. First, when planning the activity, I did not design the integration of the social planes into the classroom in a way that addressed student preferences. When planning an activity, students do not necessarily need to be given the option of what social plane they will work in. However, it can be useful during the class for all students to be given the opportunity to work in different social planes or to provide explanations as to why they are currently working in a certain social plane and to have these expectations set up front. Barring that, collaborative and individual learning likely cannot productively take place in the same classroom. This constraint is something that needs to be taken into consideration when planning the activity. To address the constraint, in my future studies I had assigned the students to social plane by class. In future studies, it would still be possible for students to work in different social planes at different times, if, for example, there was an established understanding that each student would not be doing the same thing each day and that on different days individual students would receive different opportunities.

Additionally, I also observed the importance of taking the physical space into consideration when orchestrating the activity. In Classroom Pilot 1, the students were not sitting next to each other and instead where communicated through an audio channel. The type of communication did not align with the physical space that the students were in, namely, in the same room. Because the students were able to get up easily and talk to one another to share ideas, they showed a preference for talking face-to-face so they could use visual cues that would otherwise not be available to them. By trying to have the students remain across the room from each other, the difficult task of explaining their reasoning was made even harder showing the importance of considering the physical space that the students will be working within and designing the activity to accommodate the restrictions and assets of that space. In future studies, I had changed the way that students were arranged within the room so that students who were working together would be able to sit together. This change adds some additional work to the beginning of class because students then need to know who their partner is before they can find a seat to get started.

7.2.2 Classroom Pilot 2

Before conducting Experiment 2, I ran Classroom Pilot 2 in the classroom using the materials that were designed for Experiment 2. In the second classroom pilot, I integrated the changes to the experimental procedure based upon the observations made in Classroom Pilot 1. However, Classroom Pilot 2 was not an exact replication of the first classroom pilot. The students spent more time on the tutor across more days working collaboratively allowing for more observations of orchestrating the pairing process. I was also attempting to collect the student dialogues, which added an additional layer of complexity to the set-up at the beginning of each class. Given these changes, Classroom Pilot 2 provided a more challenging classroom environment for testing the orchestration of the CITS.

7.2.2.1 Methods

I conducted Classroom Pilot 2 with 151 4th and 5th grade students from two schools in the same school district and seven classrooms. The experiment took place during the students' regular class periods. All students worked with the fractions CITS that was used in Experiment 2. However, instead of using all seven units, the students only did the naming, making, equivalent, comparing, adding, and subtracting fractions (the least common denominator unit was added based upon student performance in this pilot). During the study, students either worked on conceptually oriented tasks only or procedurally oriented tasks only, and working either collaboratively or individually for the entire length of the study. Based upon the results from Classroom Pilot 1, collaborating students were instructed to sit next to each other while working to allow the students to communicate through speech. The dialogue was then recorded on an individual stream for each student.

The study ran across five days for each class where for the three days in the middle, the students had 45 minutes to work with the tutor. The students were assigned to work collaboratively or individually by classroom (again based upon findings from Classroom Pilot 1) and were randomly assigned to work on conceptually oriented or procedurally oriented tutors by pairs. The students were paired within the ITS system at the beginning of the study. During the study, if a student's partner were absent when working collaboratively, the student would be paired with another student working on the same problem type (i.e., conceptual or procedural) for the remainder of the experiment. If there were two students that needed partners who had worked together before, they were paired together. If there were an odd number of students who needed a partner, then one student would work individually for the day.

Because pairs could progress at their own rate, if students needed a new partner, then one student would either need to be manually advanced by the researcher using the Tutorshop functionality (a learning management system for CTAT-built ITSs) (Aleven et al., 2009), which only supports moving the student to the next step or unit, to the point of the other student or a new assignment would have to be created for the pair to get them to the same starting point. To advance students or to put them in a new unit, first the researcher needs to identify where each student is in the problem sequence. If the students were close enough together in the sequence, then one student could be advanced, one problem at a time, until both students were on the same problem. If the students were in very different locations, then it is faster to create a new assignment with the necessary problem sets and add the students to the assignment. Both of these tasks are time consuming, especially if there is more than one new pair, which creates a major orchestration issue.

7.2.2.2 Results

Because of encountered orchestration issues within the pilot, I did not analyze the pretests and posttests for learning gains, and I instead present the observations around the orchestration of the task. The main complications around the orchestration occurred around the pairing of students in the class. Within Tutorshop, there was not enough flexibility built into the system to allow for realistic real-time adaptations. The main issue occurred at the beginning of class when there were student absences. When students came to class, that was often the first time that the teacher had seen that class for the day to be able to know who was and was not there that day. That meant that any new pairs that needed to be made with the students could not happen until the students were already in class. The time that it took to then pair the new students and get their problem sets aligned could take upwards of 10 minutes. During this time, the researcher was not available to help the other students in the class to get started with the tutor in addition to helping the students waiting to be paired with a new partner. Out of a 45-minute session, these 10 minutes were very crucial to learning. Not to mention, if the students do not have an activity to engage in for 10 minutes, there was often a loss of discipline within the classroom.

After the students finally got started on the lesson, there were again complications if a student left class early and they were working with a partner. If two students needed to be paired together, then again the process had to be gone through of getting them to the same place in the tutoring system. If the student had to be transitioned to working alone, then a new assignment needed to be made for them where they were advanced to the place that they left off with their partner. During this time, the students were not working who were waiting for the new assignment. Additionally, the researcher was not available to answer questions from other members of the class preventing not only the students who were waiting for a new partner/assignment from advancing but also the students that had a question or may have needed help. These results indicated that the design of the system, as presented in the methods section, did not take into account the flexibility that is needed within a real classroom and made the assumption that students would remain with the same partner for the entirety of the study.

7.2.2.3 Design Changes and Discussion

In the Classroom Pilot 2, there was such a lack of orchestration support to be able to adapt real-time to student needs that it proved to be debilitating to the ability of the students to engage in the activity. This result highlights the importance of the system being able to be adapted in real-time. Although Tutorshop allowed for adaptation, it was not efficient enough to be done in the classroom. The process that the Tutorshop required took too much cognitive load so that other students could not be helped while it was happening as well as too time consuming.

To address these issues, the pairs needed to be able to be made much more efficiently on the fly and enough information needs to be provided about the students so that fast decisions can be made. To address the issues of student pairing, I designed changes to the system to make information more visible to the teacher as well as automated the problem alignment between students. With the help of the CTAT team, specifically Octav Popescu, these changes were implemented. Figure 5.2.1 shows a screen with the additional visibility of student information to allow the instructor to make more informed pairings of students. Under the ‘Status’ header, the teacher is able to see which students are currently active in the assignment (the green checkmark) and are able to mark the students who are absent for the day (the blue checkbox). By allowing the marking of absenteeism within the system, it is easy to see which students need a new partner. In addition, the ‘Progress’ column was added to the assignment screen to quickly show how far students are in the problem set. When making new pairs, it can be beneficial to try to pair students together who are close to the same place in the tutor preventing either of the students having to redo or skip too many problems. Without knowing how far the students have progressed through the problems, it can be difficult to find the correct pairs. The ‘Progress’ column provides this information on the same page as where the pairing takes place so that the teacher would not have to flip back and forth between two pages. Each dot represents a problem set and when hovering over that dot, it shows the progress. On this screen, each row could be dragged (on the left side) to change the student pairs.

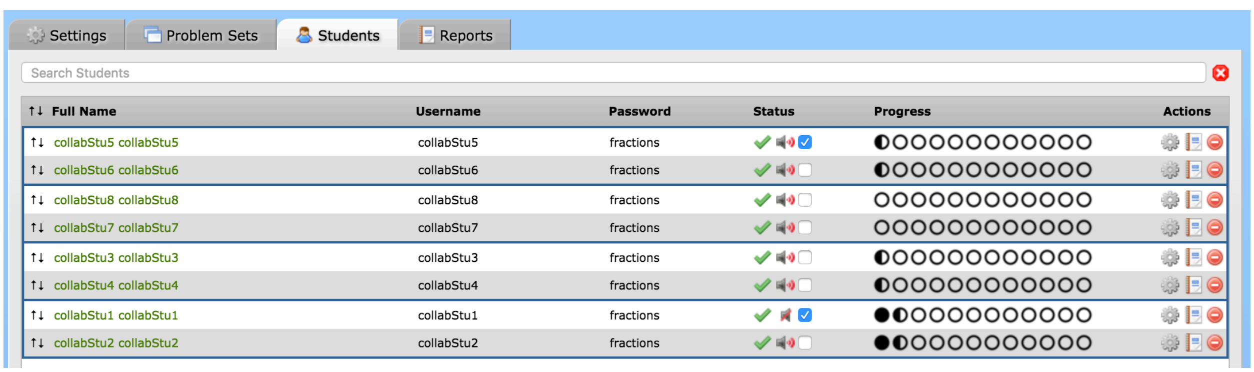

Figure 5.2.1. The Tutorshop support for the pairing of students within an assignment.

In addition to adding more information to the assignment screen to better support the teacher in making decisions around the pairing of students, the process of aligning the problem starting point for a new pair of students was automated. Before either a student needed to be advanced in their problem set until they were at the same spot as their new partner or a new problem set would have to be made for the pair (and to get them to the exact spot, manual advancement would still be necessary). With the new changes, the new pair will automatically start at the point in the assignment of the student who has made less progress eliminating the need to *manually* move students ahead in the assignment or for a new assignment to be made. Figure 5.2.2 shows students who have been repaired (compared to Figure 5.2.1) and the student who is further along now has additional problems solved in their completed problem set from doing these problems with their new partner to indicate that they have done the problem twice.

Both of these changes focus on making the pairing of students more adaptable in real-time. They cut down on the on the time needed for set-up at the beginning of class as well as making it much easier to change partners throughout the session improving the ability for the researcher or teacher to orchestrate the collaborative activity across multiple days in the classroom while students are able to work at their own pace allowing the students to use the fractions CITS as intended instead of forcing students onto a fixed schedule.

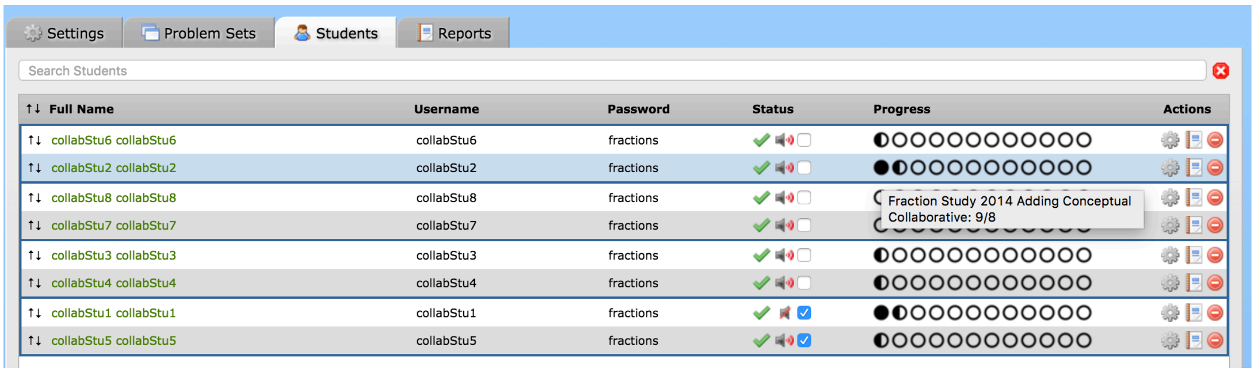

Figure 5.2.2. When students are put into a new pair, that pair begins at the progress of the student who is not as far. The further student has practice with some completed problems.

In Experiment 2, this new support for the orchestration of the fractions CITS was used in the classroom. In this experiment, although students were absent at a similar rate, with the support from the tool, it did not take as long to adapt to the students allowing students to get started faster and to engage in the learning activities.

Although these design changes made it easier to orchestrate the collaborative learning portions of the activities, they did not provide additional support for new collaborative and individual learning designs and the use of fluid transitions. By allowing for more flexible pairing in real-time, the teacher is able to have more control to adapt to classroom needs. However, the flexibility does not provide enough support to allow for fluidity between social planes. To support fluid transitions, there needs to be more support for the monitoring and adapting of the student states. Next, I present my work with teachers to design and prototype orchestration support so that it can effectively be used within the classroom.

7.3 Co-designing for Teacher Values and Classroom Needs

To be able to continue the investigation of combined collaborative and individual learning spaces, we need to not limit ourselves in the types of transitions between social planes that are currently in common use and expand learning designs from having set time transitions to allowing more fluidity in transitions by student (see Chapter 5 on the framework). Past orchestration tools have focused on improving social plane transitions through centralizing tools to make transitions faster, making it easier to transfer data from one activity to the next, and monitoring the current phase to provide more detail for the teacher to make decisions (Cuendet et al., 2011; Manathunga et al., 2015; Martinez-Maldonado et al., 2015; Munoz-Cristobal et al., 2015; Phiri et al., 2016; Prieto et al., 2014). Although these orchestration systems aim to improve the transitions between social planes, they do not expand what is currently possible within the classroom. Most of these systems support students transitioning between phases of the activity at the same time, which is a recommendation made by Dillenbourg and Jermann (2010).

However, the recommendation does not take into account student needs and that they may work at different paces. Current orchestration systems restrict students to be in sync in terms of the learning phases. To allow for researchers to investigate learning designs that take student needs into account, more support is needed for fluid transitions. In my work, I aim to expand orchestration support to include fluid transitions between social planes. To be able to develop the system, I first need to have a common understanding of the goals of both teachers and researchers.

7.3.1 Research Questions

To design support for fluid transitions in the classroom, it is important to first understand what those learning designs would entail (see Chapter 5) and how the technology support would be integrated into the current teaching and learning practices. Often to design a system that will meet classroom needs, observation of current classroom practices are used (Looi & Song, 2013; Martinez-Maldonado et al., 2015). However, in the case of expanding the types of transitions that are supported there are not any current classroom practices to observe as most classes currently only have students transition between phases based on time. It is, therefore, important to work with teachers outside of an observable classroom context to understand the values and experiences that need to be accounted for in a not-yet-realized system and how these can be integrated along with the preferences of the researcher into the system.

When designing a new system, it is important to take into account users' experiences instead of just adjusting an existing system to fit the new task. The way that a system is used is dependent upon both the system design as well as what the user is bringing to that design (Sanders, 2002). Teachers have existing cultures within their classrooms, and for a new technology to be adopted into the classroom, the technology needs to align with their beliefs about student learning and current teaching (Blumenfeld, Fishman, Krajcik, Marx, & Soloway, 2000; Windschitl & Sahl, 2002). A teacher's past experiences reflect classroom culture and can be used as a source of inspiration for future designs. Within value-sensitive design, the adoption of a new technology depends on how it aligns with the users (i.e., teachers) values and needs (Friedman, 1996).

Although previous research has established a set of guidelines around orchestration systems (Dillenbourg, 2013; Dillenbourg & Jermann, 2010; Prieto et al., 2011), these guidelines do not take into account teacher experiences. A primary aspect of orchestration systems is that they should be teacher-centric. Following this idea, it is suggested that teachers should be the drivers of the activity and maintain the control over the classroom activity (Dillenbourg & Jermann, 2010). To this end, many orchestration systems do not intervene within the learning activity and instead only monitor and provide information to the teacher (Martinez-Maldonado et al., 2015; VanLehn et al., 2016). However, this design guideline does not take into account the experiences and values of the teacher within their classroom. Although teachers are responsible for their class and need to have autonomy, when and how autonomy is provided can greatly change the value and usability of the system. By understanding teacher's experiences, automation of the orchestration can be used to support teachers within the classroom rather than restricting their control. My work builds upon previous orchestration design guidelines by investigating teacher experiences and values to better understand how we can design an orchestration system that will promote these experiences and values.

Within my work, I aim to design a system that addresses both the researcher and teacher needs through a set of co-design sessions. Within these co-design sessions, I had a researcher and teachers working together around social plane transition scenarios to create a common design for the flow of a classroom that is supported through an orchestration tool. These sessions were then used to investigate the values and experiences that teachers have and how we can support these values through technology that is being used in the classroom. As part of the process, it is important to find the balance between the automation that an orchestration tool can provide and when teacher autonomy is necessary. For more complex learning designs, the design may not be orchestrable without some automation in the system. However, it is important to understand where automation would be beneficial and where it would be removing a sense of autonomy with the teacher. In this section, I will first present my methods and then the emerging themes from the co-design sessions. Finally, I will discuss how these emerging themes impact orchestration designs around fluid social plane transitions.

7.3.2 Methods

7.3.2.1 Co-Design Methodology

To investigate the values and experience of teachers in terms of activities involving transitions between social planes, I used co-design methodology. Co-design is a type of participatory design where the users are involved in a collective creativity process with other stakeholders (Sanders & Simons, 2009). By using participatory design methodology, the tools that are developed will not just be useful to researchers but can also be valuable to the community of teachers (DiSalvo & DiSalvo, 2014). In this case, the co-design process involved teachers and researchers as both have a role in the use of the orchestration system. The co-design process is different from other types of design processes in that it values and integrates the experiences of the user into the design process (Sanders, 2002). Instead of just asking the user what they want or designing for assumed needs, co-design uses the experiences and values of the participants to inspire the designs (Sanders & Stappers, 2014).

The co-design process works by having multiple stakeholders working together to develop a common language and design (Sanders, 2002). Within the process, the end users are experts of their experiences. It is the job of the researcher to help facilitate the sessions to elicit these experiences. Physical artifacts are used within the sessions as thinking tools and to help the participants express themselves. Through the process, the facilitator guides the participants through identifying important aspects, recalling previous experiences, reflecting on values, and thinking about future situations (Sanders & Stappers, 2014). Throughout the process, different participants come in at different levels of creativity and it is important to appropriately support these different levels (Sanders & Stappers, 2008).

Although the co-design process has often been used outside of education, there are examples of it successfully supporting the process for designing technology for the classroom (Penuel, Roschelle, & Shechtman, 2007; Penuel, Tatar, & Roschelle, 2004; Spikol, Milrad, Maldonado, & Pea, 2009). Within education, much of the co-design has focused on the use of technology for the classroom, so it has included teachers, designers, and researchers within the design process. By including teachers, as the end users, in the process, the technology can be developed to include the perspective of the teacher (Penuel et al., 2007). By including the different perspectives within the design cycle, the participants can develop a shared sense of what the system needs to entail to support the teacher within the classroom. Without this shared goal, there can be tensions between the different users around the ideal solution. Teachers often view the solutions from researchers as too theoretical and not practical enough for the classroom (Shrader, Lachance-Whitcomb, Finn, & Gomez, 2001). Additionally, the co-design process allows the teacher to reflect on their own teaching practices (Penuel et al., 2007) and can create a tighter coupling between the teaching practices, curriculum, and technology (Penuel et al., 2004).

7.3.2.2 Study Design and Procedure

In the co-design sessions, a total of seven teachers (six female, one male) participated across three different sessions with two two-teacher sessions and one three-teacher session. The teachers ranged from teaching 2nd grade to 7th grade and all taught at least one mathematics class (although not all were only mathematics instructors). The teachers were recruited through connections from previous studies as well as word of mouth. The seven teachers came from five different schools. Across the schools there was a different level of technology available within the classroom. All classes had access to whole class technology, such as a SmartBoard and teachers had access to a computer. The amount of one-to-one technology for the students differed though with some schools having one class set of computers/tablets shared across the entire school and others having almost daily access to one-to-one devices, where there are enough devices for each student in the class. Access to technology greatly influences the current use and familiarity of technology in the classroom. All of the teachers did have experience with using collaboration in their classrooms with the amount ranging from once a week to daily.

Each teacher participated in a 2-hour co-design session with at least one other teacher and a researcher, who also conducted the session. Each co-design session was semi-structured with specific scenarios discussed around transitions between collaborative and individual learning that could occur in the classroom. These scenarios, along with the researcher's participation, brought the needs of the researcher into the discussion. Each of the scenarios was based upon either a challenge encountered within orchestration of studies or based upon a social plane transition presented in the framework. Before each co-design session, the teachers were emailed a short survey around their use of collaboration and technology in the classroom. At the beginning of each session, the participants had a chance to discuss the use of collaboration in their classroom including the types of activities that they used collaboration for, how often, and why they used collaboration.

After discussing how the teachers currently use collaboration in their classrooms, the teachers were asked to design the flow and distributed responsibility around different scenarios within the classroom. At this time, the teachers were reminded that they were the experts within the classroom and that the session was a discussion between researchers and teachers rather than just design proposals from the researcher. Each scenario attempted to address a different type of transition that may happen within the classroom, although there may have been others that the teachers were encouraged to add, as they felt necessary. For each scenario, the group was asked to think about how the responsibilities should be distributed between the students, teachers, and a potential orchestration system. The group was instructed to not restrict themselves to what they believed current systems could support. Through the design discussions, I intended to elicit the values, past experiences, and pain points that the teachers had within their classroom based upon where they wanted to spend their time and where they were willing to allow automation from the system.

Each of the scenarios centered on the types of transitions that were laid out within my framework for the design of collaborative and individual learning. The three main discussion topics centered on the timing of the transition, the adapting to student needs, and the grouping of students. Within the timing of the transition, the group was provided with prompts to discuss instances such as student absenteeism, tardiness, leaving early, and students completing tasks at different times and waiting for a partner to begin a task. When discussing adapting to students needs, prompts included the physical layout of the classroom, who decides the students should switch social planes, and how students are informed that they are changing social planes. Finally for the pairing, the prompts included who decides the partners and how these partners are communicated. These scenarios provided a representation of the activities that would need to be supported in the classroom for the tool to be of use to researchers. In the co-design sessions, teachers could then have a discussion around the orchestration of these scenarios in the context of their classrooms and how they could be effectively supported.

