EXPLORE THE INFLUENCES OF AR-SUPPORTED SIMULATION ON MUTUAL ENGAGEMENT OF SOCIAL INTERACTION IN FACE-TO-FACE COLLABORATIVE LEARNING FOR PHYSICS

LI NAI

(B.A., TSINGHUA UNIVERSITY)

A THESIS SUBMITTED

FOR THE DEGREE OF MASTER OF ARTS

DEPARTMENT OF COMMUNICATIONS AND NEW MEDIA

NATIONAL UNIVERSITY OF SINGAPORE

2012

Acknowledgements

Foremost, I would like to sincerely thank my supervisor, Dr. Leanne Chang, for her great instruction and support in these two years. Her insightful comments and advices on the thesis benefited me to complete this research very much.

I am grateful for Dr. Henry Been-Lirn Duh, who provided invaluable opportunities for me to investigate the social impact of AR on collaborative learning in a multi-disciplinary team. His guidance and encouragement along the whole process facilitated me to overcome the challenge in thesis writing. My gratitude also extends to Dr. Vivian Hsueh-Hua Chen who offered constructive suggestions on proposing the research question of the thesis.

I am thankful to my partner, Gu Yuanxun. The completion of the thesis was indispensible for his hard work in developing and modifying the system, and great supports for conducting the experiment.

Last but not least, I offer my best regards to all the faculty members of CNM. Your kind instructions and academic passion impressed me very much during these two years.

Table of Contents

Abstract

As more technologies are integrated with collaborative learning, the mediating functions of technologies on shaping patterns of social interaction in learning activities have received considerable attention in recent years. Mutual engagement of social interaction, being a relational aspect of socially constructing knowledge, is identified as a communication issue to address the efficacy of developing mutual understanding among participants in collaborative learning. Recognized the great potential of AR technology in supporting collaborative learning, this research directs at investigating the influences of an AR-supported simulation on mutual engagement of social interaction in face-to-face collaborative learning for physics. Equality and mutuality of engagement of social interaction serve as two dimensions for measuring mutual engagement of social interaction. 30 pairs of students collaboratively solve the physics problem about elastic collision in one of the three experimental conditions: paper-based, 2D-based or AR-based. The results reveal that the AR-supported simulation does not only possess shared capacities of traditional 2D-supported simulation for promoting the equality and mutuality of engagement of social interaction, but also furthers the enhancement in the mutuality of engagement of social interaction through increasing elaborations and reducing acceptances. Characterized with hybrid attributes of the virtual reality and the real world, the AR-supported simulation enables to motivate collaborators' mutual engagement in building shared understanding of knowledge by delivering enriched personal experience. This study contributes to the research on the social

process of CSCL and provides evidence for supporting the promise of AR technology in enhancing face-to-face collaborative learning for physics.

List of Tables

List of Figures

Chapter 1 Introduction

The development of information and communication technologies (ICTs) has great impacts on the whole society. Computer-supported collaborative learning (CSCL), the integration of ICTs with collaborative learning, emerges as a significant field to explore the values of ICTs in fostering learning activities. The social process of collaboration involves participants' interaction with each other to jointly solve problems; as an integral component of the social process of collaborative learning, social interaction among participants has impacts on the quality of collaborative learning (Roschelle & Teasley, 1995). Nowadays there is an endeavor to explore how social interaction in CSCL can be enhanced by technologies (Kirschner & Kreijins, 2005).

Augmented reality (AR) that allows computer-generated virtual objects overlaid onto the physical world has been recognized as the "next generation" pedagogical medium to advance learning quality (Dede, 2008, p.19). With the support of AR technology, multiple learners can not only obtain enriched personal experience brought about by virtual reality through manipulating 3D objects in a shared visual space, but also communicate with each other to solve problems in real-time and real-space. Some researchers assessed the effectiveness of AR applications and found that AR technology entails great capabilities to augment collaborative learning experience (Kaufmann & Dünser, 2007; Klopfer, Perry, Squire, & Jan, 2005; Wagner, Schmalstieg, & Billinghurst, 2006). However, there is still little understanding of the impacts of AR technology on social interaction in collaborative learning.

Recognized the potential of AR technology for visualizing scientific phenomena, I plan to explore how AR-supported simulation enhances social interaction in face-to-face collaborative learning for physics in this research. The efficacy of social interaction in collaborative learning is manifested in approaches adopted by collaborators to coordinate the social process for developing shared understanding of knowledge (Erkens, 2004). A relational aspect in building shared understanding, mutual engagement of social interaction, serves as the focus to evaluate the impacts of AR-supported simulation on social interaction in collaborative learning. A collaborative AR system based on mobile phones has been developed to implement interactive simulation of elastic collision for collaboration.

The socio-cultural perspective in traditional collaborative learning is incorporated into this study as the theoretical basis to deepen the understanding of the importance of social interaction in CSCL. The socio-cultural perspective emphasizes on the social process in collaborative learning and the communicative function of social interaction in knowledge construction among collaborators; it also highlights the mediating function of surrounding materials and culture in collaborative learning process (Vygotsky, 1978). Individuals' learning in collaboration is indispensible for active participation in communicating and co-constructing meaning of knowledge among collaborators. Grounded on the socio-cultural perspective, numerous studies have examined the impact of technologies on social interaction in CSCL (Arvaja, 2007b; Suthers & Hundhausen, 2003). However, a majority of them focused on depicting the feature of social interaction in CSCL, but did not assess the enhancement of social interaction supported by technologies (Arvaja, 2007a; Chiu, 2003). Working out a shared solution for a problem serves as a goal of collaborative learning. When jointly constructing knowledge in a task, collaborators have to understand each other along the process of collaboration (Roschelle & Teasley, 1995). Rather than being in a static state, collaborators' mutual understanding is dynamic and they achieve so during the process of collaborative learning. Indeed, the construction of mutual understanding can be treated as a communication issue (Barron, 2000). The pathway of establishing and maintaining mutual understanding becomes a vital topic to address when studying social interaction in collaborative learning. Although the socio-cultural perspective has contended that tools could mediate the social process of collaborative learning, specifications are needed to identify how tools support social interaction in collaboration. As more technologies are integrated with collaborative learning, understanding the mediating function of technologies in collaborators' coordination of social process to build mutual understanding is helpful for gaining an insight into the construction of knowledge in CSCL.

In order to better understand the effects of AR-supported simulation on strengthening social interaction for developing mutual understanding in collaborative learning, I further apply theory of grounding proposed by Clark and Brennan (1991) to investigate social mechanism underlying the efficacy of social interaction in collaborative learning. Rooted in linguistics, theory of grounding offers an approach to analyze how interpersonal communication takes place to effectively construct mutual understanding (Baker, Hansen, Joiner, & Traum, 1999). Effective interpersonal communication in spoken settings is featured by joint commitments of all participants, which are represented by verbal exchanges that people orient to each other's statements in the conversation (Clark & Brennan, 1991). The achievement of mutual understanding is not simple accumulations of statements made by participants. In order to ground shared understanding of meaning, after the speaker presents unshared meaning to seek common ground, the addressee needs to build upon it to display his/her understanding. Also, participants need to make joint commitments along the whole conversation to update and develop common grounds. In terms of social interaction in collaborative learning, joint commitments that are reflected by collaborators' active engagements in initiating new ideas and extending each other's ideas are important to cultivate mutual understanding of knowledge (Tao, 1999). However, due to ambiguous situations for meaning making of new knowledge, collaborators usually face challenges to make joint commitments when developing shared understanding. Lack of joint commitments in social interaction hinders the construction of mutual understanding and leads to a less ideal solution for solving the group task (Barron, 2003). It is suggested that the level of joint commitments manifested in collaborators' interaction orientations towards building mutual understanding is a key relational aspect in the social context of collaborative learning, which can affect the effectiveness of working on a shared task. Collaborative relation between participants in the conversation should be a concern when addressing the social process of collaborative learning. Recognized the significance of joint commitments in effective interpersonal communication, extending it to the context of collaborative learning is useful for analyzing the efficacy of social interaction to maintain mutual understanding of knowledge in AR-supported collaborative learning.

Mutual engagement of social interaction, emphasizing on joint commitments in social interaction to build mutual understanding of knowledge in peer collaboration, serves as the lens of this research to gain an insight into the impacts of AR-supported simulation on the social process of collaborative learning. Collaboration between peers is one of the important types of collaborative learning in educational practices (Roschelle & Teasley, 1995). A range of research has concentrated on social interaction in dyad to explore the approach of promoting the effectiveness of peer collaboration from different perspectives (Kumpulainen & Kaartinen, 2003; Kumpulainen & Mutanenb, 1999). Mutual engagement of social interaction comprises two dimensions, equality of engagement of social interaction and mutuality of engagement of social interaction (Damon & Phelps, 1989). Equality of engagement refers to the equality between the collaborators to control over the conversation flow through initiating new focuses. Alternatively, mutuality of engagement is the richness of extending each other's ideas in the course of developing shared understanding (Damon & Phelps, 1989). Effective collaborative learning is featured with both high equality and mutuality of engagement of social interaction. These two dimensions together reveal the mechanism that impacts the formation of mutual understanding of knowledge. The equality of engagement of social interaction exhibits collaborators' joint commitments to direct the conversation for seeking mutual understanding, while the mutuality of engagement of social interaction is their reciprocal engagements with each other's ideas to achieve mutual understanding. According to Mercer (1996), social interaction characterized with high mutuality is that collaborators respond to each other's contributions in a critical but positive way; the level of mutuality of positive acknowledgements and providing supportive information is medium; and simple rejections/no response are low in mutuality. Increasing the use of patterns of social interaction with high mutuality and reducing the use of patterns of social interaction with low mutuality are essential to promote the mutuality of engagement of social interaction. Thus, to assess the effectiveness of AR-supported simulation in enhancing mutual engagement of social interaction, this study attempts to examine the effects of AR-supported simulation on the equality and mutuality of engagement of social interaction in collaborative learning. And patterns of social interaction with different levels of mutuality are identified to facilitate the evaluation of mutuality of engagement of social interaction.

In sum, the objective of this research is to investigate the influences of AR-supported simulation on mutual engagement of social interaction in face-to-face collaborative learning for physics. Since equality and mutuality of engagement are two fundamental dimensions of mutual engagement in the social process of collaborative learning, this research examines how AR-supported simulation affects the equality and mutuality of engagement of social interaction in face-to-face collaborative learning for physics. One primary aim of developing new technologies is to address the limitation of traditional technologies and opens up more possibilities to enhance collaborative learning effectiveness. It is necessary to identify new opportunities provided by emerging technologies for supporting the social process of collaborative learning. Hence, in this study, besides examining the capabilities of AR-supported simulation for enhancing mutual engagement of social interaction in face-to-face collaborative learning without simulation support, the comparison between the influences of simulations supported by AR technology and traditional multimedia technology is also conducted to analyze the unique advantage of AR-supported simulation.

The contributions of this study are threefold: first, it can broaden the understanding of the mediating role of ICTs in enhancing social interaction of collaborative learning activities; second, it can extend the extant research on social interaction in traditional collaborative learning to CSCL contexts and enrich the approach of analyzing the mechanism underlying the efficacy of social interaction in CSCL; third, it can provide evidence for supporting the value of AR technology in augmenting social interaction in face-to-face collaborative learning.

The thesis comprises five chapters. Chapter 2 presents the theoretical background of the research. It begins by providing an overview of the development of research on CSCL. Next, drawing on the theoretical perspective in traditional collaborative learning and theory of grounding in interpersonal communication, it reviews the literature about the importance of mutual engagement of social interaction in collaborative learning. It then discusses previous findings on mediating functions of technology-based simulations in the social process of collaborative learning and the potential role of AR technology in supporting face-to-face collaborative learning for physics.

Chapter 3 outlines the methodology of the research. It includes the selection of participants, the materials used, and the procedure of the experiment. Then, the methods of data analyses are introduced. The results of the data analysis are presented in Chapter 4.

Chapter 5 discusses the findings of the research. Implications, limitations and future research are also addressed in this chapter. The conclusion of the study is made at the end of the chapter.

Chapter 2 Literature Review

In this chapter, I start by discussing the research tradition on CSCL, highlighting how ICTs shape social interaction in collaborative learning. To better understand the efficacy of social interaction in CSCL, two theoretical approaches are adopted to study social interaction in collaborative learning and mutual engagement of social interaction in the social process. Next, I review the literature of technology-based simulation on social interaction in collaborative learning. Finally, I introduce the potential role of AR-supported simulations in fostering face-to-face collaborative learning and propose related hypotheses.