To support the co-design process around the scenarios, each group was provided with a set of materials that they could use within the design process. The materials consisted of markers, pens, construction paper, poster board, glue, and scissors. The construction paper has presented both in full sheets and pre-cut shapes that could be used to represent different people or things within the classroom. The teachers were encouraged to use these materials, as they felt fit into the design process. Although the materials were provided, the majority of design was expressed through discussions rather than through used of the materials.

7.3.2.3 Data Analysis

Co-design sessions were captured with video. For each session, with a total of three sessions, there was one 2-hour video. To analyze the results, I reviewed the videos to reveal salient themes and values expressed during the co-design sessions. During the review of the videos, I took notes on the conversations. Across the three sessions, I had 147 notes. Using these notes, I went through an iterative process in which I used affinity diagramming to cluster and re-cluster the different notes to reveal the main themes around social plane transitions (Miles, Huberman, & Saldaña. 2013). Additionally, I took the culture and flow of information in the classroom into consideration through the development of cultural and flow diagrams (Beyer & Holtzblatt, 1997). The cultural diagram presents the current values and influences of the different actors within the school system while the flow diagram presents information and artifacts as it flows between the different actors within the classroom. These diagrams help to capture the breakdowns as they occur in the current classroom and where an orchestration system can provide support by addressing the breakdowns.

7.3.3 Results

During the co-design sessions, the teachers and researchers worked together to develop an understanding of how to support orchestration within the classroom that revealed the values of the teachers. Although materials were provided for the teachers and research to work with, much of the development occurred through discussions between the participants. My data analysis revealed several significant themes around the development and execution of collaborative learning activities that I present below. The first theme provides insights around the importance of planning before the class both activities and the student groups. The second theme addresses the commitment adapting teaching to the students, which entails both monitoring and adapting to student needs. The final theme entails the tensions between spending time teaching and managing the activity for both teacher and student responsibilities.

7.3.3.1 Activity Planning

Figure 7.3.1. The teachers discussing that there should be something for the students to do the minute they enter the classroom and that the students know to begin this task.

When designing for transitions between social planes in the co-design sessions, a topic that kept emerging was the importance of planning the activity before students were ever involved. Although I was originally focused on the real-time classroom support of fluid social plane transitions, I found that the planning of these transitions was essential to a well-executed activity. Part of the planning process is to plan the tasks that the students will engage in but also to choose groups for the students to work within when they are working collaboratively. Although both of these steps are part of the planning process, the teachers addressed these steps very differently in terms of their impact on how the activity would develop and run within the class.

When it came to planning the activity phases, the teachers expressed the importance of having a plan in place that has a well-established structure (see Figure 7.3.1). When an activity is not prepared ahead of time, there is more downtime within the class for the students to lose their focus. To then get students back on track takes additional time. By having the activity preplanned and structured, the teachers expressed that the students would be much better at being able to move to the next step. Teacher T5 said, "for that quick and quiet transition, that is having the materials ready ahead of time. All of that has to be front loaded." These transitions between phases are a time when it is easy to lose the class' attention and the materials have to be ready ahead of time for these transitions to go smoothly.

In general, having these routines and structure to the tasks are very important. During the class, students not only need to engage and learn the domain material but also must be taught the types of processes with which the teacher would like them to engage. To have students engage in a complex task, it is important to teach the students what actions they need to go through procedurally. For the students to then correctly engage in these procedures during class, it is important for a routine to be followed so that the students understand what is expected of them at each step. Having students collaborate within the classroom is difficult. Students confuse the time spent collaborating with socialization time and may not know how to engage their partner in a productive conversation. By teaching and following a routine, the students are more likely to be able to engage in the activity as intended. Teacher T5 expressed that getting students to collaborate "is a ton of frontloading…but once it is up and running, it is truly beautiful." showing the importance in planning an activity ahead of time and to have set student expectations with what is expected of them within the activity. This does not mean that the activity must be structured in the same way each time but that the students can clearly follow the directions laid out for them and that the expectations for these directions follow a structure that is consistent. The structure needs to be in place for both working within a phase and also the transitions between the phases.

The second part of planning an activity is to assign students to groups. Although the teachers often planned groups ahead of time as well (unless students were choosing their own partners), the group assignments played a very different role in the success of the activity than the main activity planning. The activity was often planned around specific learning goals while the groups were designed to be much more motivational for students. When discussing group assignments, the teachers expressed much more desire for variability and student buy-in to the group structure.

Although groups are often formed based upon academic criteria, teachers still want groups to be able to change so that students have a chance to work with more than one person but also worry about how students react to the groups. When planning groups, the teachers need to consider how well the students work together as well as how a grouping will impact the student's learning. When they find a good pairing, it is then often easier to keep that group together than to try to take the time to change groupings every time with teacher T6 expressing that "groups are not based on academics but based on social behavior." However, these changed groups are desirable so that students have a chance to work with a variety of peers. Teacher T5 said she "would not want it to get stagnant and where the same students are working with the same partner all the time." The teachers expressed difficulty in changing groups though because students would blame them if they were in a group that they did not want to be in or sometimes are just resistant to new groups. By having support in the group formations, the teachers would not have to spend as much time on choosing the groups and would be out of the line of fire when students did not like the group.

That does not mean that teachers want to relinquish the group formation process all together and instead would like to understand why students are paired together. When pairing students, the teachers want the students to not just engage in the collaborative task with their partner but to learn from their partner. As part of the process, the teachers want to understand why students are paired together and share information with the students themselves. The teachers want to motivate the students in the collaboration by developing an understanding between the students of what each is bringing to the group to help break down some of the social walls.

7.3.3.2 Monitoring and Adapting to Student Needs

The second theme that emerged from the co-design sessions was the discussions around being able to understand the student's current state so that the on-going learning activities could be adapted to the students. For understanding to occur, there needs to be a way to effectively monitor the students as well as make changes to the lesson depending upon the students' current understanding. Teachers need to be able to do these activities both between classes and in real-time.

The teachers expressed the desire to not just be passive players during class but to be able to be active contributors to the learning. When the students are working in a social plane that is individual or small group, it can be difficult to monitor and connect with the individual groups. The teachers expressed often walking around the class to check in with students both who are struggling and for reinforcement for students who are doing well. Teacher T6 said, "You are hoping for a well-oiled machine so that you can do the individual meetings." However, it can be difficult to get to each of the groups and to provide them with the help that they need in a timely manor. Teacher T1 expressed frustration around the inability to know which groups are quality and said, "Well, are the other groups really quality? And that is how I feel sometimes, that they are not. And then I get so frustrated sometimes." The teachers want a way to monitor student progress when it is difficult for them to check in with every group. Currently, the teachers mentioned that they gauge how the students are performing by checking over the work that the students have completed, often outside of the class period, which is very time consuming and can cause the delays in interventions. To be able to adjust the social plane to the student needs for fluid transitions, more support would be needed to monitor the students.

During the planning process, the teachers also use student progress from previous sessions. Currently, the teachers reflect on the previous lesson to understand how they can adapt the lesson approach to the students' learning as well as what material to cover in the activity. In each activity, the teachers cannot monitor everything and want support from a system to catch the things that they miss. For example, when forming groups, they have general impressions about their students' skill levels and do not always realize when a student may have more or less prior knowledge in an area than assumed. A system, though, could provide support by monitoring the student activities.

Teachers do not find it enough to just monitor the current state of the student activity, but they want to use information to be able to adapt the activity to the students. For example, teachers mentioned liking to pair students together who have taken different approaches to solving the problem. Teachers expressed feeling like they are restricted to enacting these adaptations between classes rather than within classes because of the limited time in class and getting to visit every group. Although teachers expressed frustration in knowing that not all groups or students may be currently at a good quality or being as productive as they could be, they did not feel that there was much that they could do in the class. They could not personally support each group and welcomed a system that could as long as they could quickly check on the state of the students and had an understanding of why the change was made.

Although the teachers wanted to share the responsibility of adapting to the students with the system, they still wanted to have the final control over the system. Teacher T7 said, "There are times you are going to need to have that override button." Currently in the classroom, the teachers make adjustments when they see they are needed. They help to pair students when someone is absent, increase or decrease the time for a phase when needed, and split groups up when they are repeatedly interrupting class. Although they may never need to intervene when some of the responsibility is shifted to the system, they want to be able to override the actions so that they feel they can make the changes that are needed to maintain control in the classroom.

7.3.3.3 Tensions Between Management and Teaching

The final theme that emerged from the co-design sessions was the tension between management and teaching. The management activities included things that the teachers had to do to make sure that the activity ran smoothly. For example, this could include pairing students, going over the directions of the task, or even dealing with behavior issues. Real-time in a class, what makes a teacher feel valued is helping their students to reach the moments when they understand the material. However, during class, so much time is spent on other tasks besides teaching students. Limited time causes tension between what teachers would like to be spending their time on (i.e., supporting student learning) and what they actually spend their time on (e.g., classroom management). Tension came out in terms of both the activities that the teachers wanted to engage in as well as the activities the teachers wanted the students to engage in. For activities that are more complex to orchestrate, tension becomes greater as less time can be spent directly teaching.

When in the classroom, teachers feel that much of their time is spent in managing the class. They feel that currently so much of how a teacher is judged is based upon their management opposed to their teaching. Teacher T4 expressed optimism for a system that could support the management process by saying, "It would just free up so much of your management…If you could just focus on the teaching, that would be incredibly helpful." In real-time, teachers have to split their time between the management of the activity and teaching students. They do not always feel that they have the support in the classroom to allow students to reach their potential and find it "frustrating that students leave the room knowing that the students could have done more," as expressed by teacher T6. Managing activities is not often why teachers get into teaching. If automated support were provided for this necessary, but not necessarily exciting or fulfilling, part of the job teachers could spend more time on teaching related activities.

During class, teachers want time to work with students individually (or in their small groups) to support the student as needed. During these more personalized sessions, the teachers can teach and reteach to the students' specific needs to get more accomplished than is often possible in a large group setting. This case is especially true when a student has missed part of class and needs to be caught up. To be able to have these individual meetings with students, the rest of the activity needs to run smoothly to give the teacher some time not managing it.

However, in reality, teachers are often getting interrupted in one-on-one time with students by other students. When teachers are working with one group or student, all of the other groups are currently being ignored and if students are not sure what to do, then they interrupt. To try to avoid interruptions, teachers write down the instructions, go over them in class, and try to anticipate any problem that the students might encounter. In the classroom, the teachers are still viewed as the source of the management so will get interrupted. With short class periods, every minute with the students is important and an interruption can make something take double the time. Teacher T2 mentioned that "[She doesn't] want to have to go back and touch something or press something. That's not going to work for [her]." Therefore, the orchestration system can best support the teachers by communicating instructions and transitions directly to the students, which can limit the interruptions that the system has for the teacher as well as the interruptions from the students since the source of the management would now be shifted providing teachers with the ability to step out of the classroom or to work with individuals providing them with more flexibility over their time.

The tension between management and teaching also extends to how the teachers viewed their students' responsibilities. The teachers expressed a desire for the students to take responsibility for their own learning, yet they do not trust the students to stay on task when they are completely unmonitored making it difficult for teachers to focus on the teaching rather than the management. Teacher T2 mentioned, "Students will work while you are there and then when you leave, they just stop." One of the reasons that teachers have all students switch phases at the same time is so that they can more easily track students when they are moving. Although the students may be aware of what there are supposed to be doing, teachers feel the need to walk around to monitor the students and keep them on task. At the same time, the teachers expressed that collaboration in the classroom only works when there is trust between the teacher and the students. Teacher T3 mentioned, "A key to a collaborative classroom is trust with the students." The students are accountable for their learning and actions and the teachers must trust them to be making good decisions. An orchestration system can support tension by providing information to the teacher about the state of the students while at the same time providing the instruction to the students to support them in guiding their learning.

7.3.4 Design Recommendations

From the co-design findings, I formulated several design recommendations. In contrast to design recommendations from the current literature (Dillenbourg, 2009; 2013; Prieto et al., 2011), these design recommendations are focused on how to develop an orchestration tool to balance the automation that an orchestration tool can provide and when teacher autonomy is necessary. These recommendations apply to all orchestration systems, but I feel are particularly relevant for complex orchestration activities, such as when fluid transitions are involved. In this section, I present five orchestration recommendations including planning as part of orchestration, automation for real-time decisions, direct communication to students, providing monitoring and information to teachers, and allowing for flexibility through teacher overrides.

First, the planning of an activity is an important part of the orchestration process and should be included in the orchestration support. Although there has been some debate within the literature if the planning of the activity is part of the orchestration process (Dellatola & Daradoumis, 2014; Dillenbourg, 2013; Kollar & Fischer, 2013; Prieto et al., 2011; Tchounikine, 2013), through the co-design sessions I found that planning was a vital part of orchestrating the activity, as emphasized by the teachers. During the planning process is when decisions are made for the activity. During this time, teachers are able to take the time to make informed decisions around the lesson and learning goals that later help them real-time in the classroom. By structuring the activity before class to follow a common routine for the classroom, the teachers are able to better react to unexpected events that happen within the classroom. Additionally, the planning stage of the orchestration support is an ideal place to provide teachers with control and leadership over the activity (Dillenbourg & Jermann, 2010). When teachers are not in class, they have more time to focus on developing their plan for the activity design and management so that they can adapt the activity to their class's needs. For the fluid transitions, teachers are able to plan the transitions ahead of time for what will work in their classroom and with the tasks the students are engaging in for the activity. During class, the teacher can focus on working with students and relinquish some of the management control to the system to carry out their planned activity. The planning could provides the teachers with one way to have a sense of autonomy over the activity without overwhelming them in real-time.

By supporting the planning process, the teachers do not have to be making or approving all decisions made in real-time. From the co-design sessions, getting to teach and interact with the students directly provides teachers with a sense of accomplishment. When they have to spend all their time on management and feel that the students leave the classroom without learning as much as they could, they become frustrated. To allow teachers to have more uninterrupted one-on-one time with students and groups, much of the orchestration management of the activity in real-time can become automated. By automating the real-time management, teachers do not have to be interrupted every time that a decision needs to be made, which is important when the students are engaged in an activity that has more fluid transitions. Each time that students need to switch social planes, the teacher does not have to get interrupted if the process is automated. When students are transitioning at different times, these interruptions may span across a length of time and prevent the teacher from spending the time teaching. While they are working with a small group, they can focus on the small group without worrying that the other groups are not progressing. The teachers view classroom management as an important part of their job, but not necessarily the part that is most meaningful to their job. By supporting the real-time orchestration of the activity through the orchestration tool, the teachers can have peace of mind that it is not being neglected while not having to spend their limited time on it themselves.

It is not enough though to automate the orchestration if all communication still goes through the teacher, so it is important that information can be directly shared with the students. Even if the teacher is not making decisions, if they act as the moderator between the students and the orchestration tool, then they will still be interrupted for every change and update to the activity. An orchestration tool could possibly remove these interruptions and management role by providing information directly to the students. By doing so, the tool could also provide more support for the students taking responsibility for their learning, which was a concern for the teachers. The students would no longer have to wait for their teacher to tell them what to do and could instead proceed with the activity with instructions from the orchestration tool. This tool could also support more fluid transitions between social planes as the orchestration tool could directly inform the students of a transition and who their partner is. The students would then have the responsibility for making the correct decisions for their learning but not without any support.

Although the teacher does not necessarily need to be part of the decision-making process in real-time, it is still important to provide enough information so that they can monitor the state of the classroom. The teachers are responsible for the discipline and student learning within the classroom. As the students work through the activity, it is important to provide teachers with an easy way to check on students to see if they are on task or are struggling. Currently, teachers walk around the classroom to check on their students, but they often do not have the time to monitor and get to every group. Ideally, the system would provide an easy way for the teachers to monitor the classroom, even as they are working with the individual students. Classroom monitoring is a feature that current orchestration tools often include (Alavi & Dillenbourg, 2012; Looi & Song, 2013; Martinez-Maldonado et al., 2015; Raca & Dillenbourg, 2013; Mercier, 2016; Wang et al., 2015a) and is an important part of the orchestration design (Dillenbourg, 2013; Prieto et al., 2011). However, in these cases, the students are often all working on the same phase of the activity at the same time. When there are more fluid transitions, it becomes important to provide enough information to the teacher so that they know what phase their students are currently in and what social plane the students are working within. One set of students may be talking in the classroom not because they are off task but because that is what the orchestration tool had instructed them to do. By providing monitoring to the teachers, they no longer have to rely on the task structure to make sure that students are on task (e.g., having all students transition between phases at the same time).

In addition to the monitoring, teachers need to be flexibility intervene in real-time when needed. Although the teachers have control over the assignment in planning, even the best-laid plans may encounter external constraints that need to be adjusted to. Having flexibility in the learning activity is a primary aspect of classroom orchestration (Dillenbourg, 2009; Dillenbourg & Jermann, 2010). This adaptation could be done automatically, such as with forming new pairs for absent students, but it must be possible for the teacher to override any decisions, so as to support the teacher's autonomy and ability to run their class. If the orchestration tool makes a decision that the teacher does not agree with, the teacher is still responsible for the classroom and the students in that class. If the social plane transitions become too complex for the teacher to feel like they have control, then that activity may not be viable for the classroom. Therefore, it is important for the teacher to have the flexibility for the teacher to intervene.

7.3.5 Discussion

Before developing an orchestration system to support fluid transitions between social planes to support researchers, it is important to have an understanding of the balance between the automation that the system can provide and the autonomy provided to the teachers over their own classrooms that can be refined through prototyping and deploying systems into the classroom. Although previous research has provided design recommendations for orchestration systems, these recommendations do not focus on the division of responsibilities between the system, teachers, and students within the classroom. Orchestration systems are intended to be teacher-centric and allow the teacher to have control and leadership over the classroom activities (Dillenbourg & Jermann, 2010). However, as the monitoring and management for an activity becomes more complicated, it is unclear how control and leadership can be achieved to help lower the cognitive load of the teacher in the classroom while still providing them with a sense of control. In this study, I conducted a series of co-design sessions with teachers to explore how and where the support from the orchestration system could be designed to support teachers in a way that would reinforce their value as a teacher while providing support for researchers to further investigate the combination of collaborative and individual learning. From the co-design sessions, three main themes emerged around the orchestration of the activities that suggest five design recommendations.

In the co-design sessions, the teachers emphasized the importance of planning, monitoring and adapting, and balancing between teaching and management. Many of these themes are not necessarily novel to the area of orchestration. However, the approach and insights into the themes do build upon the current orchestration knowledge. Although planning is already part of the orchestration debate (Dellatola & Daradoumis, 2014; Dillenbourg, 2013; Kollar & Fischer, 2013; Prieto et al., 2011; Tchounikine, 2013), the findings from the co-design sessions suggest that further distinction is needed. The activity planning was expressed as being very important to develop structure and align with the routines within the classroom. On the other hand, the teachers wanted to distance themselves from group formation so that they were not responsible for the emotions that are associated with the groups. During the real-time activity, the importance of monitoring and adapting to the constraints in the classroom were emphasized (Dillenbourg, 2009; Dillenbourg, 2013; Dillenbourg & Jermann, 2010; Prieto et al., 2011). However, the teachers did not express the need to be in control of the management and adaptation. On the contrary, they struggled with balancing teaching and management aspects of the class and preferred to spend their time teaching.

These findings led to five design recommendations that add to the current body of literature. Previous orchestration recommendations and tools have focused on supporting teachers in activities that already take place in their class and making them more efficient. To be able to broaden these learning activities in their complexity that may not be able to be supported by a teacher alone, it is important to understand how the responsibilities can be divided to still have a functioning classroom. My design recommendations provide insight into this divide. Much of the teacher control can be provided during the planning session. During the class, to allow teachers to spend more time teaching, adaptations can be made by the system and directly shared with the students. However, it is still important to provide the teachers with the overall control through support for monitoring the orchestration and the flexibility to intervene when needed. These recommendations suggest that with complex learning designs, the teacher interactions may be more effective during the planning while the automation can be successful in real-time adding to current design recommendations that do not distinguish between these orchestration stages.

In this study, I conducted a set of co-design sessions with teachers to understand their values and how to better support them through orchestration automation. These co-design sessions had a limitation in that some had few participants. With conflicting schedules, it was difficult to find a time that would work well for a large number of teachers. Additionally, some of the sessions had only teachers from the same school limiting the discussion and exchange of new idea between the teachers because they often followed the same procedures for teaching. However, despite these limitations, the co-design sessions provided insights into when automation is appropriate in the orchestration process and when teachers need more autonomy. The next step would be to use these recommendations along with proposed framework presented in Chapter 5 to develop an orchestration system, as is presented in the next section.

7.4 Orchestration Prototype

Based upon the findings from the co-design study, I developed an orchestration prototype that focused on the fluid transitions between social planes. The development of this tool was designed with the needs of both the researcher and teacher in mind by integrating the design dimensions provided in the framework with the results from the co-design sessions. The prototype was developed using Axure RP.

Axure RP is a prototyping tool that allows the user to develop an interactive, dynamic prototype quickly with little coding overhead. Although the results from the co-design sessions ranged across the different orchestration and dashboard aspects, for the prototype, I focused on the tasks that involved the transitions between social planes as these are a substantial point of management in the classroom. However, other steps need to be taken both before and after the activity planning and real-time orchestration of the activity, such as forming the class list or analysis of student learning. Because these were not the primary interests in the tool, the features were not fully developed, but, instead, the teacher could see this functionality would be part of the tool through the menu bar. Because the focus of the prototype was on the transitions between social planes, based upon the co-design results, the main elements of the prototype focused on the activity planning and the real-time monitoring of the class through in class scenarios. The orchestration prototype is developed for use in the classroom where there is a one-to-one matching between students and technology allowing each student to work on their own device. Within the prototype, it is assumed that students would be working on a computer or a tablet. The prototype is primarily provides front-end capabilities that allow interactions to occur around a certain set of scenarios. To improve the usability of the prototype, I tested it with teachers and iterated, based on observations and comments from the teachers. Within this section, I first present the overall structure of the elements that are included within the system. I then present the prototype planning and in class scenarios in the prototype.