2.1 Computer-supported Collaborative Learning (CSCL)

ICTs have been increasingly adopted in educational practices with attempts to support collaborative learning. Driven by the advancements of computing technologies in recent years, CSCL, the integration of technologies with collaborative learning, broadens the possibilities of using technologies to complement traditional education in school settings (Zurita & Nussbaum, 2004b). With the advantage of connecting learning contexts and learning activities, CSCL provides a new setting for understanding natures of collaborative learning in pedagogical practices (Kaptelinin, 1999). Despite discussion on technical issues of CSCL, the social influences of this instructional medium have received considerable attention (Fischer & Mandl, 2005; Suthers, 2006).

In recent years, there has been a growing effort to investigate the impacts of technologies on the effectiveness of collaborative learning, and their focuses have shifted from learning outcomes to social processes (Chiu, 2003; Stahl, Koschmann, & Suthers, 2006). Regarding CSCL, technologies for supporting collaborative learning are designed to affect the way in which individuals socially construct knowledge and enhance learning effectiveness (Dillenbourg & Fischer, 2007). So far, a great amount of research has concentrated on learning outcomes and investigated the influence of technologies on the effectiveness of collaborative learning by evaluating objective individual learning achievement or group task performance (Reamon & Sheppard, 1997; Sun & Cheng, 2007). Also, there have been some studies using individuals' perceptions towards learning activities to subjectively measure the effectiveness of CSCL (Alavi, 1994). Rather than attributing knowledge acquisition in collaboration to individual information processing, an increasing number of researchers stressed that the social process of collaborative learning should not be ignored; the social process involves participants' interpersonal communication with each other to jointly solve problems in collaborative learning (Erkens, 2004; Sangin, Dillenbourg, Rebetez, Bétrancourt, & Molinari, 2008; Stahl et al., 2006). This process-oriented perspective highlights that the efficacy of social interaction is an important aspect to explain the effectiveness of CSCL. "Social affordances", referring to "properties of a CSCL environment that act as social-contextual facilitators relevant for the learner's social interaction", are proposed to address social interaction while building a successful CSCL environment (Kreijns, Kirschner, & Jochems, 2002, p.13). Kreijns et al. (2002) contended that the efficacy of social interaction in CSCL should be emphasized apart from paying attention to the implementation of technology and pedagogy in CSCL; it is crucial to create a CSCL context that motivates collaborators to actively engage in social interaction. The efficacy of social interaction has become a key indicator to assess the success of a CSCL environment (Kirschner & Kreijns, 2005). Thus, examining the social process of CSCL helps to gain an insight into the effectiveness of CSCL.

The technologies are not isolated from the social process in CSCL and have the capacity to change patterns of social interaction. Koschmann (2002) proposed that CSCL is “a field of study centrally concerned with meaning and the practices of meaning-making in the context of joint activity and the ways in which these practices are mediated through designed artifacts” (p. 20). The artifacts are important resources for mediating meaning making in CSCL. Individuals in the group can co-construct knowledge by referring to shared learning content provided by technologies (Roschelle & Teasley, 1995). Crook (1998) also placed high value on the resources mediating social interaction in collaborative learning, and pointed out technologies could be significant resources for creating optimal environments by creating referential anchors for collaborators. Linell (1998) proposed the concept of contextual resources to illustrate potential resources that can be used by individuals to negotiate the understanding in social interaction. From the perspective of contextual sources, a range of researchers began studying CSCL as contextual phenomena to explore how social interaction is shaped by technologies, and found that technologies can mediate the process of making sense of problem-solving situations and constructing mutual understanding among participants (Arvaja, 2007a; 2007b). Thus, physical instructional tools are not separated from social interaction in CSCL. It is necessary to explore how technologies influence the efficacy of social interaction in CSCL.

Instead of replacing face-to-face communication, a cluster of technologies for supporting co-located collaborative learning has been developed for enhancing the efficacy of face-to-face interaction in the learning process (Reamon & Sheppard, 1997; Zurita & Nussbaum, 2004b). The research on the impact of incorporating computing technologies into face-to-face collaborative learning provided supportive evidence that computing media can create innovative environments for augmenting social interaction in real-time and real-space (Zurita & Nussbaum, 2004a; 2004b). Despite the widespread use of networked technologies to support distributed collaborative learning, face-to-face collaboration among peers is popularly used in educational settings. It has gained rising attentions as more ICTs are introduced to school environments (Liu, Chung, Chen, & Liu, 2009). Thus, face-to-face collaborative learning serves as an important context to examine how technologies affect social interaction in CSCL.

Although technologies show potential for supporting social interaction in collaborative learning, integrating technologies with collaboration does not guarantee desired outcomes. Evaluating the effectiveness of CSCL is needed. Media characteristics are capable of affecting learning practices (Lai, Yang, Chen, Ho, & Chan, 2007). Thus, media characteristics need to be taken into account when applying technologies to collaborative learning. As more emerging technologies are developed for promoting collaborative learning, assessing the influence of technologies on collaborative learning is critical to further exploit the capability of technologies for enhancing learning activities. Meanwhile, considerations should be given to the method of measuring the efficacy of social interaction in CSCL. There are growing interests on the impact of technologies on the social process of CSCL, however, a large portion of them only proposed instruments to characterize types of social interaction in a single CSCL context or across different contexts (Chiu, 2003; Sangin et al., 2008). Although this approach facilitates to understand how technologies shape patterns of social interaction in CSCL, it fails to evaluate how technologies influence the quality of social interaction and thus provides limited knowledge on the effectiveness of technologies to foster social interaction in collaborative learning. Adopting the features of social interaction that could reflect the quality of social interaction is significant for analyzing the impact of technologies on the efficacy of social interaction in collaborative learning. Since the research tradition on CSCL is relatively new, there is a need to integrate relevant works conducted within traditional collaborative learning and along with those on interpersonal communication contexts in order to better understand the feature of social interaction in face-to-face CSCL.

2.2 Social Interaction in Collaborative Learning

This section has two parts. First I present the theoretical approach to explain the role of social interaction in collaborative learning and the underlying mechanism that influences the efficacy of social interaction. Next, I describe the significance of treating mutual understanding as a communication problem in collaborative learning. Then I proceed to a review of mutual engagement of social interaction and discuss the rationale of adopting it to evaluate the efficacy of social interaction in collaborative learning.

2.2.1 Theoretical foundations for collaborative learning

Studying social interaction in collaborative learning has become a key issue in the research agenda of collaborative learning nowadays. Traditionally, individual functioning was stressed while social interaction among participants was identified as an external environment for individuals to acquire knowledge in collaborative learning (Dillenbourg, Baker, Blaye, & O’Malley, 1996). Since individuals are integral parts of a group and they need to interact with each other to jointly solve problems, ignoring social interaction limits the understanding of group functioning in collaborative learning. In recent years, the salience of social process in collaborative learning is much more emphasized (Erkens, 2004). An increasing amount of literatures have studied the social process in collaboration through identifying characteristics of social interaction in different conditions or the effects of types of social interaction on learning outcomes (Barron, 2003; Hogan, Nastasi, & Pressley, 1999).

The socio-cultural perspective serves as a theoretical basis for interpreting the social process of constructing knowledge and the mediating role of external circumstances in collaborative learning (Vygotsky, 1978). This perspective posits that the meaning of knowledge is built on shared speech, tools and activities. It explains the significant role of social interaction in cognitive growth by stressing participation in knowledge construction among collaborators in learning activities. The communicative functions of social interaction are highlighted rather than simply considering its functional role as a catalyst in fostering mental development (Barron, 2000). Additionally, this perspective explains the mediating function of material tools and culture in affecting individuals’ social interaction to jointly construct knowledge in collaboration. Generally, the socio-cultural approach suggests that integrating social and material surroundings with collaborative learning is significant to understand how knowledge construction is socially shaped in problem-solving (Arvaja, 2007a).

The socio-cultural perspective offers a foundation for analyzing the critical role of social process of constructing knowledge in collaborative learning. It has inspired a body of studies to explore social interaction in collaborative learning by focusing on different aspects of the social process (Barron, 2003; Staarman, Laat, & Meijden, 2002). A majority of them investigated the meaning of individual statements rather than incorporate the meaning linkage between individual statements into the analyses (Chin & Brown, 2000; Russell, Lucas, & McRobbie, 2004). They typically examined the content of individual statement based on the depth of cognitive processing of knowledge with attempts to gain an understanding of how collaborators construct knowledge (Chin & Brown, 2000). Whereas assessing the quality of each individual statement is helpful to evaluate the cognitive approach used by individuals in collaborative learning, examining social interaction at the group level by taking interaction sequences into account could give insight into the process of meaning negotiation. In recent years, more attention has shifted to the establishment of mutual understanding in collaborative learning (Barron, 2000; Erkens, 2004).

Developing mutual understanding among participants is acknowledged as the heart of collaborative activities, and the dynamic nature of mutual understanding provides a basis for further addressing relevant social interaction issues. Roschelle and Teasley (1995) defined collaboration as “a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem” to heighten the dynamics of mutual understanding and its significant role in collaborative learning (p. 70). It is suggested that the pathway of achieving mutual understanding is a key aspect to assess the effectiveness of collaborative learning. Solving a problem towards a shared goal among participants is an aim of collaborative learning, and thus participants need to reach mutual understanding of solutions for tackling the problem. The efficacy of social interaction in collaborative learning is manifested in individuals' communicative strategies to coordinate social interaction for developing mutual understanding. The moment-by-moment feature of social interaction has been identified by a growing number of researchers (Erkens, 2004; Kumpulainen & Mutanen, 1999). They contended that the continuous interpretive process among collaborators is needed to construct mutual understanding of knowledge. Since constructing mutual understanding is a social dynamic activity along the collaboration, it is necessary to concentrate on social interaction of collaborative learning and explore how collaborators manage to build mutual understanding of knowledge in the social process.

While the socio-cultural perspective identifies the significance of social interaction in constructing knowledge in collaborative learning, theory of grounding, explicitly addressing the association of joint commitments in interpersonal communication with the development of mutual understanding, is useful for furthering the understanding of social mechanisms underlying the achievement of mutual understanding in collaborative learning (Baker et al., 1999). Rooted in linguistic research, grounding refers to the interpersonal communication process of developing shared understanding among participants through verbal interaction (Clark & Brennan, 1991). It is suggested that communicative acts, the coordination of participants' utterances, function as media for people to negotiate their understanding in conversation. Based on the viewpoint of Clark (1996), communicative acts are inherent joint actions in collaborative activities, which result in accumulations of shared understanding through coordinating the social process. Joint commitments of all participants are required to effectively build shared understanding in the conversation (Clark, 1996). And the construction and maintenance of common grounds are indispensible for joint efforts of individuals involved in. Regarding collaborative learning, verbal interaction is perceived as “a social mode of thinking”, which serves to be a medium of jointly constructing knowledge rather than merely sharing one’s own thoughts with each other (Mercer, 1996, p. 374). Not only do collaborators verbally exchange their own understanding on the problem, but also evaluate and reflect on others’ ideas and negotiate meaning in the conversation. According to the perspective of grounding, meaning negotiation is indispensible for social interaction engaged by participants, and joint commitments should be stressed when studying collaborators’ social interaction (Clark, 1996; Clark & Brennan, 1991). Establishing and maintaining mutual understanding of knowledge are significant to the effectiveness of collaboration. Thus, extending the investigation of joint commitments in social interaction to the context of collaborative learning is beneficial for attaining an insight into the efficacy of the social process to construct mutual understanding of knowledge in collaborative learning.

There are series of challenges for participants to jointly construct mutual understanding in collaborative learning, and collaborative relation represented by participants’ interaction orientations to build mutual understanding relates to the effectiveness of collaboration. When students are required to solve a problem on new knowledge together, they have to cope with some challenges in the process of reaching shared understanding, for instance, collectively carrying out explorations, interpreting ambiguous situations, negotiating socio-cognitive conflicts and refining shared cognition (Barron, 2000; Roschelle, 1992). Storch (2002) found that not all groups in collaborative activities behave in a collaborative manner, and low level of joint commitments have impacts on the effectiveness of achieving mutual consensus in meaning negotiation. Based on the view of Barron (2003), joint commitments reflected by collaborators' interaction orientations to each other in the group should not be ignored since this relational aspect can significantly affect the success of developing mutual understanding of knowledge in collaborative learning; identifying opportunities and challenges for motivating joint efforts in social interaction of collaborative learning is important to foster the effectiveness to build mutual understanding.

Therefore, it is necessary to examine social interaction in collaborative learning through the lens of joint commitments to better understand the characteristics of the social process in collaborative learning as well as the opportunities and challenges for developing mutual understanding. Mutual engagement of social interaction, stressing joint commitments in social interaction for reaching mutual understanding, has emerged as a vital relational issue in the research on social interaction of collaborative learning (Damon & Phelps, 1989). In the following part, relevant literatures on mutual engagement of social interaction in collaborative learning are reviewed.