7.4.1 Overall Prototype Elements

Although the main part of the prototype design was focused on the planning and real-time scenarios of social plane transitions, I wanted the prototype as a whole to reflect all aspects of the orchestration that were discussed and would practically be needed in an orchestration tool. To this end, I included the set of elements within the prototype menu that would be needed within the system for it to work as a whole (see Figure 7.4.1). The menu included classes, lesson, problem sets, and analysis. Given the nature of the prototype, the majority of the interaction took place within the lesson section for both planning and real-time monitoring. The other menu items were also included in the prototype to show important aspects of the system (i.e., classes and problem sets) and co-design findings that were out of scope for the prototype (i.e., analysis).

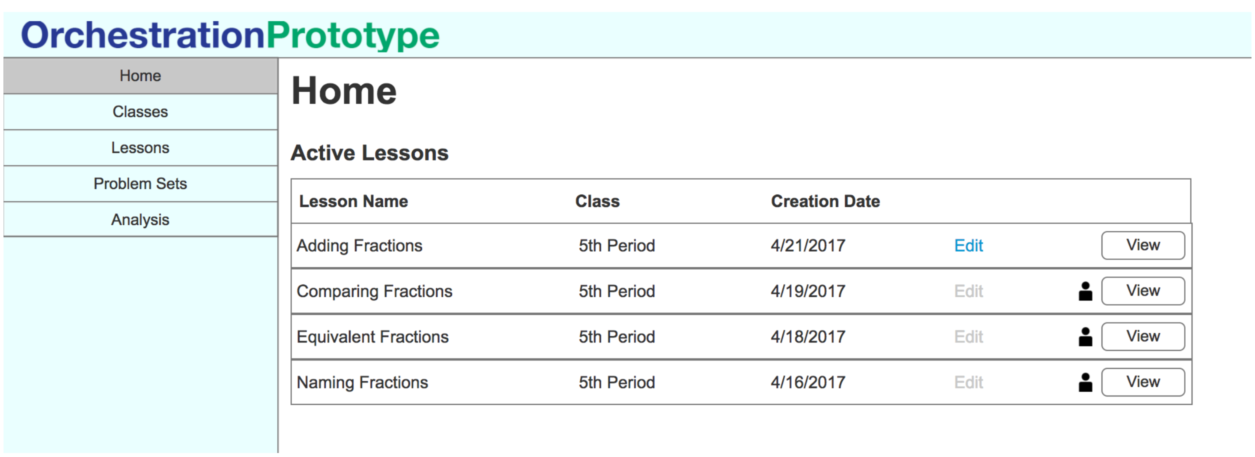

Figure 7.4.1 Home screen of the orchestration prototype showing the sidebar menu selection of the overall supported tasks within the system.

Within the co-design results, the three main findings revolved around the planning, executing, and reflection on the activity, which aligns with the three stages laid out in the ICLC framework (Kaendler et al., 2015). Given the focus of my prototype on transitions between social planes, I chose not to focus on the reflection stage of the teacher work. However, because of the importance of reflecting and analyzing the activity that was emphasized in the co-design sessions, I did feel that it would be an important step to support in the orchestration tool since it helps to shape how the next activity will be conducted. To fully develop the analysis stage of the activity, it would be important to build upon the work that has been conducted around teacher dashboards (Van Leeuwen, 2015).

The other menu items that were not fully addressed within the prototype were the classes and the problem sets. Classes and problem sets were added as basic features needed within the software to support different tasks and classes. Under classes, the teacher would be able to add the students to the class and specify the students that do not work well together. The teacher would also be able to assign students basic logins and passwords. Under the problem sets, the teacher would be able to add tasks for the students to complete, such as worksheets or a series of activity prompts. When working with an ITS, the problem sets would be a set of individual problems. Although these items are essential to the higher-level usability of the software, because they are not closely tied to the orchestration of an individual activity, they were not expanded upon in the prototype.

7.4.2 Activity Planning

From the co-design session, a major theme that emerged was that for an activity to run well in the classroom, it needs to be well planned in advance. Although having fluid transitions in the classroom on the surface appears to be a real-time classroom concern, these transitions need to be planned in advance for them to run smoothly in the classroom. Therefore, an orchestration system needs to support the planning of the transitions and not just provide the real-time support for the transitions. Within the planning, there are two different steps that need to be considered. The first is planning the activity and what the different phases are that the students will engage in. The second is planning groups for any collaborative phases that will occur within the activity. Because these were addressed as two very distinct items in the co-design sessions, within the orchestration prototype, I also treated these as two distinct parts of the planning process.

7.4.2.1 Phase Planning

For the orchestration tool to also be used in research, it needs to be able to accommodate different types of activity designs. Therefore, when planning an activity that includes both collaborative and individual phases, it is important to include the four dimensions laid out within my framework. When outlining the activity, the user needs to be able to choose the alignment of activities with social plane, ordering of social planes, how groups are formed, and transitions to the next phase. Within the orchestration prototype, some of these decisions are made much more explicit than others by having all of the choices directly on the screen (see Figure 7.4.2). For example, the ordering can be fully controlled but the ordering options are not shown on the screen. The order is just made implicitly through the ordering of the phases. Within the orchestration tool, the user is able to add different phases and within each phase assign problem sets (or tasks) that the students will engage in, social plane that students will work within, and how students will transition to the next phases. Each phase can be assigned a name by the user because through the validation, I found that many of the teachers thought about the parts of the activity not as phases, but as a section of the lesson (i.e., direct instruction, individual work) and by allowing them to name the phases, they were able to better make connections to their current planning.

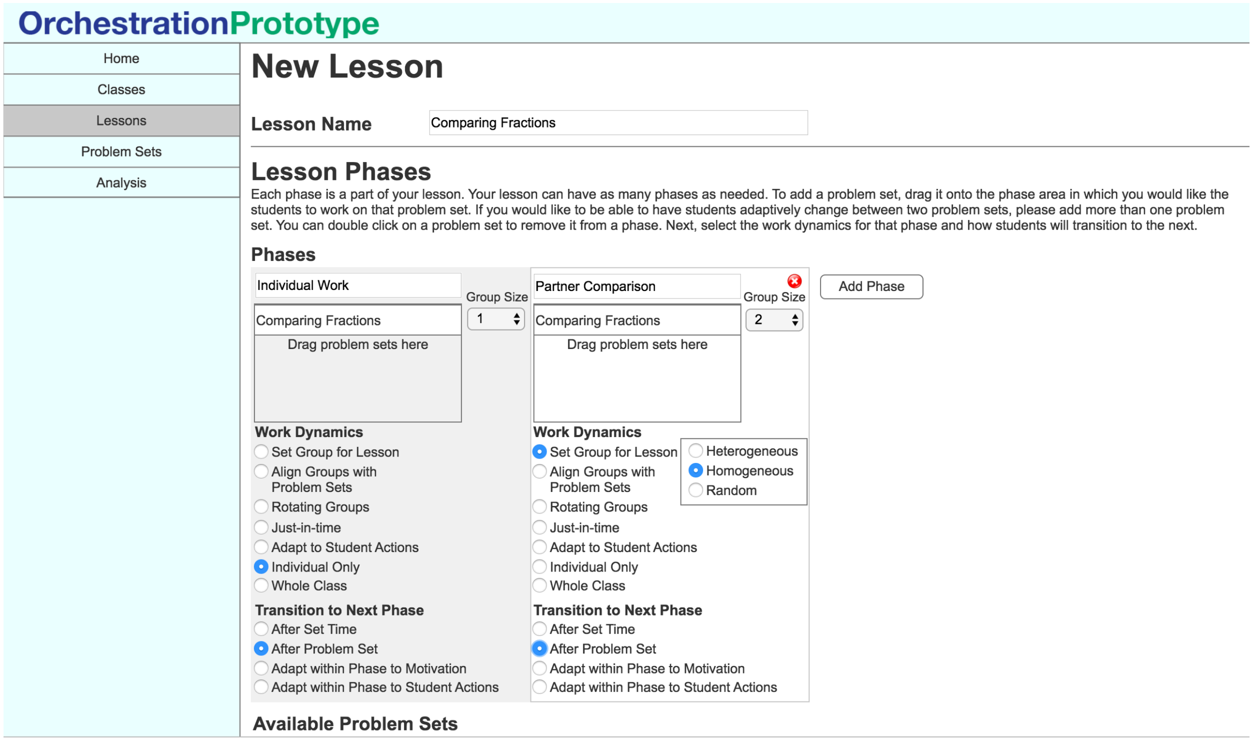

Figure 7.4.2. Orchestration prototype screen where the user can develop the lesson outline and set the social plane, order, transitions, and group formation.

To assign a social plane to a phase, there are two different steps that must be taken within a phase. First, the user must drag the problem sets that they would like to be worked on during that phase into the phase assigning that problem set to the phase. After a problem set is assigned to the phase, the user can choose the group size for the phase (See Figure 7.4.3). If the group size is one, then the students will be working individually on the phase. If the group size is the whole class, then the students will be working as a whole class during that phase. Although the orchestration tool is intended to support transitions between individual and collaborative work, whole class activities are an important part of the lesson and then need to be included in the planning stage. Finally, if the group size is between 2 and the whole class, then the students are working collaboratively during that phase. By selecting the problem sets and group size for a phase, the user is able to align the social plane with the tasks.

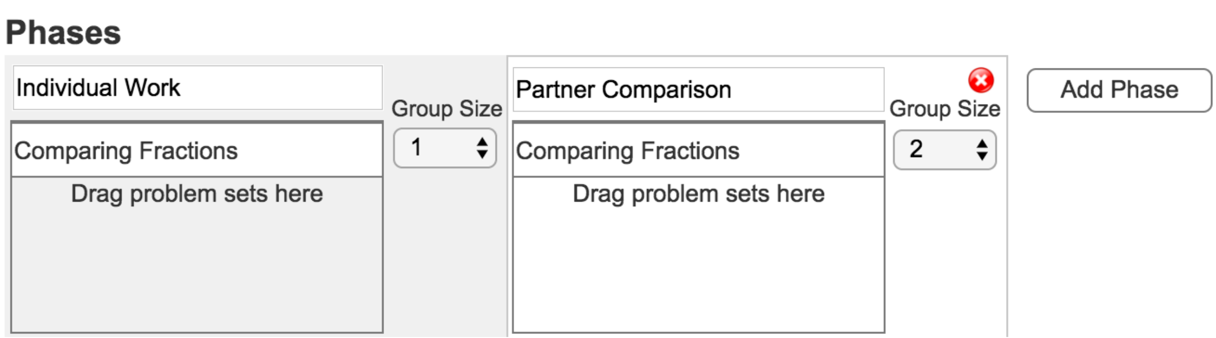

Figure 7.4.3. Two phases displaying the alignment of problem sets and social planes along with the ability to add more phases to determine the ordering.

Second, the user is able to assign the order of social planes through the ordering of the phases. In the orchestration tool, the user can add multiple phases to the activity. These phases are executed in the order that they are displayed on the screen. So as a new phase is added and the user can determine the order of the social planes (see Figure 7.4.3). To change the order of the social planes, the user would just need to change the order of the phases.

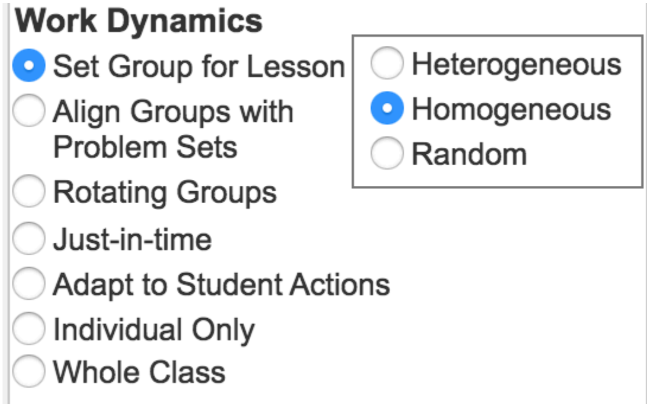

Figure 7.4.4. Group formation choices for each phase of the activity.

Third, when students are working collaboratively, how these groups are formed for each phase needs to be selected. The ways to assign groups reflects the choices outlined within the framework (see Figure 7.4.4). From the co-design sessions, teachers often still consider the group composition, so although group composition has less to do with the orchestration of the activity, it is still an important part of the planning. For group formations options where the make-up of the group can be an option, the user is able to make a selection. The prototype does not currently include the entire criterion that can be considered for group make-up but instead includes what teachers most often mentioned in the co-design sessions. For user clarity, I additionally included if the students would be working individually or as a whole class to clarify that these choices only apply when students are working collaboratively. In these other instances, groups are not being formed, so the choices do not apply.

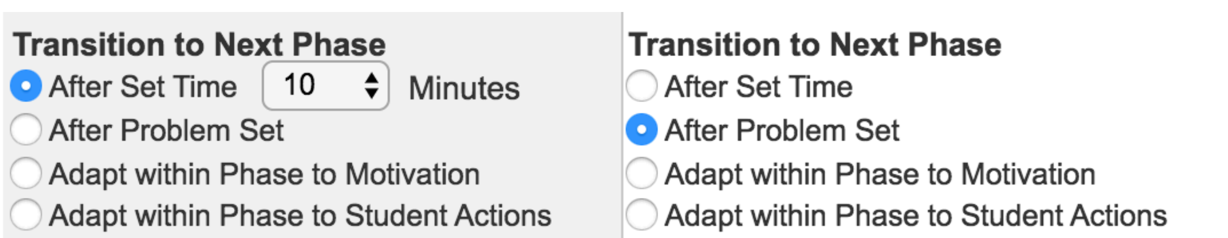

Figure 7.4.5. Transition options from one phase of the activity to the next. These also include the transition options within a phase.

Finally, the orchestration tool allows the user to select how the transition to the next phase will be executed during the class. Teachers often only use one type of transition throughout a class, basing it upon time. In the orchestration tool, I wanted to provide the flexibility within a lesson to mix different transitions. For example, the students may have 10 minutes of direct instruction as the beginning of class before working in groups until they finish their problem set (see Figure 7.4.5). As with the group formation, these options align with the options presented in the framework for the transitions. Additional to the between-phase transitions, the orchestration tool also allows the user to transition the students between social planes within a phase by adapting to the students actions and motivation. If within-phase transitions were selected, the system would monitor the students' actions and recommend to the student when it may be beneficial for them to switch social planes. For monitoring to happen by the system, future work is needed, as discussed in Chapter 6.

7.4.2.2 Group Planning

During the co-design sessions, another theme that emerged was the difficulty in forming groups. Teachers expressed concern over forming groups that were a good match for the students yet were different from groups that they had assigned students to previously. However, not all students could work well together in groups, which was often a concern when pairing students or allowing students to choose their groups. To help address this concern, the orchestration system provides suggested groups for the phases that are collaborative (see Figure 7.4.6).

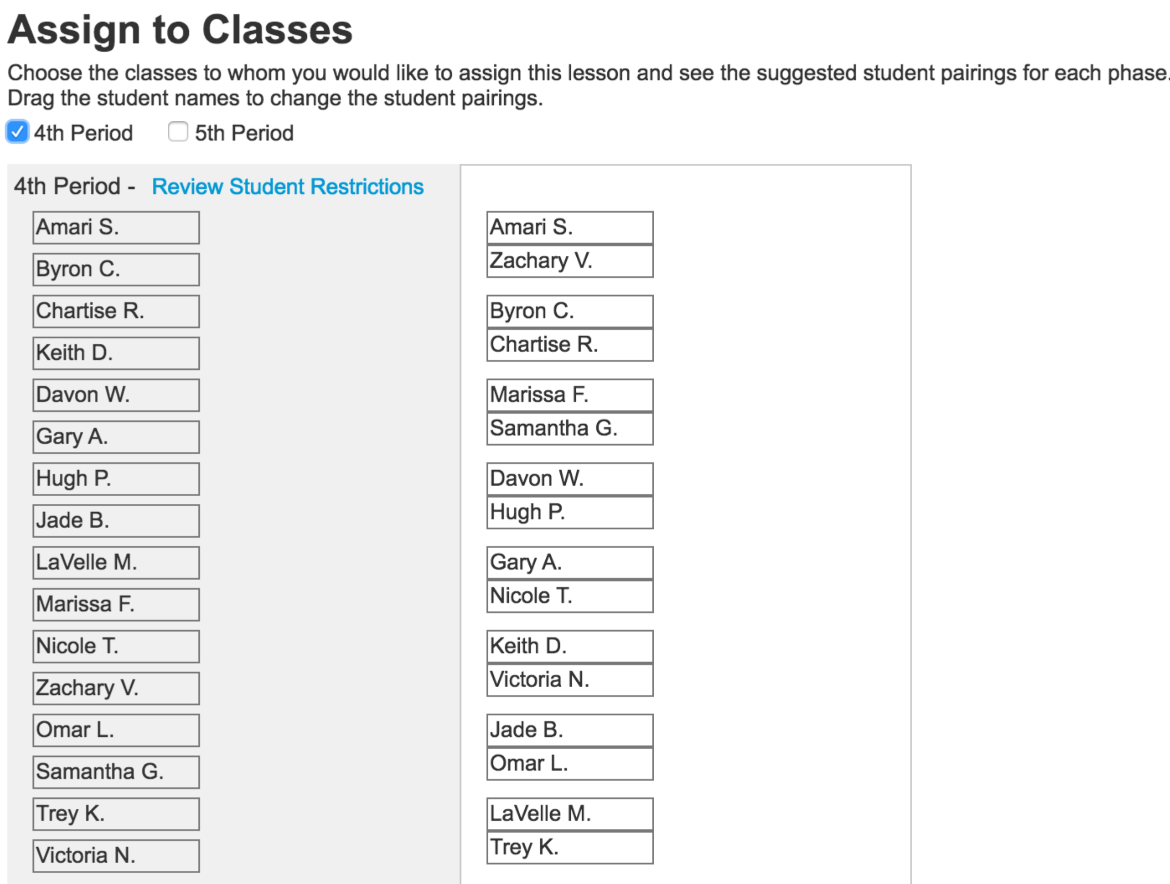

Figure 7.4.6. Suggested group pairing by the orchestration system when doing lesson planning.

For each phase where the students are working collaboratively, the system suggests a set of student groups that are dependent upon the group size specified for that phase as well as the group criterion specifications (see Figure 7.4.4). The system is also able to take into account student restrictions that the teacher has entered about the class previously (See Figure 7.4.7). Although the system suggests group pairs, the teacher still has the final say in the groups. By starting from the suggested groups, the user is able to drag student names between groups to change the group composition allowing teachers to have the final say in the groups while removing the overhead of initially having to make groups. Through the system suggesting groups, there can be more variety in what students work together while still taking into account any restrictions. During the step, the user can also assign the activity to multiple classes (if they are teaching more than one) to minimize the amount of double work that has to be completed.

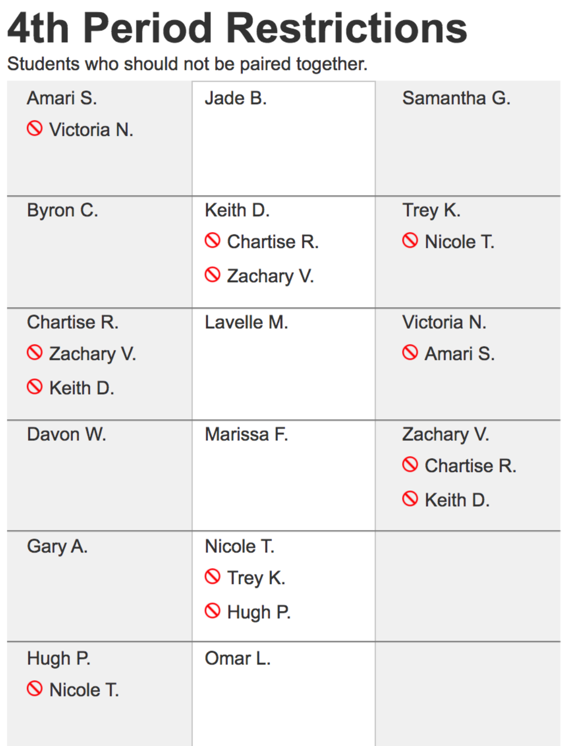

Figure 7.4.7. Class restrictions previously entered by the teacher. These can be reviewed at the time of group formation.

7.4.3 In-Class Scenarios

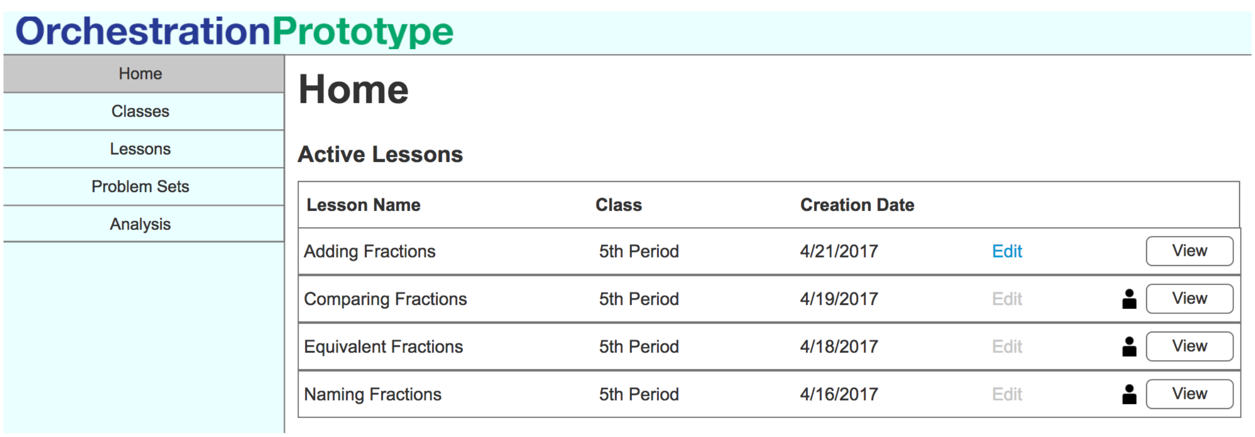

Figure 7.4.8. Home screen displaying the currently active assignments for quick access.