2.2.2 Mutual engagement of social interaction in collaborative learning

With respect to peer learning, equality and mutuality of engagement of social interaction are two fundamental dimensions used to illustrate mutual engagement of social interaction (Damon & Phelps, 1989). Peer learning is a significant way to motivate students to actively construct knowledge through negotiating the understanding of tasks with each other within a small group (Kumpulainen & Kaartinen, 2000). A body of studies has focused on characterizing social interaction between peers in order to improve the effectiveness of peer learning (Kumpulainen & Kaartinen, 2003; Roschelle & Teasley, 1995). Equality and mutuality of engagement of social interaction are two vital aspects to examine social interaction in peer learning (Damon & Phelps, 1989). Equality refers to the level of controlling over the group task, which is represented by the control of the direction of social interaction between two people (Damon & Phelps, 1989). Hence high equality indicates that both parties in a group actively engage in controlling over the flow of social interaction rather than only one party dominates the conversation. Mutuality is described as the degree of engagement with the contribution of the partner's (Damon & Phelps, 1989). In terms of high mutuality, it is characterized with rich extension of each other's statement between two parties in a group. Achieving high equality and high mutuality of engagement of social interaction are the objective of constructing effective collaborative learning environments.

Interaction sequences in conversation serve as an important context to analyze the equality and mutuality of engagement of social interaction in collaborative learning. Barnes and Todd (1977) distinguished four features of the social process in collaborative learning, which includes initiating new focus of topic, eliciting information from others, building upon preceding ideas, and qualifying the disagreement and complexity in previous utterances. They proposed that the concept of collaborativeness, referring to "links between succeeding utterances", to illustrate joint actions engaged by individuals within a small group (p. 3). Initiating a new focus functions as a shared frame in the conversation, and extending and qualifying statements are needed in order to sustain the development of social interaction in collaborative learning. Hogan et al. (1999) proposed "interaction sequence" to define the flow of social interaction, which is “a series of turns bounded by statements that initiate a new level of focus” (p.388). The formation of an interaction sequence is constituted with two elements, initiating a new level of focus in the conversation and extending this focus at the same level. After one person presents a statement at a new level of focus, the response to the initiation at the same level of focus from other group members is required to build an interaction sequence. Then, the conversation centering upon this level of focus contributes to the richness of interaction sequence. And mutual understanding is developed during the extension of the initiating statement. An interaction sequence ends when one group member changes the previous level of focus to a different one. In the context of an interaction sequence, the statement that initiates of a new level of focus plays the role of a controller of conversation direction, which is essential to measure the equality of engagement of social interaction, while the statements that extend this level of focus could be used to characterize the mutuality of engagement of social interaction (Galaczi, 2004). So, analyzing the initiating statement and the development statements in an interaction sequence facilitate to get a deep insight into mutual engagement of social interaction in collaborative learning.

The equality of engagement of social interaction highlight the relationship of peers formed in the social process of collaborative learning for seeking mutual understanding (Damon & Phelps, 1989). Different levels of equality are evaluated by collaborators’ equality of initiating a statement with a new focus in the conversation (Galaczi, 2004). The members in dyads with high equality play relatively equal roles in opening new focuses in the process of collaborative learning. However, high equality of engagement of social interaction does not guarantee group functioning in a collaborative manner. Galaczi (2003) found that dyads might behave in a “solo vs. solo” pattern, which indicates that both participants actively introduce new focuses but do not like reacting to each other’s ideas and further expanding them in the conversation (p.2). This type of dyads has a high level of equality of engagement of social interaction, while the level of mutuality of engagement of social interaction is low. Hence, apart from high equality, effective collaborative learning should be characterized with high mutuality at the same time. The behavior of opening a new focus is only the beginning for establishing mutual understanding and responses to it is needed to reach mutual understanding (Clark & Brennan, 1991).

Research usually links communicative functions of social interaction to analyze the mutuality in the process of constructing mutual understanding in collaborative learning. Two basic patterns of social interaction are identified to heighten the importance of mutuality when forming shared understanding in collaborative learning, “construction and co-construction of meaning”, and “constructive conflict” (Bossche, Gijselaers, Segers, & Kirschner, 2006, p.495). The introduction of specific meaning of a situation or an approach to solve the problem is described as construction of meaning, and this will generate co-construction of meaning among group members, resulting in new understanding of the situation within the group. The construction and co-construction of meaning is not merely the aggregation of independent meaning inserted by individuals, but the integration of meaning and the achievement of mutual understanding based on proceeding negotiations. Also, construction and co-construction of meaning is not the only path of building mutual consensus (Fischer, Bruhn, Gräsel, & Mandl, 2002). When the viewpoints expressed by individuals are different, further negotiations on the meaning are needed to obtain mutual agreement. Constructive conflict is defined as tackling different views arisen from the conversation with attempts to reach reciprocal understanding (Fischer et al., 2002). Empirical evidence has also been offered to support the vital role of construction and co-construction of meaning, and constructive conflicts in developing mutual understanding of knowledge (Bossche et al., 2006). Identifying construction and co-construction of meaning and constructive conflicts in collaborative learning can yield insights into general mechanisms underlying the mutuality of engagement of social interaction. However, a body of research only relied on construction and co-construction of meaning or constructive conflicts to assess mutuality without taking the variability of mutuality within co-construction of meaning and constructive conflicts into consideration (Barron, 2003; Fischer et al., 2002). Since social interaction patterns reveal different levels of mutuality, a broad conceptualization of mutuality makes it difficult to investigate detailed characteristics of social interaction on the path of achieving consensus. So it is crucial to identify patterns of social interaction with different levels of mutuality in collaborative learning. Indeed, the central issue of enhancing mutuality of engagement of social interaction is increasing the use of patterns of social interaction with high mutuality and reducing the use of patterns of social interaction with low mutuality.

Interaction patterns featured by different levels of mutuality have impacts on the effectiveness of constructing mutual understanding in collaborative learning. Mercer (1996) distinguished three major interaction patterns for analyzing the quality of social interaction in collaborative learning based on communicative functions, which includes “exploratory talk”, “cumulative talk” and “disputational talk” (p.369). They represent different ways that collaborators build on each other’s statements in the social process. Exploratory talk occurs "when partners engage critically but constructively with each other's ideas" (p.369), such as presenting arguments, proposing alternative hypothesis and asking for clarifications. Cumulative talk refers to "speakers build positively but uncritically on what the other has said" (p.369), which is manifested in confirmations and repetitions. Disputational talk usually takes the forms of "disagreement and individualized decision making" (p.369). Among these types of talk, exploratory talk is conceived as the most productive one in group learning activities that strengthens the reciprocity in social interaction and thereby promotes shared knowledge construction (Mercer, 1996). By incorporating collaborators' reciprocal engagements into the analysis of social interaction, Mercer's (1996) categories lay a foundation for identifying social interaction patterns with different levels of mutuality in the social process of collaborative learning. The integration of joint commitments in social interaction with shared knowledge construction reveals the social process underlying the development of mutual understanding of knowledge in collaboration.