The goal of the orchestration system, when supporting teachers in real-time, is that teachers do not feel they need to be constantly monitoring and can instead spend their time on activities that they feel make them better teachers while supporting designs of interest for researchers. For the in-class scenarios, I focused on instances around when students are transitioning between social planes. Part of the transition process is also forming new groups when students first start the activity or when students leave class and groups need to change, which in personal experience have been challenges in orchestrating studies in the classroom. Within my prototype, I included four different scenarios to address the types of transitions that teachers may encounter in class. These scenarios included student absenteeism, student tardiness and time transitions (i.e., all students transition synchronously), task transitions (i.e., students transition between phases asynchronously), and adapting transitions (i.e., students transition between social planes within a phase asynchronously). These scenarios aimed to display how automation can support the teachers within the classroom while still providing enough information and autonomy within the system to allow teachers to feel in control. From the home or lesson screens, a user could see which activities are currently active and if any students are currently engaged in each activity through an icon display (see Figure 7.4.8). When an activity is active, students can see that activity when they log in. Activities that are active can still be edited, as long as students are not currently working on that activity, which allows activities to be quickly changed between class periods if something from an earlier period did not work well in the classroom.

7.4.3.1 Student Absenteeism

The student absenteeism scenario is the first scenario in the prototype. It is the only scenario to address an activity from the very beginning before students have signed in to the computers. Within the prototype, this scenario is meant to illustrate how the system can support the re-grouping of students at the beginning of class when teachers may be focused on supporting other classroom activities.

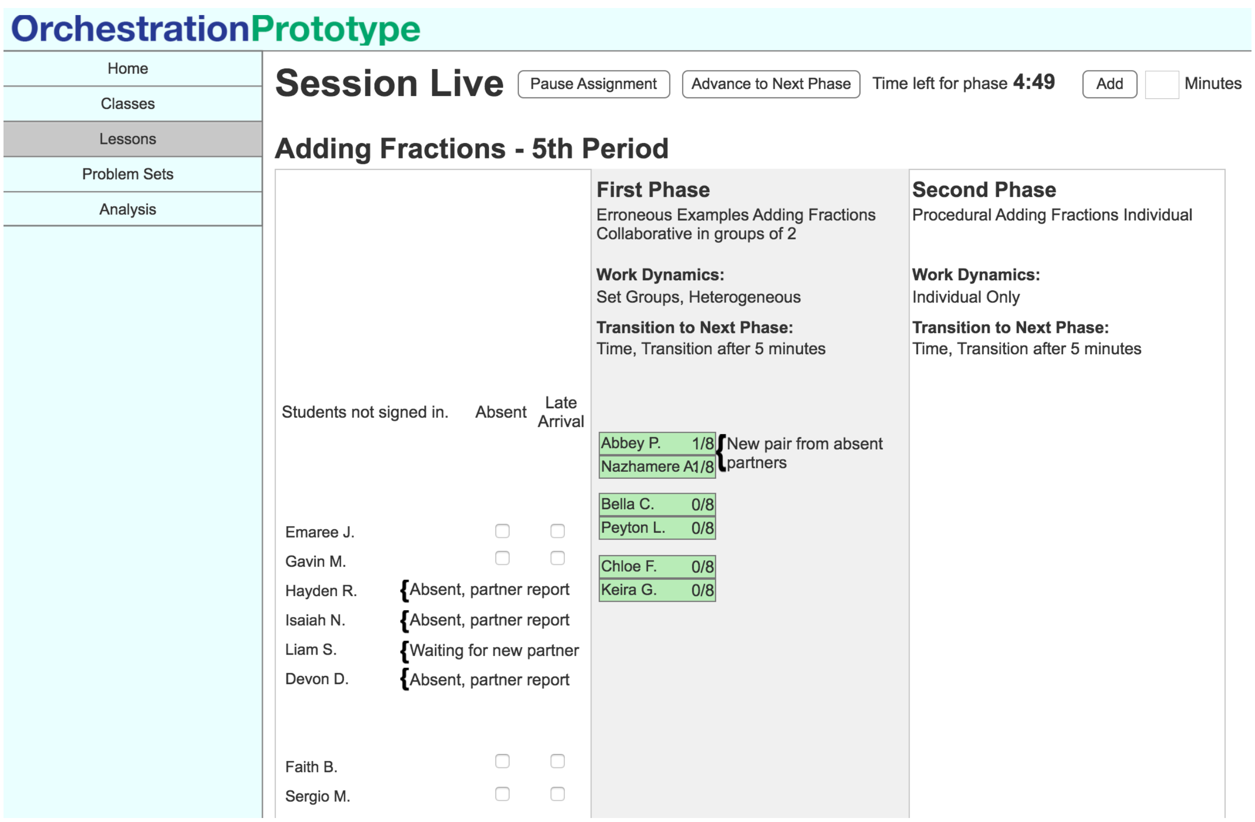

Figure 7.4.9. As students sign into the system, they can mark their partner absent or the teacher can mark the students absent or expected to be late. Students are then automatically given new partners when a student is absent.

Within the scenario, the teacher can track students as they sign into the system and get started with their partner. As the students sign in, they are prompted if their partner is absent that day, which is a feature that came from feedback from teachers that if they do not have a class for homeroom, often the students are more familiar with who is there that day than they are. This feature allows the teacher to focus on other things as the beginning of class rather than having to take attendance right away, which currently very few do. As students sign in, if all members of a group are present, they are instructed to go and work together. If a student has their partner missing (with group sizes of 2) or all other group members (with group sizes greater than 2), then they are instructed to wait until a new partner is assigned. If another student's partner is absent and there are not any restrictions between those students, then the system will pair the students together and a note will be displayed to the teacher that about the new pairing. If the teacher does not like a pairing, they can always drag the students to form new pairs as they did during the planning stage and the students will be informed of the new pair. Even if the students have already started working, the teacher can still make new pairs. The system allows them to see how far the students have already progressed to allow them to make an informed decision. The process mimics what teachers currently do in class around absenteeism by waiting to see which students are absent, but does the process automatically. However, in this case, the teachers do not have students approaching them to find a new pair and interrupting whatever they are doing as the system is able to provide support directly to the student.

7.4.3.2 Student Tardiness and Time Transition

In the student tardiness and timed transition scenario, the user experiences the pairing of students coming in late, new pairs when a student leaves early, and a transition to the next phase (see Figure 7.4.10). In these cases, the orchestration can be even more complicated than students being absent because the changes are not restricted to the beginning of class. As with the absenteeism scenario, this second scenario primarily deals with the forming of groups when students come into class late or leave early and transitions around these group formations.

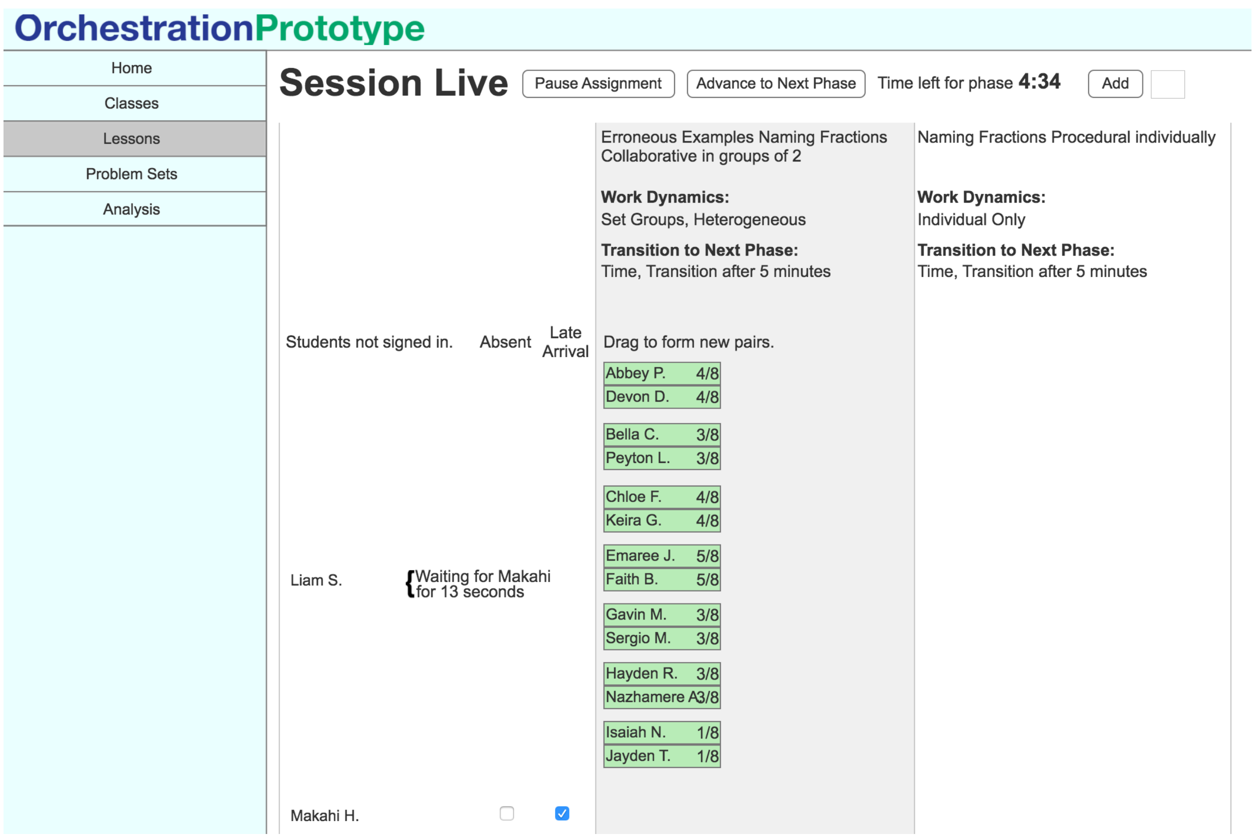

Figure 7.4.10. Example of a timed transition where students may come into class late or leave early.

Additionally, the scenario includes a timed transition where all of the students switch phases at the same time. Although a timed transition does not provide much fluidity, it is currently what is most commonly used within the classroom, so it is still important to support. Within the scenario, the user is shown the timing along with the tools to allow for flexibility around the transition (see Figure 7.4.10).

At the beginning of the scenario, there are three students that the teacher had marked as coming late to class. Because these students have set partners, as they come in, they are paired with their intended partners, who have already begun the task with another group. The teacher can track how far the students have gotten on their problem sets and if a student is paired with another student that just came into class, then they start from the beginning of the problem set. The teacher can also track how long a student has been waiting for their partner.

The scenario then gives an example of a student leaving class early (something that often happens during class due to students being sick or having an outside appointment). The student's partner is asked to join another group that is closest to where they currently were in the problem set, which is reflected on the screen for the teacher by showing that the one student is no longer signed in and that their partner is in a group of three. It is displayed that a new group that was formed. If the teacher did not want this group of three, they could either drag the student into a new group or by themselves to finish individually.

For the timed transition, after the timer gets to 0, the students are informed that they are moving onto the next task. The change is shown on the screen, as the student's names will be moved to the next phase as they begin that phase. The teachers are provided flexibility on timing by being able to add more time to a phase. Often things may take more or less time than originally planned. The teacher is able to add a few more minutes to a phase when students need the time. If students take less time than expected, the teacher is able to advance the students to the next phase quickly with a click of a button. Finally, the teacher is able to pause the assignment when they need to get the attention of the entire class.

7.4.3.3 Task Transition

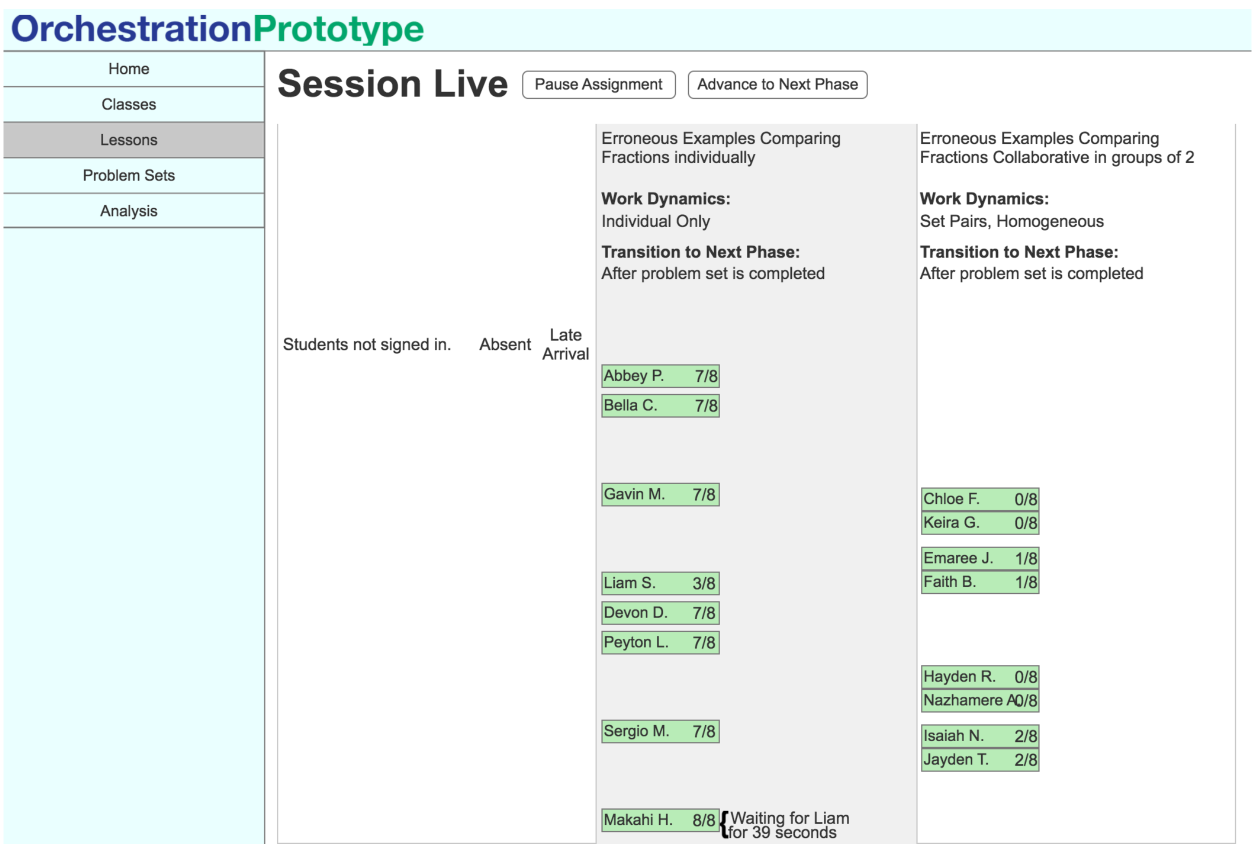

Figure 7.4.11. Example of a task transition where students are in different phases at different times.

The third scenario included examples of task transitions where the students advance to the next phase after completing the tasks allowing students to work at their own pace so that they do not have to wait for other members of the class to finish before continuing through the activity. When students transition between phases at their own pace, students will not all be in the same phase at the same time (see Figure 7.4.11). This makes it important to be able to track where the students are in the activity but also to automatically support students transitioning through the phases so that teachers do not have to spend all of their class time supporting the transition.

In the task transition scenario, the students have all already signed into the activity and are working on the first phase individually. As the students work on the problem sets, the user can see how far they have progressed. When students finish the problem set, the next phase has set partners, so it is marked that the student is waiting for their partner to finish the phase. As the partner finishes, both students are informed of their partner and are progressed to the next phase. If a student is taking longer on a phase than expected, the user can drag the students name to the next phase to have that student move forward in the activity providing the user with some flexibility in the transitions based upon information that they are provided on the screen.

7.4.3.4 Adapting Transition

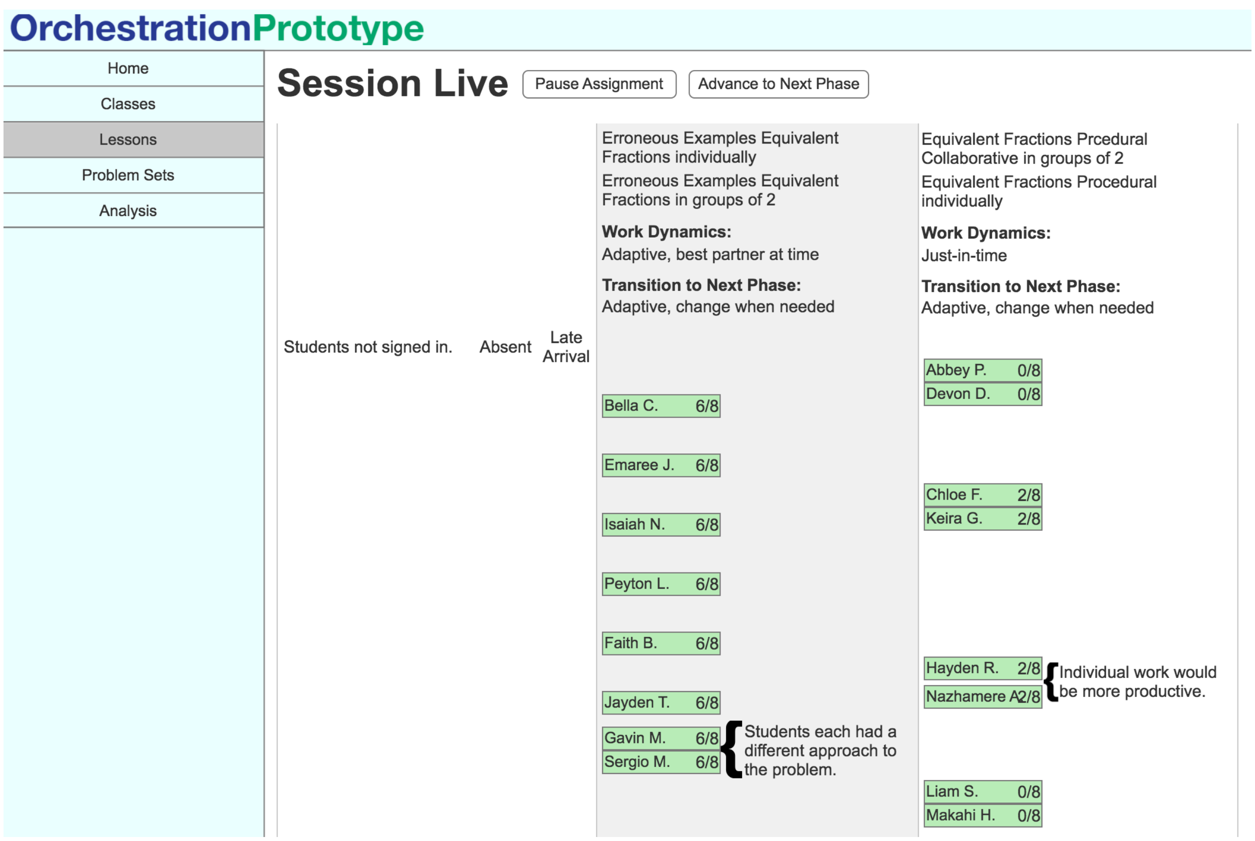

Figure 7.4.12. Example of an adaptive transition where students may switch social planes within a phase when it is beneficial for their learning.

The final scenario in my orchestration prototype demonstrated transitions where the social plane is adapted to student actions within a phase. In this case, through the system monitoring student actions, students can be paired together on a problem set when it may be appropriate or divided to work together when a collaborative setting may not be productive (see Figure 7.4.12). The student actions that the system can adapt to are still an open question. To be able to provide better support for this type of transition between social planes, we would need better student modeling for collaborative learning. However, this scenario in the orchestration prototype was intended to show how different transitions could be supported within the classroom to see if it would be feasible to provide enough information and autonomy to the teacher within the classroom.

Within the adapting scenario, the students have already begun the activity. As the students go through the activity individually, the system can track the misconceptions and strategies that the students are using. It can then recommend that students work with a partner on the tasks if it would be beneficial. The students are directly informed when it would be beneficial for them to change social planes and the teacher or researcher is informed of these pairings and why it suggested that the students work together. As the students finish the phase, they can move onto the next phase. Again, the student learning is tracked by the orchestration system and it can instruct students to work individually if it would be more productive and makes a note for the user. Within this scenario, the user can easily track what phase the different students are working within as well as what social plane the students are currently engaged in.

7.4.4 Discussion

In this section, I described the prototype of the orchestration tool that was developed to support researchers in investigating more fluidity in transitions between social planes within the classroom. The orchestration prototype combines the suggested design considerations for social plane transitions from the framework in Chapter 5 along with the design recommendations from the co-design sessions from Section 7.3. This combination allows the orchestration system to be a tool for researchers to further explore the space of combined individual and collaborative learning while meeting the needs and constraints of a real classroom.

The prototype focuses on both the planning process of the activity as well as the real-time management of the activity. To illustrate the real-time management, four scenarios were created demonstrating different types of social plane transitions for when students are first starting the activity, between phases, and within a phase. To investigate the balance of automation and teacher autonomy within the prototype, I conducted validation sessions with teachers presented in the section below.

7.5 Validating the Orchestration Prototype

To validate the orchestration prototype, I conducted a series of sessions with teachers to investigate how it would fit into the context of the classroom and validated the tool design against desired learning designs to explore how it would fit with the needs of the researcher. With the evaluation of past orchestration tools, the focus has often been on how frequently the tool has been used in the classroom along with observations of the tool in use and interviews to gather impressions of the tool (VanLehn et al., 2016). Because my orchestration prototype is attempting to not just make existing activity designs easier but to expand the boundaries of viable activities to orchestrate in the classroom, it is necessary to first validate the prototype with teachers to evaluate how it balances automation and autonomy and to allow teachers to further reflect on their needs with a physical artifact (Martinez-Maldonado, Pardo, Mirriahi, Yacef, Kay, & Clayphan, 2015). In this section, I present the validation of my orchestration prototype along with my findings to provide further insights into how to balance automation and autonomy in an orchestration system when supporting fluid social plane transitions. Further, I present additional insights from the validation sessions on how to integrate my work with other teacher tools and designs to create a complete orchestration tool for the classroom. Finally, I present a validation of the orchestration tool against the research needs as presented in my framework.

7.5.1 Research Questions

In the co-design sessions, I found three main themes around the teachers' values in the classroom that led to five design recommendations. From these recommendations, I developed an orchestration prototype that focused on supporting the design and execution of learning activities that have fluid transitions between social planes as outlined in my design framework. Past orchestration systems have often focused on supporting activities that already occur in the classroom and making these activities more efficient (Cuendet et al., 2011; Manathunga et al., 2015; Martinez-Maldonado et al., 2015; Munoz-Cristobal et al., 2015; Phiri et al., 2016; Prieto et al., 2014). My orchestration system aims to be a tool for both researchers and teachers to expand the way that we design combined collaborative and individual activities to have adaptable and fluid transitions to meet student needs. Before placing this system in the classroom, it is important to investigate how the orchestration system reflects teachers' values. As part of this investigation, the system can be evaluated to see how the orchestration system fits the expectations of support in the classroom. Additionally, the physical artifact of the orchestration prototype acts as a device to help the teachers further reflect on their needs and division of responsibilities with the system in the classroom.

The validation sessions were designed to evaluate both the planning process and the real-time classroom support. For the planning process, there were two main questions to be evaluated. First, did the planning process provide enough flexibility and support that the teachers could plan an activity of their choice and were there any missing dimensions or values? Second, did the planning process broaden the way that the teachers thought about combinations of collaborative and individual learning? For the real-time scenarios, the evaluation focused on supporting the teacher in the management of the activity and understanding the current state of the students. First, did the system balance the automation and teacher interventions in a way that developed trust in the system, allowing teachers to engage in tasks that they find meaningful? Second, does the system provide enough information that the teacher can understand the current state of the classroom and intervene in the orchestration when necessary? Finally, I reviewed the orchestration prototype to validate how it met the needs of the researchers in supporting fluid transitions, as outlined in the framework under the transition dimension.

7.5.2 Methods

7.5.2.1 Study Design and Procedure

In the validation sessions, a total of seven teachers (six female, one male) participated individually to work with the orchestration prototype. The teachers ranged from teaching 2^{nd} grade to 7^{th} grade and all taught at least one mathematics class (although they were not necessarily only mathematics instructors). Six of the teachers had participated in the co-design sessions while one teacher was new to the project. The teachers were again recruited through connections from previous studies as well as word of mouth. The seven teachers came from five different schools.

Each validation session lasted for one hour and was semi-structured to give teachers time to interact with the planning portion of the orchestration prototype and to explore each of the four scenarios described in the previous section, which demonstrated a range of social plane transitions. The sessions were audio recorded along with screen capture to record any actions taken within the system. During the session, the teachers were asked to think aloud and were encouraged to ask questions about the system.

The first half of the validation sessions focused on the planning of an activity for class to test the range of the activity planning supported by the tool and to see how well the tool matched how teachers currently think about activity planning, I first had teachers plan an activity on paper. The teachers were instructed to plan an activity as they would for their regular class where the students are working individually for part of the activity and collaboratively for part of the activity. After completing the planned activity on paper, the teachers were asked to design the same activity using the collaboration prototype preventing the teachers from designing an activity that was already supported by the system and provides a better evaluation of what activity design features may have been missing. After the planning, a short interview around the planning process was conducted to prompt a discussion around the provided features.

After the activity planning, the researcher walked the teacher through the four real-time scenarios. Each scenario was designed to allow the researcher to click through the steps instead of having it on a timer, which allowed a discussion to occur during the scenario without the risk of missing certain actions happening. The teacher was informed that each of the scenarios assumed that the students would be working on their own device allowing the students to be tracked during the activity. The researcher introduced each of the scenarios and, as actions happened in real-time, pointed out and explained the changes. During each of the scenarios, an ad hoc discussion occurred around the real-time support being demonstrated. At the end of all four scenarios, again a short interview took place around the real-time orchestration support.

7.5.2.2 Data Analysis

Audio and screen capture were collected for each of the validation sessions. To analyze the results, I reviewed the videos to reveal salient themes and experiences with the orchestration prototype through an iterative process in which I used affinity diagramming through the clustering and re-clustering of different notes to reveal the main themes around social plane transitions and the automation of the orchestration process (Miles, Huberman, & Saldaña. 2013).

7.5.3 Teacher Validation

From the analysis of the validation sessions, four main themes emerged providing insights into the balance of responsibilities between the teacher and orchestration tool within the classroom to support social plane transitions. The four themes involve the sharing of control over the classroom management, how the tool benefits the teachers within the classroom, the support of understanding through information, and the broadening of perspectives on learning activity design. As with the co-design study, the availability of technology in the classroom influenced the reactions to the orchestration prototype. In this section, I present both the ways that the tool support was well received within these four themes and where additional design is needed.

7.5.3.1 Control

The first theme is around the sharing of control between the orchestration tool and teachers in the classroom. In the co-design sessions presented above, I found that teachers needed the flexibility to intervene when needed (Prieto et al., 2011). From the validation sessions, in general, the teachers felt they had freedom to both design the learning activity as they wanted and had the ability to intervene in real-time when needed without being flooded with too much information. When planning the activity, teacher T3 commented that they "did not think that one was missing" for the transition options provided when planning the activity. All of the transitions that they had planned in their paper lesson plan could be transferred to the orchestration system.

During the real-time scenarios, teacher T2 said that they could "override pretty much everything" that they needed to. Some of the features that the teachers specifically mentioned were being able to pause the assignment, rearrange groups on the fly, and move students between different phases when needed. Together, these features allowed the teachers to be able to deviate away from the planned activity when they saw the need to in the classroom. It also allowed the teachers to override any of the decisions that the orchestration tool made during the activity if they did not agree with it.

During the real-time activities, there were two places where the teachers expressed not having enough control over the system. The first was around students entering the class part way through a phase and having control over how the students get paired and start the activity. Depending upon the activity, many teachers were concerned with where students would start in the problem set with their partner. In the scenario, it was shown that students in a group would start from where the least far student was in the set. However, teachers wanted some flexibility in making this decision so that they could gear it towards their student's needs. The second place where teachers wanted to have more control was in choosing what the social plane would be adapting to when pairing students within a phase. In the adapting scenario, the students were shown being paired base upon misconceptions, strategies, and working individually based on step correctness. Although the teachers expressed excitement around pairing being done automatically, they did want to choose what criterion the system used when putting students together within a phase. Currently, during planning, the teacher can select that there should be adaption to student needs within phase; however, there was no way to select the features to adapt to.

Although teachers expressed that they felt they had control when it came to being able to take different actions within the system, there was still a general hesitation to handing over so much control to the system. The teachers would often have comments about the system that expressed hesitation, such as teacher T2 saying, "I felt like it had control, but I was okay with that." This hesitation demonstrates the importance of having features within the system that allows the teachers to intervene. If there were ever an occurrence in the classroom where they lost control, the system would most likely no longer be used.

7.5.3.2 Orchestration Tool Benefits

The second theme is around how the orchestration tool benefits the teacher within the classroom. Within the co-design sessions, there was a persistent theme of teachers not getting interrupted and having a chance to work with students individually as well as the pressures associated with pairing students. Within the orchestration tool, a primary goal was to automate the orchestration system to provide flexibility to balance managing the activity with teaching students and to relieve the emotions that go along with pairing students. During the validation sessions, teachers expressed their preference for the support provided by the system in the pairing of students and the fluid transitions. Within this section, I present how the orchestration tool provided support for teachers in terms of saving time and cognitive load efficiencies.

During the planning phase, the system recommends groups based upon the teacher choices for the phases. It can also support making new pairs in real-time. The teachers were enthusiastic about the support in pairing students and teacher T3 mentioned that it "takes away [their] bias." In general, teacher expressed that having to pair students took their time and effort for a task that is not crucial to the teaching process. They liked the support from the system because with the support taking over this task, teacher T3 mentioned that they did not have to "waste any brain power on reassigning" students. The teachers liked having the process automated so that they could just review the pairs rather than having to spend time thinking about all of the variables themselves to make pairs both during the planning and during the real-time activity.

During the real-time scenarios, teachers liked the automation of the different features so that they would have fewer interruptions in class and so that students did not have to wait for the teacher. Through the automation of the system features, teachers felt they would be able to spend more time focused on helping individual students and that students would be able to take more charge of their learning. In the real-time scenarios, the teachers found the support for forming new groups on the fly very beneficial. When the students were absent, coming in late, leaving early, or even switching phases, the teachers thought that automated support for grouping would make fewer interruptions for them. Students would no longer need to ask the teacher if they could work with a partner or who their partner is going to be for that day, as this information would come from the system. Additionally, the students would not have to wait for the teacher to provide them with the pairing. "They can just move on," as expressed by teacher T1. Getting interrupted during class was a primary concern for teachers during the co-design sessions. By automating pairing and phase transitions, teachers expressed belief that these interruptions would be minimized.

Overall, the teachers also felt that the orchestration tools would save time both during the planning process as well as in the classroom. Teacher T2 mentioned that they "envision time savers in pairing, transitions, and grouping". During the planning of the activity, the teachers liked the grouping of the students and thought that it would help save them time. The time saving for grouping is mostly likely tied to the reduction in cognitive load that the teachers discussed. Grouping students takes effort and automating the process reduces the time that teachers spend. Teachers also felt that their time would be saved in the classroom with the system automatically grouping students when they are absent, come late, and leave early. Teachers would not have to spend the time to make sure that each student is in a group but instead can just quickly check the information provided by the system. Finally, the teachers mentioned that the support in transitioning between the phases would help save them time. Instead of having to manage students as they finish a task and move to the next one, the system provides this support. Teacher T1 commented, "You do not have to deal with the transitions and you can focus on the misconceptions." By automating the grouping and phase transitions, the teachers are able to have a better balance between managing the activity and teaching, which was a concern that was mentioned in the con-design sessions.

7.5.3.3 Display of Information

Although the system supported the teachers in managing the learning activity through automating aspects of the support, monitoring to understand the state of the classroom is an important aspect to be able to maintain control of the classroom. When going through the real-time scenarios in the orchestration prototype, there were some features that the teachers commented provided them with useful information while others raised questions about how the system worked.

Within the real-time scenarios the teachers had not developed the activity and could only understand what was happening in the class through the information provided on the screen. During these scenarios, the teachers often commented on different pieces of information that they felt were useful in understanding the state of the classroom. These different features included the time left for a phase, how long students had been waiting, student progress in the activity, and information around new group formations. Together, this information allowed the teachers to monitor the students without having to walk around the classroom. They could quickly get an idea of what students were working together and if they are close to finishing a phase or moving onto the next one. They can also see if more time is needed for a phase. These features allow the teachers to react quickly to classroom needs.

During the real-time scenarios, the teachers often inquired about how the system was able to make a certain decision. Although the system always presented the teachers with information about why it made a pairing, it was often a question of how the system knew this information. Inquiries around the decisions often arose when it came to the adaptive scenario when the system was deciding how to pair students in real-time. Currently, the teachers understand what information they use when pairing students in the classroom. However, in the orchestration prototype, it was like a black box for these decisions being made. The teachers wanted to know how the system knew what misconceptions the students had made, the prior knowledge the students have, and the strategies students are using. Although not having this information did not seem to be a major concern for the teachers, having a way to access this information would allow the teachers to be more comfortable in letting the system adapt to student needs as they could better understand how those needs are being measured.

7.5.3.4 Change Perspective

Finally, the fourth theme was around how teachers viewed activity planning and social plane transitions differently when working with the system. The developed orchestration system was intended to go beyond how teachers currently design activities for the classroom and to also support fluid transitions. Teachers may not currently use these transitions because they are difficult to support in the classroom. By demonstrating how these fluid transitions can be supported in the classroom, one goal of the orchestration system is to expand what teachers view as possible within their classrooms.

During the paper planning of the classroom activity, teachers either used a time based transition or did not define the transition at all (see Figure 7.5.1). However, while planning the activity within the prototype, there were significantly more transitions to choose from. The teachers expressed liking these choices, as teachers T6 and T3 expressed respectively, “it gives you different ideas of what to group the students by and then how to transition” and that they “had not thought of transitions in that way”. Teachers expressed that having the options laid out made them consider each step more thoroughly as they went through the planning process. For each phase, they had to decide if the task would best be done individually or collaboratively and how they wanted the students to transition to the next phase. They felt that there was more thoughtful reflection that went into the process.

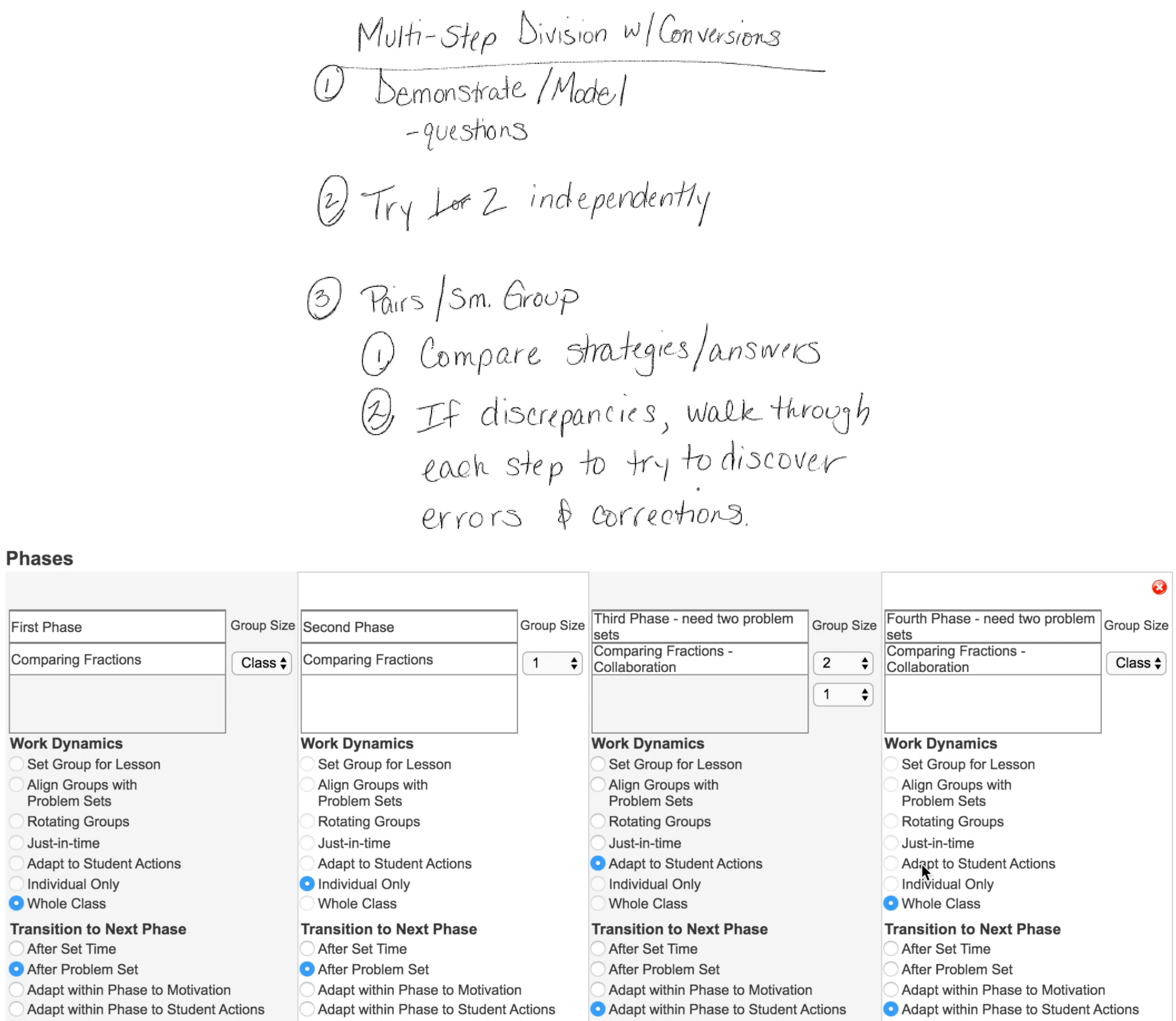

Figure 7.5.1. Example of a teacher’s lesson on paper with no defined transitions and then choosing adaptive transitions within the system.

During the real-time scenarios, the teachers were able to see how the system could support these more fluid transitions. Although not used in their own activity design, teacher T1 expressed that they really liked the last two scenarios that involved the transitioning based upon task completion and adapting to student needs. The teachers liked that the system would be able to pair students together when they needed it. Teacher T7 said that they currently try to pair students based on strategies, but it can take them a few days before getting back to the task since they need to do the pairing themselves based on the students’ work. Teacher T2 said that “[adaptive] is an ideal situation. Fantastic if I could do it.” Through this comment the teacher displayed how the orchestration system could expand the transitions that are currently supported in the classroom, which was true of the task-based transitions. Teachers expressed that they currently did not use this type of transition because they would spend most of their time helping students to transition. However, they felt that the orchestration system would allow the students to move easily from one phase to the next with minimal interruptions to learning. In general, the teachers displayed much more excitement over the task and adaption scenarios than the time-based scenarios.

7.5.4 Expanded Features

Although the orchestration prototype and subsequent validation of the prototype were focused on developing a orchestration tool that can support a broader range of social plane transitions, including fluid transitions, during the validation often other desired features were raised. Although these features do not impact the support that the orchestration system is able to provide for fluid transitions, they are important considerations in developing orchestration tools moving forward. In this section, I address five primary orchestration features that were raised during the validation sessions.

7.5.4.1 Student Interface

Because the orchestration system was designed to communicate information to the student rather than having the teacher involved in each decision, it was often a point of discussion within the validation sessions about what the students' screens would look like. Although the current process was focused on the teacher support, it was important for the teachers to understand what the students would be seeing to know if there would be a need to further support from them. From the current orchestration system, they could not always tell what was being shared with the students and what would be private. To understand the full impact of the orchestration system on the classroom, it would be important to address the student interface as well as the teacher interface.

7.5.4.2 Dashboard

When designing the orchestration prototype, teacher dashboard features around student learning were purposefully left out because they were not needed to understand the transitions between social planes and there is already extensive work on the development of these tools (Aleven, Xhakaj, Holstein, & McLaren, 2016; Van Leeuwen, 2015). However, during the co-design sessions, the most requested feature by teachers, with all seven teachers mentioning the feature, was for a way to monitor student misconceptions and to view student work. Although teachers did not necessarily want dashboard features on the main screen, as they did not want the information to become too cluttered, they did want a way to view what their students were doing. Teachers can currently review student work outside of class by looking at the papers that have been turned in. Within class, they can walk around the classroom and can see what students are currently working on. It is not always easy for them to know where to focus their attention though (Van Leeuwen et al., 2015b). By integrating current teacher dashboards with orchestration systems, teachers would be able to monitor the activity while planning their approach for helping students during the class period.

7.5.4.3 Communication

Within the orchestration system, teachers also wanted a way to communicate with students that limited the interruptions to class. When teachers are walking around the classroom, they can often address behavior disruptions by tapping on the student's shoulder or by sending another non-verbal signal. When teachers are working with individual students, it can become harder to provide these signals from across the room. Additionally, some students will interrupt group work time to receive praise from the teacher. During the validation sessions, the teachers wanted a way to communicate brief messages with their students. These types of communications are already supported in orchestration tools (Manathunga et al.,

2015) and would be a way to not draw attention to the behavioral problem and to reduce interruptions when the teacher is working with another student.

7.5.4.4 Hierarchy Organization

During the planning of the activity, with a few teachers, there was a disconnect between the way that they thought about their activity planning and the way that was allowed within the orchestration system in terms of having a hierarchy for organization. By having a hierarchy, some teachers were able to better organize their thoughts around what activities they wanted to do when during the class. For example, teacher T6 thought about their activity design in terms of when the students would have the most focus. At the beginning they would have the most attention, in the middle the least, and at the end something in between. This teacher wanted to design their lessons so that when students had the least attention, they could do the most hands-on tasks. Within the orchestration system, they were not able to implement an organization where they could group the phases for their own planning purposes. Teachers T2 and T3 desired to have students rotate through the different phases in groups rather than as a class. Although the rotation did not impact the transitions that the students had between the phases, the current structure of the planning did not allow the teacher to divide their students into groups that could cycle through the different phases. By having a hierarchy in the planning, they would be able to make a distinction without having to create a new activity for each group of students.

7.5.4.5 Completion Tasks

Finally, during the scenarios, teachers expressed concern over students having nothing to do while they were waiting for their partner. Although teachers stated that they currently have tasks that students know to do when they are waiting, they wanted these tasks to be more connected to the system to make the transitions smoother. There were two different time periods that teachers wanted students to have something to do: when waiting for a partner in between phases and when they have completed the activity as a whole. These are activities that the teachers could provide during the planning phase or be a repository of learning activities within the system and that the orchestration system could direct the students to when appropriate allowing the system to still have communication with the students while they are doing a different activity to let them know when their partner is ready.

7.5.5 Researcher Validation

Within the framework chapter (Chapter 5), I outlined three scenarios of increasing complexity that could be designed to support the combination of collaborative and individual learning. Within this section, I will review each of the learning designs to explore how the developed orchestration tool can support that transition aspects within each scenario. Through presenting the support for orchestrating these learning designs using the prototype, I will demonstrate the strength of the tool in supporting the investigation of the theoretical question of how to effectively combine collaborative and individual learning.