On the basis of Mercer's (1996) instrument, some researchers sought to further operationalize social interaction in order to examine the features of mutuality of engagement of social interaction in collaborative learning (Barron, 2000; Visschers-Pleijers, Dolmans, Wolfhagen, & Van der Vleuten, 2005). Among these, Barron (2000) developed five main types of responses to new proposals in the social process of collaborative learning, namely, "acceptances", "clarifications", "elaborations", "rejections" and "no response", to investigate how collaborators coordinate verbal interaction for establishing and maintaining mutual understanding (p.414). For these types of responses, elaborations, characterized with offering extra information, advices and justifications, have a high level of mutuality. Clarifications are proposing follow-up questions. They are also high in mutuality since the person has to integrate new meaning of the knowledge stated by the partner with his/her prior understanding to make clarifications. Acceptances include simple agreements or repeating prior statement. Rejections and no response belong to “disputational talk” mentioned above, which represent a low level of mutuality and exert negative influences on mutual understanding development (Mercer, 1996, p.369). After analyzing communicative functions of social interaction in collaborative learning based on this scheme, Barron (2000) found that the variability of levels of mutuality exists across different groups, which affects the efficacy of building understanding among collaborators. In particular, elaborations do contribute to effective coordination among group members to reach mutual understanding, while rejections and no response hinder the construction of mutual understanding. This scheme gives an insight into interaction patterns with different levels of mutuality of engagement of social interaction in collaborative learning. However, the limitation of this study is that it did not separate solely adding positive information from those critical responses. Accumulating information benefits building common grounds, but the contribution to the other’s statement is limited and the reciprocity is lower than critical elaborations. Since exploratory talk is highly appreciated to enhance the quality of social interaction, it is necessary to examine critical elaborations and accumulations respectively. Also, although acceptances have positive effects on quickly reaching consensus among collaborators, they are less constructive to develop an understanding at a higher level since little new information about the meaning of knowledge is added (Gijlers, Saab, Van Joolingen, De Jong, & Van Hout-Wolters, 2009). Fostering the richness of accumulative talk is important to promote the mutuality of engagement of social interaction. Therefore, increasing critical elaborations, clarifications, accumulations and reducing simple acceptances, rejections and no responses are significant to enhance the mutuality of engagement of social interaction in collaborative learning.

Extending mutual engagement of social interaction to the research on CSCL is helpful for enriching the understanding of the influence of technologies on the efficacy of social interaction in CSCL. Social interaction characterized with a high level of mutual engagement relates to the effectiveness of reaching mutual understanding of knowledge in collaborative learning. Nowadays, working in pairs is a commonly used form of collaborative learning in school environments. Since the levels of equality and mutuality of engagement of social interaction are important to create a constructive collaborative learning context, it is necessary to explore the impact of technologies on mutual engagement of social interaction in face-to-face collaborative learning. Tao (1999) has introduced mutual engagement of social interaction into the research of CSCL for science subjects. He used equality (high/low) and mutuality (high/low) to qualitatively evaluate the engagement of each dyad. But simply utilizing a continuum with a range of low to high level is inadequate to identify the salient features of social interaction, making it difficult to understand the mechanism underlying the construction of mutual understanding. Hence, more considerations should be given to the approach of characterizing and evaluating equality and mutuality of social interaction in CSCL. On the basis of literatures on collaborative learning, interaction sequences are regarded as vital contexts to examine the equality and mutuality of engagement of social interaction (Galaczi, 2004; Hogan et al., 1999). Initiating statements and development statements in interaction sequences are examined in this study to capture the features of equality and mutuality of engagement of social interaction. Also, to better understand the efficacy of technologies, the patterns used to analyze mutuality of engagement of social interaction should be able to indicate social interaction with different degrees of mutuality. Therefore, the instrument developed by Barron (2000) is applied and modified for this study.

2.3 Collaborative Learning with Technology-based Scientific Simulation

This section is organized into two parts. I first present the benefits of technology-based simulations for science subjects and review the literature on the impacts of collaborative use of simulations on mutual engagement of social interaction. Then I proceed to introduce the promising role of AR-supported simulation for enhancing face-to-face collaborative learning.

2.3.1 Mediating functions of technology-based scientific simulation

The simulation is a typical genre of computing technologies applied in face-to-face CSCL. “Learning with simulations” is conceived as one of the important impacts of technologies on science education, which is able to provide more pedagogical opportunities for students to actively explore and acquire knowledge (Webb, 2008, p. 134). In order to make better use of technology-based simulations, it is suggested that more research is needed to investigate to what extent such kinds of applications benefit learning activities.

Simulations reveal great potential for supporting learning activities of science subjects. Technology-based simulations are largely used to convey meaning in abstract and complex education practices through visualizations, which contribute to making sense of the knowledge and enhancing the quality of peers’ interaction (Reamon & Sheppard, 1997;

Roschelle & Teasley, 1995). Regarding science subjects full of abstract information, interactive visualizations of science phenomena make it more possible for learners not only to access concrete information to comprehend conceptual knowledge, but also to provide an exploratory tool to construct knowledge based on hands-on experiences (Shaer, Kol, Strait, Fan, Grevet, & Elfenbein, 2010). Especially at the initial stage of learning science knowledge that needs high-order information processing, the opportunity of conducting experiments are invaluable to understand scientific phenomena and principles that cannot be directly observed in the real world (Järvelä, Bonk, Lehtinen, & Lehti, 1999).

The collaborative use of technology-based simulations in learning activities attracts more attentions from designers and researchers these years as the value of CSCL are acknowledged by an increasing amount of literatures (Chee & Hooi, 2002; Sangin et al., 2008). Great importance has been attached to the shared experience in collaborative learning (Pauchet et al., 2007). It is suggested that the shared experience of manipulating artifacts can broaden common grounds among collaborators, which fosters to build mutual understanding in problem solving by referring shared artifacts. In recent years, experimenting with visual simulations has been widely used to support collaboration in science education with an attempt to motivate students to propose scientific inquiries and stimulate learning interests. There are some studies on the benefits of technology-based simulations in science domain focusing the attention on the influence of simulations on individuals' conceptual understanding of knowledge in collaborative activities (Reamon & Sheppard, 1997; Whitelock et al., 1993). As the significance of social interaction in collaborative learning is increasingly acknowledged, the effects of technology-based simulations on social interaction in collaborative science learning become crucial to the research on CSCL (Colella, 2000; Tao, 1999).

Technology-based simulations reveal a promising role in mediating social interaction to build mutual understanding of meaning in collaborative learning. Within the setting of collaborative science learning, shared visual information displayed by the simulation can be significant resources for social interaction instead of merely providing external representations of knowledge to assist the demonstration of scientific concepts and principles (Andrews, Woodruff, MacKinnon, & Yoon, 2003). A number of researchers interpreted the role of visual information in mediating social interaction and establishing mutual understanding of meaning in collaborative learning (Rochelle & Teasley, 1995; Suthers, 2006). For example, Rochelle and Teasley (1995) analyzed the mediating function of a scientific simulation in the process of collaboratively solving a physical problem and concluded that experimentations serve as a means to coordinate meaning negotiation by continuously providing shared resources and references. They claimed that shared activities supported by the interactive simulation encourage collaborators generating new ideas, refining the prior understanding and resolving conflicts, which in turn benefit the accumulation of shared understanding of scientific knowledge. Järvelä et al. (1999) also noted that the simulation is a shared referential anchor for individuals in small groups to negotiate the meaning of new knowledge in a more reciprocal manner. They contended that it is significant to provide interactive instructional supports to knowledge learning since reciprocal understanding during interpersonal communication have facilitation effects on learning effectiveness.

Furthermore, embedding scientific simulations supported by technologies in the context of collaborative learning is regarded as a method to stimulate collaborators' mutual engagement of social interaction to form shared understanding (Järvelä et al., 1999). "Representational guidance" is used to illustrate the role of external representations in shaping social interaction in CSCL, which exerts positive influences on expressing, explaining and refining ideas in collaboration due to "ease of reference" and "reminding" (Suthers, 2001, p. 260). Suthers (2001) claimed that collaborators prefer to elaborate on the knowledge that is salient in their shared context, and emerging knowledge yielded from common experiences of manipulating external representations is useful for organizing the conversation in collaborative learning. Suthers and Hundhausen (2003) expanded this point of view and systematically clarified three main functions of external representations based on the process of jointly negotiating the meaning in collaborative learning, which provided a deep insight into the mechanism underlying the effects of external representations on mutual engagement of social interaction. The three functions include initiating the negotiation of meaning, creating a shared reference in mean-making of the situation, and offering group memory for furthering elaborations. Interacting with external representations can motivate people to develop new ideas about the topic. When individuals in the group have a new idea about shared representations, they feel obliged to initiate the conversation and negotiate meaning with others to seek mutual understanding of knowledge. During the process of meaning negotiation, the shared experience of using external representations and observing subsequent effects of the manipulation can engage collaborators in reflecting on the information presented by external representations and discussing related topics. Additionally, external representations function as shared memory of collaboration since collaborators can refer to prior information offered by external representations, which afford them to modify their solutions to the problem over time. Therefore, external representations open up new possibilities for encouraging both initiations of topics and extensions of meaning in ongoing conversation to construct mutual understanding. As a kind of external representation of scientific phenomena, technology-based simulations enable to offer shared referential resources to motivate collaborators to initiate new focuses related to the phenomena and further negotiate meaning of it, which are key aspects of mutual engagement of social interaction in collaborative learning.

Even though technology-based simulations generally show positive impacts on the process of collaborative learning, simulations might be ineffective to improve learning quality. The mediating role of simulations characterized by different visual representations in social interaction of CSCL can be various (Reamon & Sheppard, 1997). The capabilities of technology-based simulations for supporting mutual engagement of social interaction should be clearly identified to gain an insight into the opportunities that contribute to the enhancement of social interaction in collaborative learning. As more emerging technologies are developed for implementing scientific simulations in collaborative learning, it becomes important to concentrate on analyzing the influence of collaborative use of these new applications on mutual engagement of social interaction in learning practices.

2.3.2 Potential roles of AR technology in face-to-face CSCL

Continuing advancements of technologies afford new possibilities for supporting face-to-face CSCL in small groups. This type of emerging technologies directs at augmenting face-to-face interaction among co-located collaborators in the learning process by addressing the limitation of traditional technologies. In recent years, more new interactive simulation tools supported by emerging technologies have been developed to introduce innovative experience of collaborative science learning (Cole & Stanton, 2003; Colella, 2000).

AR is an emerging interactive medium whereby virtual graphics overlay physical objects in the real world in real time. More recently, an increasing amount of explorations have been carried out to apply AR technology for supporting collaborative learning activities, and AR is recognized as a powerful tool to facilitate face-to-face collaborative learning (Kaufmann, Schmalstieg, & Wagner, 2000).

Building on the characteristics of traditional multimedia technology, AR shares the capacity of implementing interactive simulations of scientific phenomena. It can simulate scientific phenomena interactively and allow users to constructively explore abstract knowledge of science subjects by running simulations. Supported by collaborative AR technology, multiple users are able to manipulate three-dimensional objects to do collaborative tasks while interacting with each other in a face-to-face setting. To date, a range of AR-supported scientific simulations have been developed to aid the education of science subjects such as math, physics, and chemistry (Kaufmann et al., 2000; Weghorst, 2003).

Meanwhile, the unique interface of AR possesses the capability to construct a more engaging collaborative learning environment compared to traditional multimedia technologies. Entailing the power of bridging real and virtual environments, AR-supported collaborative learning environments have a mixture of attributes of the virtual reality and the real world, which facilitate to create enriched hybrid learning experience for students in collaboration.