The first learning design is to have students all remain in the same phase at the same time. This type of design is often common both within the classroom and within research (Mullins et al., 2011; Olsen et al., 2016; Olsen et al., 2017). Experiment 3 provides an example of this design in the combined condition. In this condition, the students all worked collaboratively on erroneous example problems and individually on procedural problems. The students all had the same order of first collaborating and then working individually and transitioned between these phases part way through class. Additionally, all students remained in the same groups for the entire activity. Within the orchestration tool, this activity could be easily supported during the planning stage. For each phase, the students would be in set groups and would transition after a set time (see Figure 7.5.1). The ordering could easily be set by ordering the phases of the activity by selecting the first phase to be collaborative and the next to be individual and so forth. Finally, the activity could be supported in real-time through the system. As the timed scenario showed, the system would automatically advance the students to the next phase after the time ends.

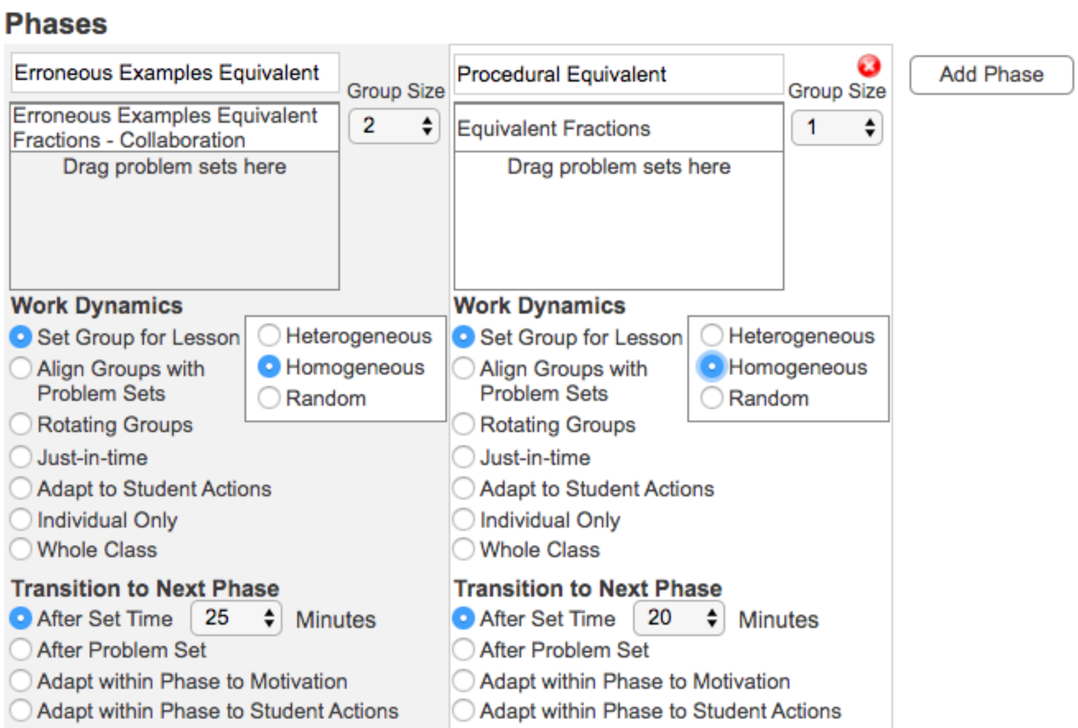

Figure 7.5.1. Example of planning an activity in the orchestration prototype that is fixed across students.

A slightly more complex design would allow for more flexibility in the execution of the activity by student. In this case, the activity is planned to allow students to have some flexibility in the speed that they are learning; however, there is still no adaptation of social plane to immediate student needs. As seen in Experiment 3, students worked at a different pace, which meant that some students did not get through as many problems in each phase. To allow students to work towards mastery, the students could transition from one phase to the next after they complete the problem set (see Figure 7.5.2). In addition, after students work individually, instead of waiting for their assigned partner, partners could be assigned as they become available when they finish their individual task. In real-time, the orchestration prototype demonstrated support for this design through the timed and adaptive scenarios, which demonstrated the pairing of students in real-time. The timed scenario demonstrated the monitoring of students as they change phases at different times while the adaptive scenario demonstrated just-in-time pairing and how these activities can be monitored.

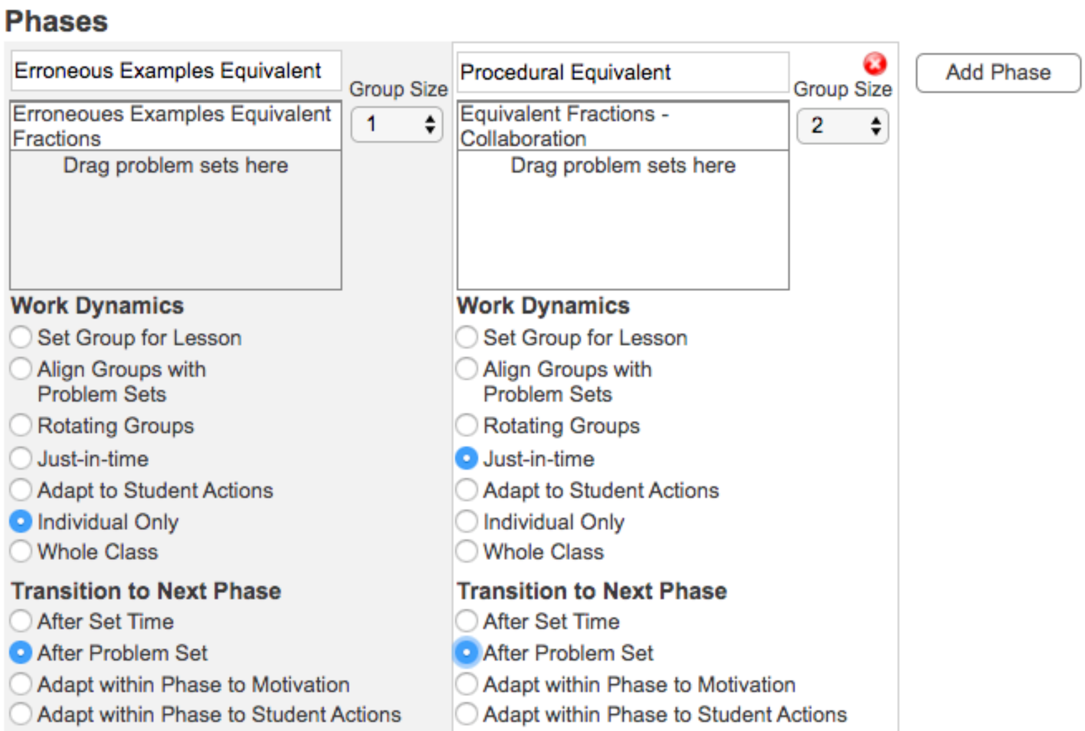

Figure 7.5.2. Example of planning an activity in the orchestration prototype where there students can transition between phases at their own pace.

Finally, designs that allow for adaption to student actions within a phase add additional complexity. An example of this adaptation would be to have students work individually until a student makes a string of errors on a skill that can be identified as a misconception. The student would then be paired with a partner in real-time who had previously overcome the misconception. In this design when the students are working collaboratively and individually is being adapted to student actions, as are the groups. As with the last example, the students would be transitioning between social planes at different times. However, in this case, it would be within a phase instead of between phases. In the orchestration prototype, teachers can plan this learning design by selecting the option “adapt within phase to student actions” (see Figure 7.5.3). The system will then identify when it would be beneficial for a student to transition between social planes and will pair the student when appropriate, as seen in the adaptive scenario.

All three of these learning designs demonstrate the range of ways to transition between social planes that would be used by researchers in their learning designs. However, when doing research, there may be a desire to have students be in different conditions in the same class, which requires students to be divided into groups. The feature that teachers requested to allow students to rotate would also provide this functionality for grouping. Within this section, I have demonstrated that each of these learning designs can be planned and supported in real-time through the orchestration prototype. This demonstration provides an initial validation of the orchestration tool to meet researcher needs.

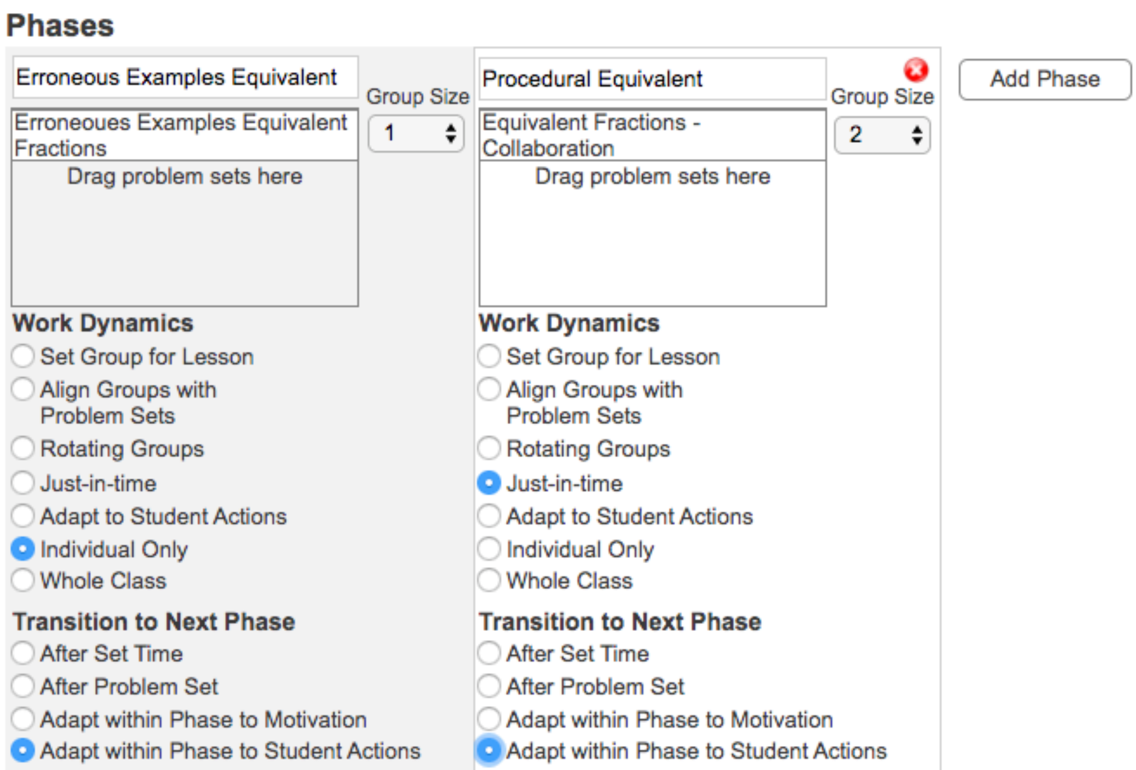

Figure 7.5.3. Example of planning an activity that involves adapting the social plane to student needs.

7.5.6 Discussion

Through validation of the orchestration prototype, I aimed to both test the balance between system automation and teacher autonomy in supporting fluid transitions as well as allow teachers to further reflect on their needs within the classroom. The reaction to the orchestration system was positive from the teachers with teacher T4 expressing, “At the beginning, I was a little hesitant, but after seeing some of the sessions in action, I feel like it is something that I could do” while teacher T2 said, “I hope I am alive when this happens and still teaching.” During the sessions, the teachers expressed excitement for the system to take over some of the management responsibilities giving them less of a cognitive load and more time working with students. They felt that the system still provided them with enough information and control so that they could intervene when needed. However, there were a few places for improved control around the adaptive transitions. Moving forward, it may be beneficial to distinguish between the transitions that happen between the phases and the transitions of social plane that happen within the phases to provide teachers more control over these features during planning.

Additionally, the validation of the orchestration prototype provided initial evidence that fluid transitions could be successfully orchestrated in the classroom without creating too much overhead. The teachers were receptive to these scenarios in the orchestration tool and often preferred them to the time-based scenarios despite not planning their own lessons using these transitions. Once teachers saw the different options in the system, they were enthusiastic to use the options in their designs. By developing a tool where multiple transitions can be planned and supported, the field will be more open to researchers to investigate how best to combine collaborative and individual learning. In the validation of the orchestration tool in terms of supporting research needs, I found that with the tool, the different types of social plane transitions that might be used in a learning design could readily be supported. Within this study, I have shown that by balancing automation of the orchestration process and flexibility for teacher intervention, we can support more complicated transitions between social planes in the classroom.

During the testing of the prototype, the teachers also mentioned additional features that they would like in the system that were out-of-scope for this iteration. Although the orchestration system is focused on supporting fluid transitions between social planes, for teachers to be able to run their classroom efficiently, additional features may be needed. It is important for the field of CSCL to not develop tools within isolation. Many of the teacher dashboards being developed would pair well with current orchestration systems (Aleven et al., 2017; Van Leeuwen, 2015). By having these parallel lines of research work together, teachers may be able to more productively adapt to student needs both in terms of activity support but also in domain learning.

From a researcher perspective, the orchestration tool could also be extended to more fully support the other dimensions laid out in the framework. Although support for a range of transitions between social planes is supported, there is less of a range in individualizing the order or social plane alignment to individual students. Currently, unless there are adaptive transitions between social planes, the orchestration tool only supports students working in the same order and in the same social plane for each task. To fully support researchers in investigating the combination of collaborative and individual learning, these other dimensions will need to be as fully supported as the social plane transitions.

For future work, the tool needs to be implemented so that it can be tested in a real classroom environment, which would include the design for the student communications. Although there were positive reactions to the orchestration tool in this study, within the classroom there are different pressures that are important to understand how the system would work under. This system has provided a first effort at providing support for fluid transitions to teachers in a way that can also be used as a research tool. The system does not just try to solve a current classroom need but expanded what can currently be done easily within the classroom to provide a tool that researchers can use.

7.6 Summary and Discussion

Within this chapter, I present the development and testing of an orchestration tool that can be used to support researchers in investigating combined collaborative and individual learning environments by specifically supporting fluid transitions between social planes. The orchestration tool was developed to account for the values of the teacher so that it could be used effectively within the context of the classroom while also providing flexibility in learning designs to allow for support of a range of research questions. This allows the tool to be used by researchers in an ecologically valid environment and for teachers to be able to integrate the tool into their everyday use. To align with teacher needs, I went through a co-design process before developing the orchestration tool and then assessed the orchestration prototype. To align with the needs of researchers, the orchestration tool was developed to align with the framework presented in Chapter 5. Overall, the orchestration system balances the use of automation and teacher autonomy to support fluid transitions in the classroom, although the prototype did not have a backend so did not provide real automation in the scenarios.

Before developing an orchestration system that can support fluid transitions between social planes, and thus enabling researchers to investigate a wider range of combined collaborative and individual learning designs, it is important to understand how to develop the system to align with teacher values. My work builds upon previous orchestration literature that has provided characterizations and factors to be considered within orchestration systems (Dillenbourg, 2013; Dillenbourg & Jermann, 2010; Prieto et al., 2011). Although current literature provides guidelines for developing teacher-centric support, it is still unclear how to balance between the automation that the system can provide and the autonomy provided to the teachers over their own classrooms. In the co-design sessions three main themes emerged around activity planning, monitoring and adapting, and balancing teaching and management. Within these themes, there was emphasis on teachers being able to spend their time in the class working individually with students and less time managing the activity. Although the teachers wanted to still be able to monitor the task, they did not need to okay every change that happens in real-time. These findings led to five design recommendations that add to the current body of literature by providing insights into how to divide the responsibilities within the classroom. Teachers want to have control during planning and then have that plan execute flawlessly. For this to happen, the system can automate adaptations in real-time but still allow teachers the flexibility to intervene. These design recommendations distinguish between the control the teacher has during planning and in real-time, which has not been distinguished in the past literature.

The findings from the co-design session were used to develop a prototype of an orchestration tool that supports both the planning of an activity in addition to four scenarios demonstrating the real-time support for fluid transitions. Within the orchestration prototype, the teacher is able to plan their learning activity with the options for different types of group formations and social plane transitions that align with the framework presented in Chapter 5. By covering a breadth of choices instead of only what teachers currently do, researchers can use the tool for investigating combinations of collaborative and individual learning. The orchestration prototype also demonstrates the real-time support for pairing students as they enter or leave class due to absenteeism, late arrival, or early dismissal, which addresses the challenges that I, and other researchers, have encountered when using an intervention in a classroom. Additionally, the orchestration prototype demonstrates the real-time support for transitions between social planes from a basic time-based transition where the whole class changes at the same time to more fluid transitions where students switch at different times based upon task completion or adapting social plane to student needs. There is currently little support for learning designs with fluid transitions, which prevents the investigation of how these transitions may be able to be used to support learning.

Finally, the orchestration prototype was assessed by a set of teachers to evaluate the balance between the automation and teacher autonomy provided within the system. The validation also provided the teachers with an opportunity to reflect further on their needs in the classroom with a physical artifact. Within the validation of the orchestration prototype, teachers expressed excitement for the orchestration tool in the support that it would be able to provide in classroom management. The teachers indicated that they felt the orchestration tool would be beneficial to their classroom by lowering their cognitive load and saving them time while still providing them with enough flexibility and information to control their classroom. At the same time, the system was able to broaden their perspective on activity designs by presenting these designs during planning and demonstrating how they could be supported in real-time. By demonstrating how the tool could be used to orchestrate a range of social plane transitions, I also demonstrated the strength of the tool for researchers. The validation of the orchestration prototype demonstrated how the orchestration tool had used automation of the orchestration process can be used to support a broader range of social plane transitions than are regularly used within the classroom.

Although the concept for the orchestration tool originally came from my work with ITSs, the design and findings of the tool are not limited to this domain. In my studies, only one teacher had ever used ITSs in their classroom themselves while an additional three had experienced them through researchers running studies. Four of the teachers had never used an ITS in their classroom. However, all teachers viewed the orchestration tool positively and suggested ways that they could see using the system in their classroom. One teacher, who was at a school that did not have one-to-one technology, suggested that they would project the orchestration teacher screen on the Smartboard so that all students could see what they should be doing even when students were working on paper tasks. Displaying student progress for the entire class has been shown to be productive for learning in previous work (Alcoholado et al., 2012). Although using the orchestration tool without students working on a device would negate many of the automated benefits, the teacher still liked the planning and organization that the tool provided. Additionally, other teachers were asking questions about how they would get their assignments into the system so that the orchestration could be used with the materials that they are already using in class. One teacher expressed wanting to use the system to find what designs worked best for their class and to allow them to experiment more. Although the design of the orchestration tool is most beneficial with tasks where student steps and errors can be tracked, the orchestration system does not need to be limited to the use of ITSs.

Although the orchestration tool was developed to be a tool used by researchers to investigate theoretical questions within the classroom, the orchestration tool can implement a greater change to the practice and attitude towards research in society by providing teachers with the tools to conduct research as well. The orchestration tool provides a platform through which teachers can make comparisons between different learning designs to find what works well within their classroom. This allows research to be done everyday within the classroom rather than having to wait for researchers to conduct the research. Not only does the orchestration tool provide a platform for this research to take place, the automation supports the teacher in the classroom opening more of their time to be used to observe the implications of different lesson designs. The orchestration tool provides easier access to conducting smaller-scale studies in the classroom, which can benefit schools by the implementation of new practices being streamlined. However, there may be concerns that by having more people conducting research, the research may not be as rigorous. In this case, it would still be important to distinguish what the impact of different results can have. The orchestration tool also has the possibility of improving education through the results of the research that it enables. As a society, we will know more about how to better support learning in the classroom through the use of different social modes. It is well established that having better educated students benefits society as a whole and by allowing students to collaborate often, students are able to develop collaboration skills that are beneficial to work with others. However, with more automated support from the tool, it may be a concern that teachers would become obsolete. Currently, the automation of jobs has become a concern across society. It is important to note that the orchestration tool cannot replace the teaching that happens within the classroom but is meant to supplement the management of the classroom so that more teaching can take place.

My orchestration prototype makes a contribution to the CSCL and HCI by adding to the understanding of when and how to provide teacher control within the system. For a system to be adapted into the classroom and be regularly used, it needs to support the teacher in their goals as a teacher. If the teacher feels like it is hindering their process, the tool will most likely be abandoned. As part of my orchestration development process, my co-design sessions provided insights into the values that teachers have in the classroom so that tools can be developed to include these values. Current literature on orchestration discusses the importance of having the tools be developed for the use of teachers without addressing the values of the teachers in the classroom. Additionally, I developed and tested a prototype of an orchestration tool that takes into account these teacher values along with the needs of the research community to be able to further investigate the combination of collaborative and individual learning. This tool contributes to the orchestration literature by providing support for social plane transitions that are not often used in the classroom. Many orchestration tools have been developed to meet the needs of a specific classroom issue. The tool instead aims to expand what learning activities researchers and teachers can use in the classroom. Finally, this tool contributes to CSCL literature in general by providing the first steps towards a research tool that will allow for a more thorough investigation of the combined individual and collaborative learning space.

8 Conclusion

Taken together, my dissertation work is comprised of two broad themes (i.e., combining collaborative and individual social planes to support student learning and classroom orchestration support for researchers to further investigate collaborative and individual learning combinations) that encompass six contributions. My work provides both theoretical contributions, through the studies I conducted, as well as technical contributions, through the tools I developed and evaluated through the studies. In this chapter, I review the contributions of my work to the learning sciences and computer supported collaborative learning (CSCL), artificial intelligence in education (AIED) and intelligent tutoring systems (ITS), and educational data mining (EDM). I end by reflecting on the limitations of my work and future directions for this line of research.

8.1 Collaborative and Individual Intelligent Tutoring System For Supporting Fractions Learning

As part of my research, I developed the fractions CITS that uses both collaborative and individual learning to support fractions knowledge acquisition. The fractions CITS consists of three different problem types that cover seven different fractions units. For all units and problem types, I developed a collaborative version of the tutor as well as an individual version of the tutor. The collaborative version is identical to the individual version, except that it supports collaborative learning through an embedded collaboration script within the tutor itself (Kollar et al., 2006). By integrating the collaboration script directly into the ITS, I was able to directly provide both cognitive and individual support to the students within the tutor (Weinberger et al., 2005). Across three experiments, I evaluated the effectiveness of the tutors and iterated on the tutor design as needed. In Experiments 1 and 2, the students working collaboratively had learning gains equivalent to those working individually. This finding contributes to the field by demonstrating that a collaborative ITS can successfully support learning with elementary school students and adds to the body of literature that has shown collaborative ITSs to be successful with older students but has not yet extended these findings to younger students, as my work has done. Additionally, across all three experiments, I found that the students had significant learning gains from pretest to posttest. These results demonstrate the effectiveness of the tutor. Because the fractions CITS has both collaborative and individual versions, it can be used to mix and match the different social planes to support learning in the classroom.

The fractions CITS makes a novel contribution to AIED and ITS research by adding collaboration to what has primarily been an individual learning field (Kulik & Fletcher, 2016; Ma, Adesope, et al., 2014; Steenbergen-Hu & Cooper, 2014; VanLehn, 2011). Individual ITSs have been developed to support a range of ages; however, collaborative ITSs have mostly been developed to support older learners (Baghaei & Mitrovic, 2005; Diziol et al., 2010; Harsley et al., 2016; Lesgold et al., 1992; Suebnukarn & Haddaway, 2004; Tchounikine et al., 2010; Walker et al., 2006). The fractions CITS extends previous work to support collaboration within an ITS for younger students. Additionally, the fractions CITS provides an example of embedding the collaboration support directly into the tutor for joint problem-solving tutors. Past research has often supported collaboration through prompts (Diziol et al., 2010), which can be difficult for younger learners because of the added text. The fractions CITS demonstrates an effective use of embedded collaboration scripts in an ITS where instead of providing prompts, student actions can be guided through the actions of the tutor.

The fractions CITS also makes a novel contribution to CSCL research by providing an integrated collaborative and individual learning environment. The fractions CITS provides the ability to customize the learning environment to students' needs through both individual and collaborative problem sets for each type of problem. In CSCL, interventions are often designed to be uniform across students and to have all students progress at the same pace. The fractions CITS builds upon ITS technology to allow students to progress at their own pace and because of the development of problems for both collaborative and individual learning, I can adapt the social plane students are working in to the needs of the student.

Additionally, through the use of the embedded collaboration script and standard ITS support, the fractions CITS provides both collaborative and individual support seamlessly within one system (Weinberger et al., 2005), while work within CSCL has typically only focused on the social support.

8.2 Complementary Strengths of Collaborative and Individual Learning

In Experiments 1 and 2, the primary goal was to understand how collaborative and individual learning might have complementary strengths when it came to acquiring conceptual and procedural knowledge. My work makes a theoretical contribution to CSCL through further informing the complementary strengths of collaborative and individual learning. In Experiments 1 and 2, I explored potential complementary strengths between these social planes. Within these experiments, I hypothesized that collaborative learning would be more effective for acquiring conceptual knowledge while individual learning would be more effective for acquiring procedural knowledge. In both experiments, I did not find support for my hypotheses. These findings do not support past results (Diziol et al., 2009; Mullins et al., 2011), which had aligned with the original hypotheses. It could be that my materials were not well aligned with the desired knowledge, except in Experiment 2, the students working on the conceptually oriented tutors had large effects size for learning gains on the conceptual test items compared to procedural test items, while the students working on the procedurally oriented tutors had large effect sizes for the procedural test items compared to the conceptual test items. This result suggests that the differences between my findings and previous findings may be due to another factor, such as the age of the student or prior knowledge when starting the tasks. This work adds to the field by presenting null results that contradict previous findings showing that these previous results may be more nuanced and that further work is needed.

8.3 Combining Collaborative and Individual Learning

In Experiment 3, I investigated if a combination of collaborative and individual learning was more effective than either alone. In the analysis of Experiment 3, I found evidence that the combination of collaborative and individual learning is more effective than either social plane alone. Within my study, the students were working collaboratively on erroneous example problems and individually on procedural problems. This work contributes to the field of CSCL by demonstrating the success of a combined collaborative and individual activity in the classroom. Although there has been support for combined activities in the past (Celepkolu et al., 2017; Dillenbourg, 2002; Diziol et al., 2007), studies have not compared how a combined condition to just working in a single social plane through the same phases impacts learning. In my study, I demonstrate that a combine condition can be more effective than either social plane alone. Additionally, my results demonstrate that how we combined collaborative and individual learning is a viable thread of research.

In Experiment 3, I also investigated the differences between the 4^{th} and 5^{th} grade students and found that the mixed condition was more effective (relative to the other conditions within the same grade level) for the 4^{th} grade students than the 5^{th} grade students. Through secondary analysis, I found evidence for the same pattern in the way that students requested hints, made errors, and the problems they solved. The 4^{th} grade students in the mixed condition tended to request fewer hints and make fewer errors than the 4^{th} grades students in the other conditions. The tutor log data showed that these student behaviors were much more inline with the actions of the 5^{th} grade students than the other 4^{th} grade students. I found the same pattern in the number of problems completed as well where the 4^{th} grade students were more efficient when collaborating than was hypothesized. These results contribute to CSCL by opening up a broader line of inquiry into how collaborative and individual learning can best be combined and how the use of social planes might need to be adapted for individual students. Currently many integrative scripts are designed as a one-size fits all across students where all students perform the same steps at the same time (Dillenbourg & Jermann, 2010; Martinez-Maldonado et al., 2015;VanLehn et al., 2016). My work provides evidence that there may be factors that the students bring into the learning environment that impact the success of a script that we should be accounting for and adapting to in our learning designs to better support student learning.

Finally, through the two experiments in the classroom (Experiments 2 and 3), I experienced the challenges of orchestrating a combined collaborative and individual learning environment. Through the experience of these challenges, along with the nuanced findings in Experiments 1-3, I recognized the need for an orchestration tool that could support researchers in exploring the combined collaborative and individual learning space. For this tool to be successful, it would need to align with both the needs of the researcher as well as the values of the teacher to be implemented in the complex classroom environment.

8.4 A Framework For Designing Combined Collaborative and Individual Activities

To help define the needs of the researcher in a tool that supports the orchestration of combined collaborative and individual learning environments, I developed a framework that captures the design space. The framework contributes to CSCL by providing a lens through which to analyze the space of combined collaborative and individual learning and to inform the direction of future research. The framework presents four dimensions (i.e., social plane, ordering, transitions, and group formation) that can be modified to develop different learning environments. For each dimension, the design choices are divided into purely planned choices and choices that allow for adaptation in real-time (Soller et al., 2005). The planned divisions align with the phases planned in the task while the adaptations allow for changes to occur within a phase.

The framework illustrates the range of support that is needed in an orchestration tool for it to cover the designs that researchers may be interested in for combining collaborative and individual learning. It is crucial to have an understanding of the range of this design space so that tools can be developed to support the exploration of the space. My framework contributes as a way of defining this space and providing an outline for where support is needed to aid researchers in conducting collaborative and individual research in the classroom. In past work, the stages for teacher support for collaboration have been defined (Kaendler et al., 2015) and the management cycle for collaboration (Soller et al., 2005). My framework adds to this space by defining the areas that can be adjusted when combining collaborative and individual learning and not just collaboration.

Finally, my work provides a lens through which to analyze the space of combined individual and collaborative learning. There are currently many learning designs that combine collaborative and individual learning. For each of these learning activities, thought goes into the designs and how the different phases will work together to support learning. However, there has not been a good way to compare these different designs to understand why one may have been more or less successful than another. As we explore the space of how to best combine collaborative and individual learning, it is important to have a definition of the space to be able to make these comparisons. By better understanding what designs currently exist and what designs have not yet been investigated, we can make increased progress in addressing this question.

8.5 Modeling Individual Learning In Collaborative Settings

In the framework, we saw that the design space for combining collaborative and individual learning includes many opportunities to adapt the use of the social plane to the needs of the individual student. Before adapting the social plane students are working in to student needs, we first need to be able to understand the learning processes engage in when working individually and collaboratively. From here, we can develop ways to track individual student learning in collaborative and individual learning environments to be able to adapt the social plane when it is be beneficial to student learning. My research investigates how to accurately model the individual learning that results from collaborative learning activities. Theoretically, these models explore what features of a collaborative learning environment contribute most to learning. Practically, these models have many possible applications. Most relevant to the thesis, they could provide a foundation for adaptively transitioning between individual and collaborative learning.

My results demonstrate the value of including collaborative features in a statistical model for individual learning and provide insights into the possible mechanisms of collaborative learning. From the models run on both Experiments 1 and 2, I found evidence of the importance of having different learning rates for students working individually and collaboratively. By investigating how well models with different features predict individual learning, we can develop a better understanding of what features impact that learning within a specific environment. As these models are further developed, they may be able to be used to adapt the social plane students are working in to support greater student learning. By predicting individual learning across social planes, we can allow for more flexibility in how we adapt learning environments, particularly when students work individually and collaboratively, to student needs. These models contribute to prior research in computer-supported collaborative learning as it has not, to the best of my knowledge, created statistical models to measure the gradual knowledge growth by individual students during collaborative problem-solving practice, which I do by differentiating learning with a partner from learning alone as well as learning by giving help from learning by receiving help. By contrast, the research fields of ITSs and EDM have focused on the modeling of individual learning, but primarily from individual activities (Corbett & Anderson, 1995; Cen et al., 2007) and my research contributes to these fields by extending these models to include collaboration.

Further, the models presented in my research add to the current attempts at assessing collaborative problem-solving skills (Care & Griffin, 2013; Care & Griffin, 2015) by providing a new way to assess individual learning from collaborative settings. Although I investigated my new AFM versions in an ITS, they are not restricted to this context. The models only require a log of student actions labeled with knowledge components and success criterion allowing the models to be applied to a wide range of data sets collected in a CSCL setting.

8.6 Orchestrating Fluid Transitions Between Social Planes

Finally, I developed an orchestration prototype to support researchers in investigating the space of combined collaborative and individual learning in a way that aligns with teacher values. Specifically, the orchestration system focuses on supporting fluid transitions between social planes, which are a considerable challenge in the classroom. To develop the orchestration prototype to meet both researcher and teacher needs, I conducted a set of co-design sessions with teachers that brought together the needs of the researcher in the form of scenarios (based upon the framework) and the teachers through the discussions around the support of these scenarios. The framework presents the range of designs that need to be supported from the perspective of the researcher. However, how these designs can be supported in the classroom to support the values of the teacher is still am open question. From the analysis of the co-design sessions, I then developed and assessed the orchestration prototype against both teacher's and researcher's needs.

In the co-design sessions, teachers and researchers worked together to develop an understanding of the division of responsibilities around the management of the lesson designs to better understand how to balance to efficiency of automation versus the teacher's need for autonomy. Through these discussions, I could observe the values that the teachers held for their classroom and where their current pain points are. By presenting scenarios that take into consideration the needs of the researcher, I could discover how these values could better be supported in the classroom. This work builds upon previous orchestration literature that has provided characterizations and factors to be considered within orchestration systems (Dillenbourg, 2013; Dillenbourg & Jermann, 2010; Prieto et al., 2011). Although previous literature provides guidelines for developing teacher-centric support, it is still unclear how to balance between the automation that the system can provide and the autonomy provided to the teachers over their own classrooms. From my co-design sessions, five design recommendations emerged around how to balance the orchestration responsibilities within the classroom: planning as part of orchestration, automation for real-time decisions, direct communication to students, providing monitoring and information to teachers, and allowing for flexibility through teacher overrides. These recommendations are a contribution to both CSCL and HCI by defining recommendations for developing a researcher tool in a way that takes into account the teacher needs. Although the current recommendations are centered around providing teacher support, the results of my co-design sessions take these one step further to provide insights into what teachers actually want from their orchestration tools.

Using my framework and findings from the co-design sessions, I developed a prototype of an orchestration tool that supports both the planning of an activity in addition to four scenarios demonstrating the real-time support for fluid transitions. Within the orchestration prototype, the teacher is able to plan their learning activity with the options for different types of group formations and social plane transitions. This tool contributes to existing orchestration systems by not just supporting common classroom practices, but by supporting all types of transitions between social planes. The tool provides a platform for researchers to investigate the space of combined collaborative and individual learning, which does not currently exist, contributing to existing CSCL technologies. It also provides a tool for teachers to use in their classroom to support the orchestration of activities that span multiple social planes where students do not have to all be in the same phase at the same time. Through the validation of the orchestration tool, I found teachers to be excited for the support that the tool could provide within the classroom. Additionally, from a research perspective, the tool could cover a range of transitions, as presented in the framework, demonstrating its flexibility in being used in research.

My orchestration prototype makes a contribution to CSCL and HCI by adding to the understanding of when and how to provide teacher control within the system. For a system to be adopted into the classroom and be regularly used, it needs to support the teacher in their goals as a teacher. If the teacher feels like it is hindering their process, the tool will most likely be abandoned. As part of my orchestration development process, my co-design sessions provided insights into the values that teachers have in the classroom so that tools can be developed to include these values. Current literature on orchestration discusses the importance of having the tools be developed for the use of teachers without addressing the values of the teachers in the classroom. Additionally, I developed and tested a prototype of an orchestration tool that takes into account these teacher values along with the needs of the research community to be able to further investigate the combination of collaborative and individual learning. This tool contributes to the orchestration literature by providing support for social plane transitions that are not often used in the classroom. Many orchestration tools have been developed to meet the needs of a specific classroom issue. This tool instead aims to expand what learning activities researchers and teachers can use in the classroom. The orchestration tool allows for more research to occur in the classroom, even if it is in an informal capacity, which can make research more accessible to society. Finally, this tool contributes to CSCL literature in general by providing the first steps towards a research tool that will allow for a more thorough investigation of the combined individual and collaborative learning space.

8.7 Limitations and Future Work

In my research, there were a number of limitations that point to possible areas of research going forward. In this section, I address these areas for future work and how I could address them moving forward.

First, in my three experiments with students, I only investigated one possible division of complementary strengths and only one way of combining collaborative and individual learning. In Experiments 1 and 2, I did not find any support for the division of collaborative and individual learning between conceptual and procedural learning tasks. However, this division of strengths is neither the only possible division nor the only way to provide support. From the analysis of Experiment 1, I found that the discussion of errors might be a productive point for collaboration. This result indicates that a smaller grain size may be appropriate for investigating the complementary strengths. Instead of dividing collaborative and individual learning across problem types, a different approach may be fruitful.

Additionally, future research should investigate the strengths of individual and collaborative learning, not only at the problem level, but also by taking into consideration the current learning state of the student. In Experiment 3, I only compared one way of combining collaborative and individual learning. As shown through my framework, there are many different dimensions that can be manipulated to make different learning designs. By investigating how these different dimensions impact student learning, I can develop a better understanding for how to productively combine collaborative and individual learning to make it more effective than either social plane alone. In future work, I would need to explore how the alignment of the social plane with tasks, ordering, transitions, and group formation has an impact on the success of student learning.

In these studies, all of my research was conducted in the fractions domain. Although the combination of collaborative and individual learning was effective in this domain, support for collaboration tends to differ across different domains. Depending on the activity that students are working on and the learning goals of that activity, different forms of collaboration support may be appropriate. Different support may also extend to when collaborative and individual social planes would be appropriate to support student learning. It remains an open question if the same types of combined collaborative and individual learning designs would be effective across different domains. Future work should address this open question by not just investigating different combinations of collaborative and individual learning but also using these combinations in different learning domains.

Third, in my research, I presented models to predict individual domain-level learning in collaborative environments. These models begin to explore the features in the collaborative environment that may have an influence on students' learning. Although these models provide a first step towards predicting when collaborative and individual social planes may be productive for student learning, it is still an open question of what features in the learning environment should be adapted to and how to track these features. Future work needs to tease apart what process data can be used to predict when working collaboratively or individually would be beneficial for a student.

Finally, I developed an orchestration prototype that, once developed further, could be used to support future research around the combination of collaborative and individual learning. In my work, I investigated how this prototype could be designed so it supports the needs of both the researchers and teachers so that it would be an effective tool within the classroom. However, I did not develop the tool past the prototyping stage for this project. Additionally, I took an individual cognitive approach within my research, which may limit the applications of the orchestration tool. In future work, I would want to bring this tool into the next stage of development so that it could be used in the classroom and to validate the tool against different learning designs grounded in different theoretical approaches. Although through validation of the tool with teachers, the tool was well received, use of the tool in the actual chaotic environment of the classroom may reveal further design constraints or provide a slightly different perspective on various design decisions (e.g., the balance of automation and teacher autonomy).

In this chapter, I have presented several contributions that my work has made to a range of fields. When adapting the social plane to student needs, multiple factors must come together. In my work, I addressed these multiple factors by developing a stronger understanding of student learning, modeling student learning, and how to support this learning in the classroom in a way that allows for further exploration of the space. By combining these threads within this thesis work, I bring us closer to being able to adapt the use of social plane to individual student's needs.

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Appendix 1: Experiment 1 Test Items

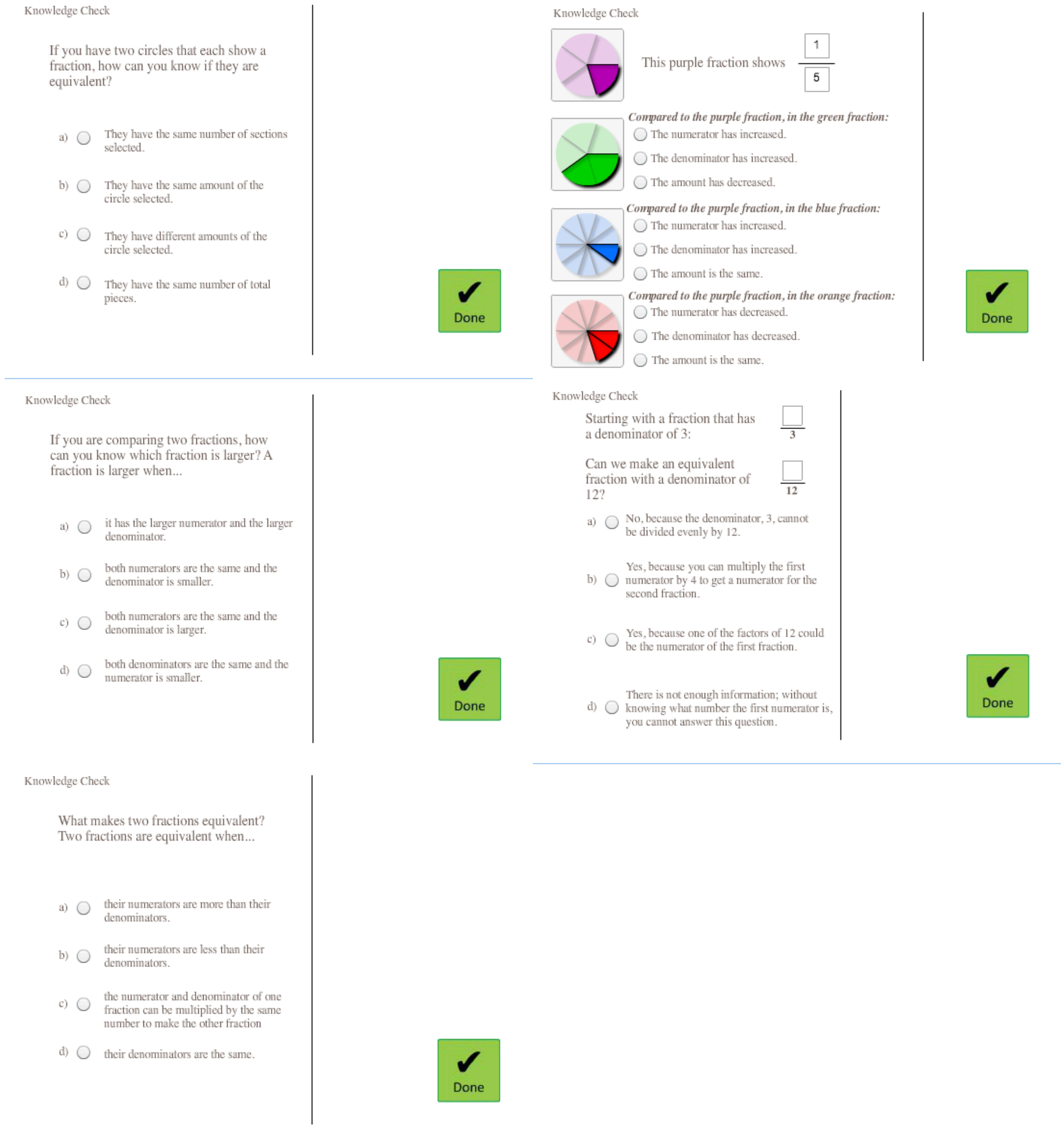


Figure A.1.1. Example conceptual test items used in Experiment 1.

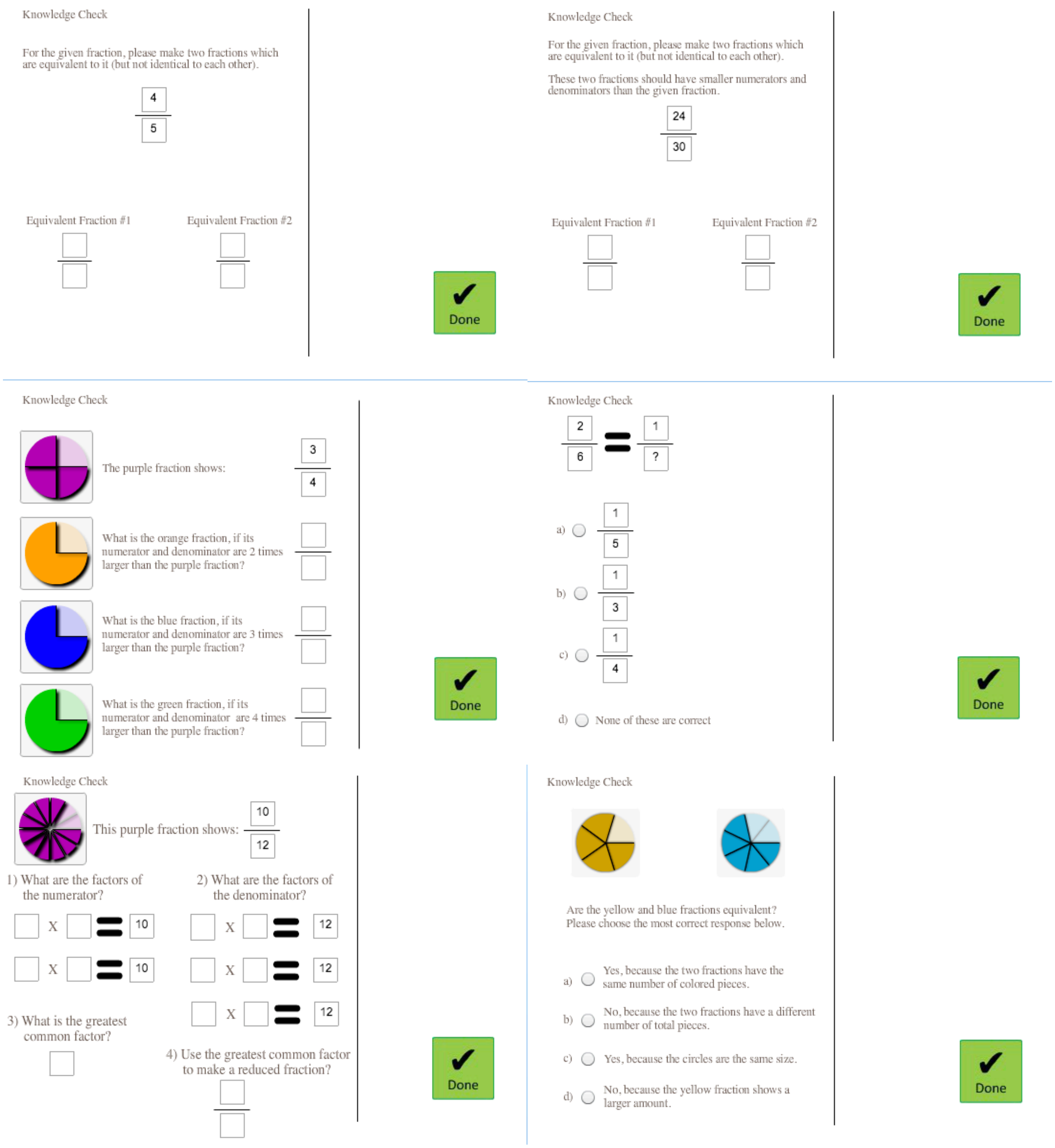


Figure A.1.2. Example procedural test items used in Experiment 1.

Appendix 2: Experiment 2 Test Items

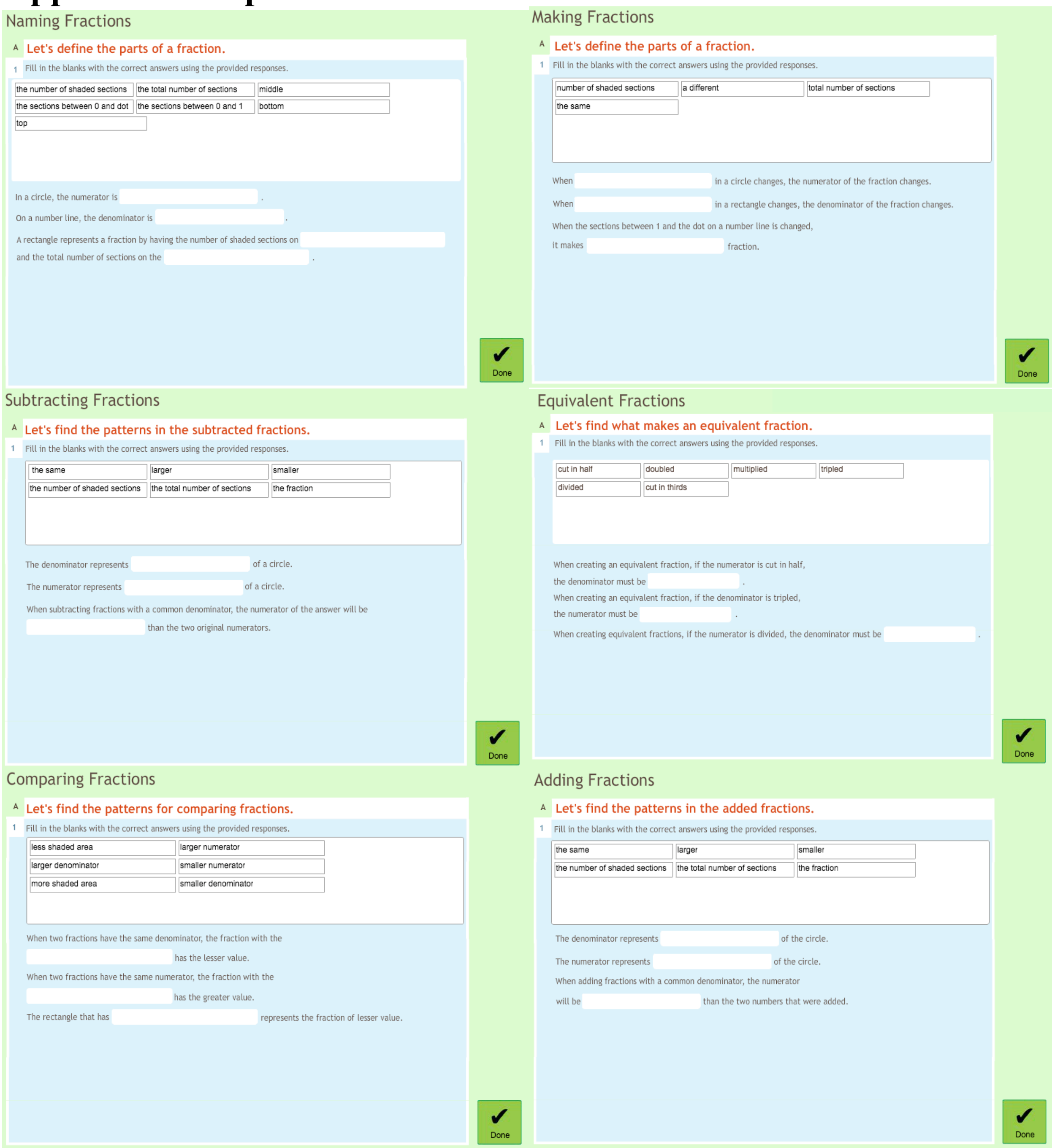


Figure A.2.1. Example conceptual test items used in Experiment 2.

Figure A.2.2. Example procedural test items used in Experiments 2 and 3.

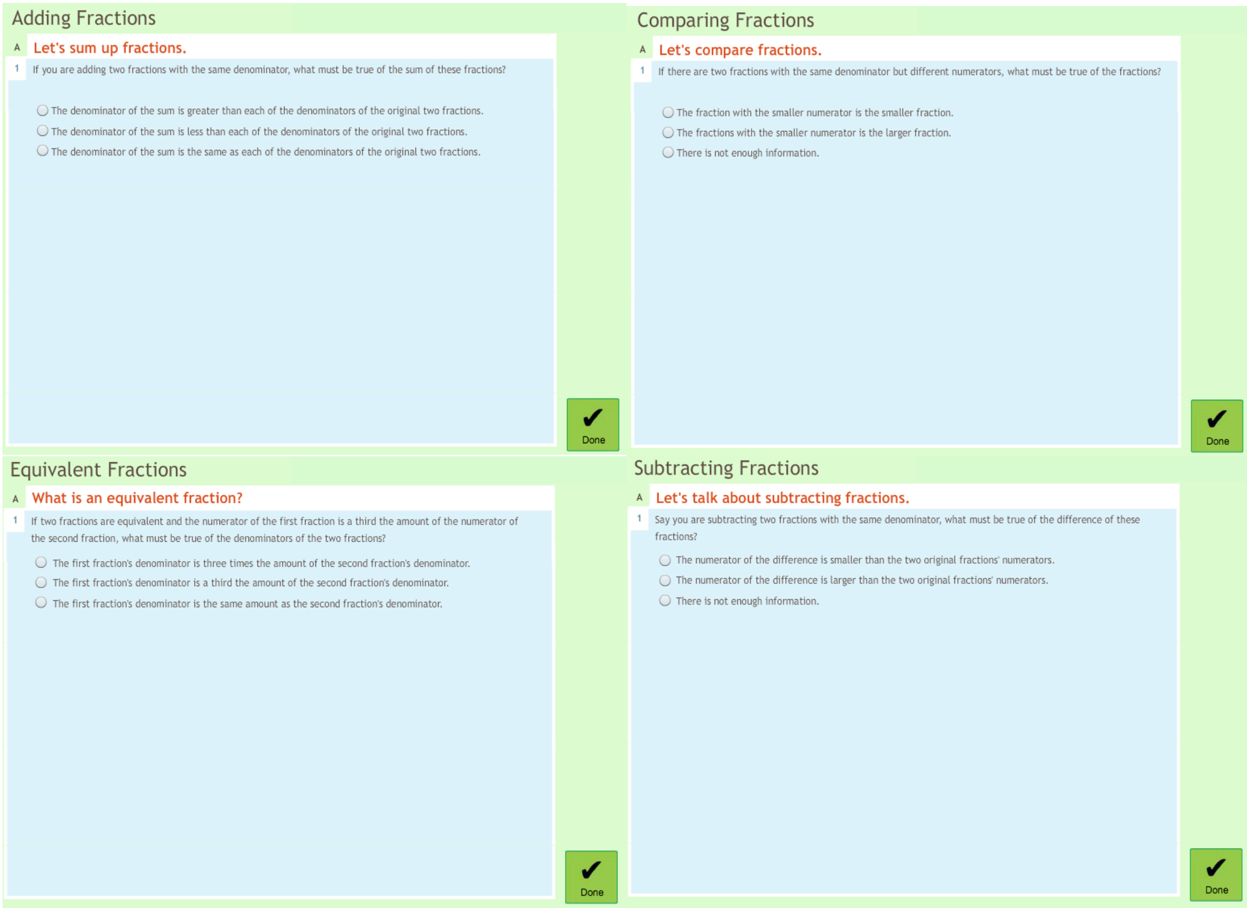


Figure A.2.3. Example transfer conceptual test items used in Experiment 2.

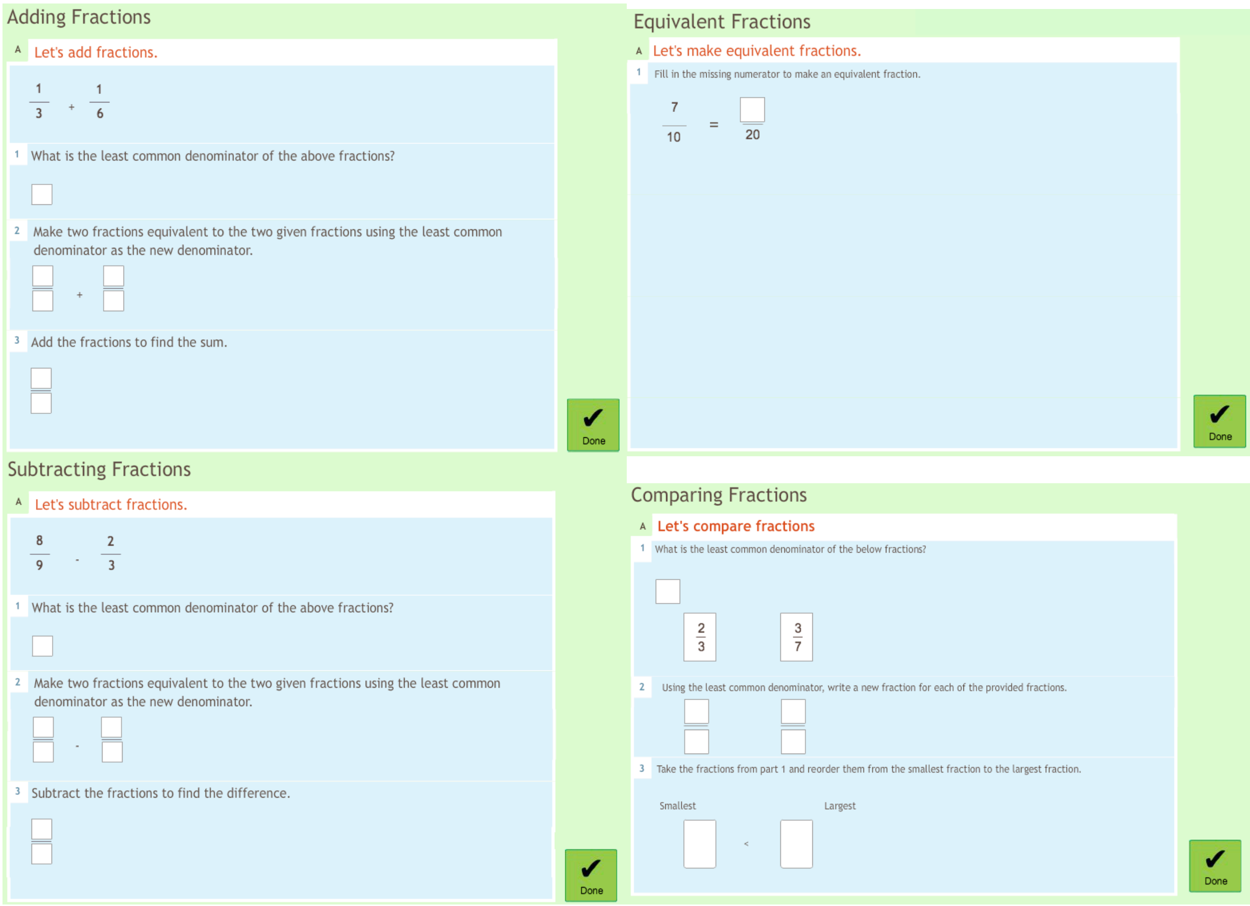


Figure A.2.4. Example transfer procedural test items used in Experiment 2.

Appendix 3: Experiment 3 Test Items

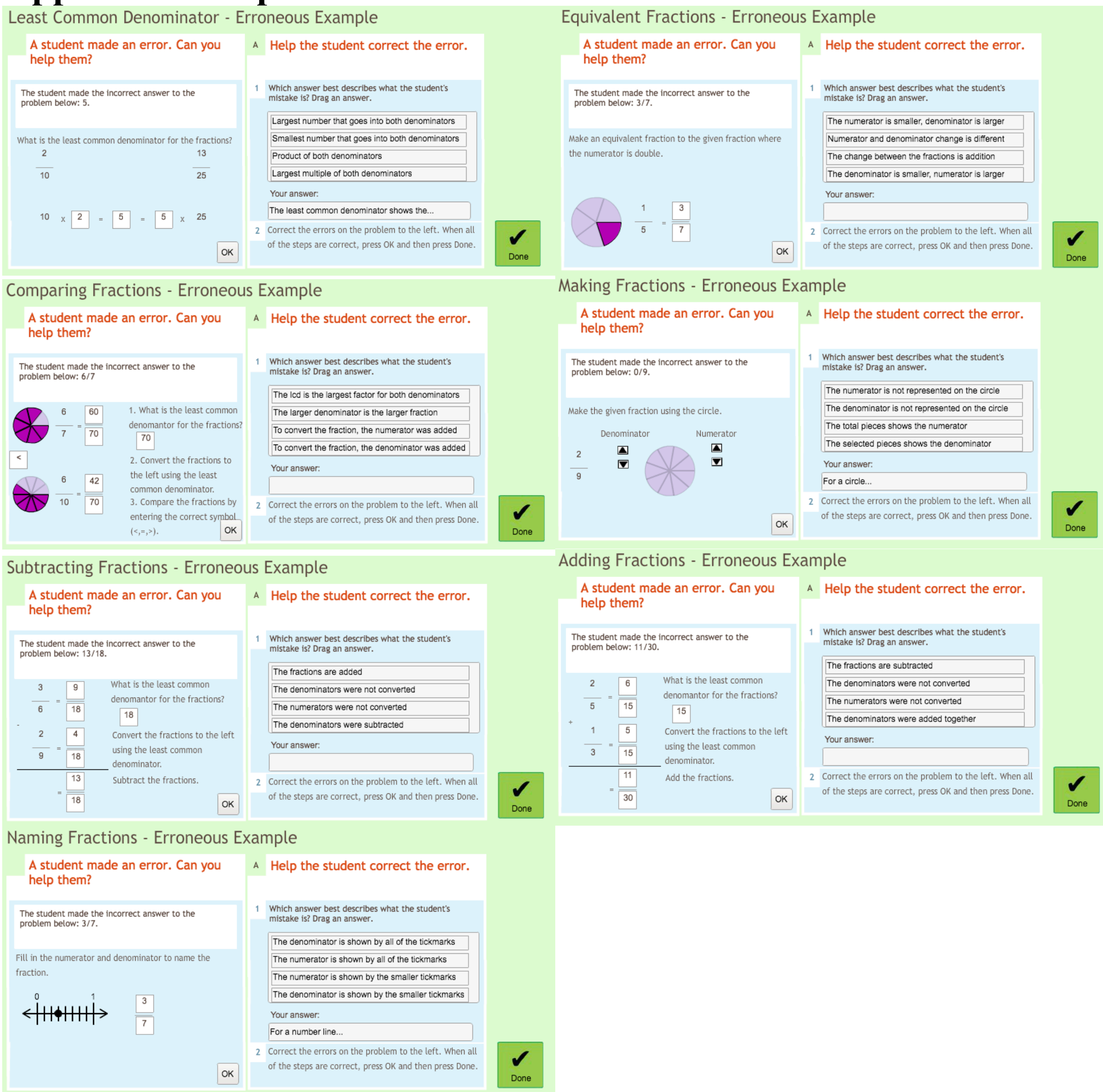
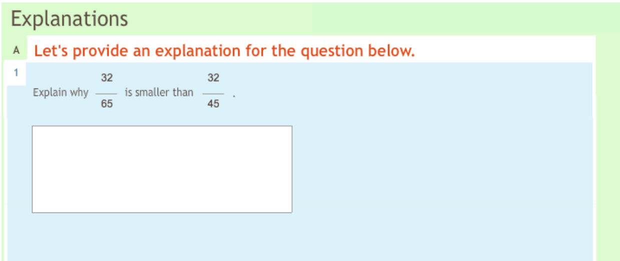


Figure A.3.1. Example erroneous example test items used in Experiment 3.



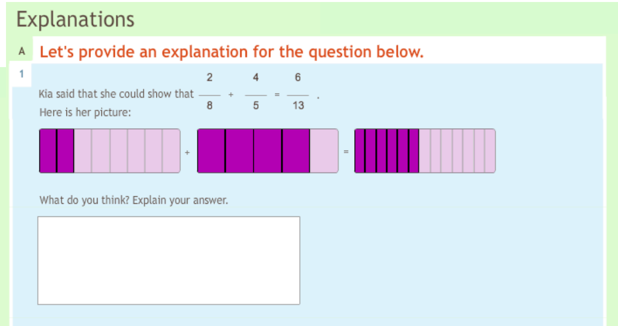
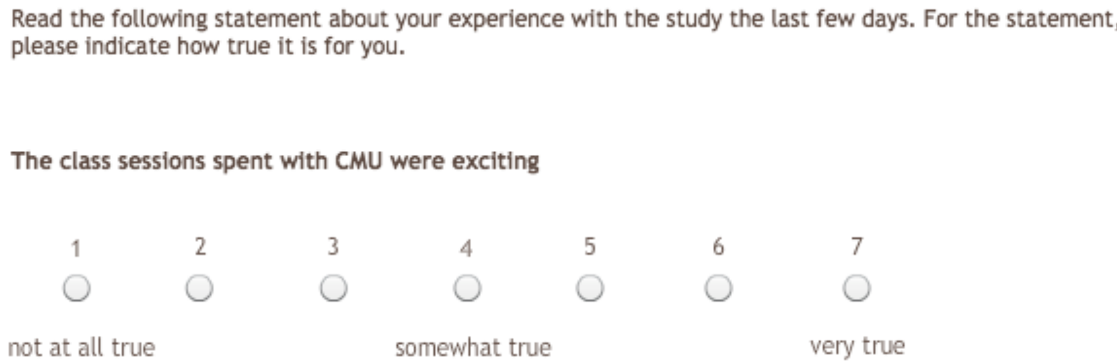


Figure A.3.2. Example short answer test items used in Experiment 3.

Appendix 4: Situational Interest Questions


Read the following statement about your experience with the study the last few days. For the statement, please indicate how true it is for you.

The class sessions spent with CMU were exciting

1 2 3 4 5 6 7

not at all true — somewhat true — very true

Figure A.4.1. Example situational interest question used in Experiment 3.

Situational interest questions adapted from Linnenbrink-Garcia et al. (2010):

- The class sessions spent with CMU were exciting
- The class sessions spent with CMU grabbed my attention
- The class sessions spent with CMU were often entertaining
- The class sessions spent with CMU were so exciting it was easy to pay attention
- What we learned in the class sessions spent with CMU was fascinating to me
- I was excited about what we learned in the class sessions spent with CMU
- I like what we learned in the class sessions spent with CMU
- I find the math we did in the class sessions spent with CMU interesting
- What we studied in the class sessions spent with CMU is useful for me to know
- The things we are studying in the class sessions spent with CMU are important to me
- What we learned in the class sessions spent with CMU can be applied to real life
- We learned valuable things in the class sessions spent with CMU