On the one hand, AR reveals great potential for strengthening personal experience of collaborators' by letting them deeply involved in scientific simulations. One of the most significant strengths of virtual reality is providing a more situated learning context that enables individuals to gain first-person experience in learning activities (Avradinis, Vosinakis, & Panayiotopoulos, 2000). Instead of being external agents, users embed themselves in virtual learning environments and engage in knowledge building based on their personal and direct experience instead of the description of knowledge delivered by a third party (Winn, 1993). In the context of AR, despite it does not create a fully immersive virtual environment, virtual objects superimposed on the physical world are still able to exert some similar effects as virtual reality on strengthening personal experience in learning activities (Shelton & Hedley, 2004). Enriched personal experience contributes to individuals' involvement in learning scenarios, and stimulates their interests and motivations for deep learning (Colella, 2000). As noted above, technology-based simulations function as referential resources for encouraging students exploring science phenomena and elaborating on the knowledge based on hands-on experience. However, one limitation of most technology-based simulations is the boundary between the personal experience and the simulation, which makes it difficult for users to take a first-person perspective towards the simulation in the exploratory learning process (Avradinis et al., 2000). People tend to feel that they are only audiences of the simulation rather than an integral part of the simulation scenario. The subjective linkage between users and simulated scenarios is weak, which may reduce their involvements in the learning practices. In the context of collaborative learning, individuals' subjective tie with the simulated setting can affect their engagement of exploring scientific knowledge (Colella, 2000). Incorporating virtual reality into learning practices provides a well-suited context to address this constraint of traditional multimedia technology and strengthen learners' subjective participatory sense in learning scenarios. Recognized the salient role of the sense of subjectivity in constructing mutual understanding in collaborative learning, Suthers (2006) suggested that the mediating role of technologies in reflecting subjectivity in the learning process should be considered in future design. He also proposed the term of "reflector of subjectivity" to describe the opportunities offered by technologies to foster the development of mutual understanding of knowledge in collaborative learning (p.328).

On the other hand, compared to collaboration in fully immersive virtual reality where individuals participate in communication in a virtual-mediated manner, collaboration supported by AR technology allows people to synchronously interact with each other in real world, which has positive effects on exchanging ideas and reflecting on simulations. The face-to-face communication channel makes it easy and convenient for collaborators to elaborate on prior simulations and develop deeper understanding of the scientific principle underlying the simulations. Colella (2000) clarified that the primary benefit of strengthened personal experience in collaboration is not to let collaborators attain immersive learning experience, but to motivate them to constructively analyze the situation and the underlying principles at the stage followed with the immersive experience. Hence, collaborators' social interaction in face-to-face situation contributes to the realization of facilitation effects of strong subjective tie between personal experience and learning scenarios in enhancing their engagement to explore scientific knowledge.

Combining the advantages of virtual reality in fostering personal experience and the significant role of face-to-face interaction in providing natural means for elaborating on the situation in collaborative learning, AR demonstrates as a promising interface to promote the subjective tie between learning experience and simulation scenarios, and transform deep personal involvement to high engagement of social interaction. So, it is plausible to assume that AR-supported simulations can provide unique opportunities for supporting mutual engagement of social interaction in collaborative learning compared with traditional multimedia technologies. Specifically, AR-supported simulations show great potential for increasing the use of patterns of social interaction high in mutuality and reducing the use of patterns of social interaction low in mutuality.

Evaluating the effectiveness of AR technology in collaboration has become an integral area in AR research (Billinghurst, 2008). To better understand the value of AR technology for supporting collaborative learning, more recent research were dedicated to measuring the effectiveness of collaborative AR applications and the findings indicated that AR technology has positive effects on learning experiences (Cole & Stanton, 2003; Klopfer, Perry, Squire, & Jan, 2005). However, most of the studies relied on learning outcomes or subjective measurements of learning experience to assess the effectiveness of AR-supported collaboration (Costabile, De Angeli, Lanzilotti, Ardito, Buono, Pederson, 2008; Wagner, Schmalstieg, & Billinghurst, 2006). Very few studies have evaluated the mediating effects of AR technology on enhancing social interaction in collaborative learning. The understanding about the influence of AR technology on the enhancement of social interaction in collaborative learning is limited. For example, Klopfer et al. (2005) used descriptive qualitative analysis to examine social interaction in a co-located role play educational game supported by AR technology. They found that the application could encourage users sharing information with each other and actively solving the problem together. However, no comparison was made between AR and other interfaces to indicate the superiority of AR technology in supporting social interaction in collaborative learning. Besides incorporating basic features of traditional technologies to facilitate certain activities, emerging technologies should provide additional features to overcome the constraints of traditional technology and enhance the effectiveness of technology to support the activities. AR serves as a relatively new medium in the field of CSCL. Identifying the unique advantages of AR interface compared with traditional multimedia interfaces is significant to further promote the usage of AR in collaborative learning. Since the effectiveness of technologies in supporting social interaction is important to build a successful CSCL environment, it is necessary to examine how AR affects social interaction in collaborative learning.

Thus, AR technology demonstrates great potential for extending collaborative learning experience for science subject. It is crucial to examine the influences of AR-supported simulation on mutual engagement of social interaction in face-to-face collaborative learning to gain an insight into how AR technology enhances the efficacy of social interaction in face-to-face collaborative learning without simulation support. Augmenting the capability of traditional technologies is a driver for developing new technologies. Besides possessing the benefits of simulation supported by traditional multimedia technologies in collaborative learning, the simulation supported by emerging AR technology should have more advantages for fostering the effectiveness of learning activities. Thus, it is necessary to simultaneously analyze new opportunities offered by AR technology to strengthen mutual engagement of social interaction compared with traditional multimedia technologies.

Based on the review above, two research questions were proposed:

RQ1. What influences does AR-supported simulation have on the equality of engagement of social interaction in face-to-face collaborative learning for physics?

RQ2. What influences does AR-supported simulation have on the mutuality of engagement of social interaction in face-to-face collaborative learning for physics?

In this study, six hypotheses are developed to assist to answer the research questions. All hypotheses are tested based on three conditions of face-to-face collaborative learning for physics, including conditions without simulation tool, with traditional multimedia technology-supported simulation and with AR-supported simulation. For the influence of AR-supported simulation on the equality of engagement of social interaction raised in RQ1, I predicted that:

H1: There are significant differences in the equality of engagement of social interaction in face-to-face collaborative learning for physics across three conditions: (1) without simulation support; (2) with traditional multimedia technology-supported simulation; (3) with AR-supported simulation.

To investigate the influences of AR-supported simulation on the mutuality of engagement of social interaction proposed in RQ2, five hypotheses are developed separately. Elaborations, clarifications, accumulations, acceptances, and rejections/no response are five typical patterns of social interaction featured with different levels of mutuality in the social process of collaborative learning. The use of each pattern of social interaction represents the approach adopted by collaborators to construct mutual understanding of knowledge in collaborative learning. The following hypotheses are proposed to examine the impacts of AR-supported simulation on patterns of social interaction with different levels of mutuality.

H2a: There are significant differences in using elaborations in face-to-face collaborative learning for physics across three conditions: (1) without simulation support; (2) with traditional multimedia technology-supported simulation; (3) with AR-supported simulation.

H2b: There are significant differences in using clarifications in face-to-face collaborative learning for physics across three conditions: (1) without simulation support; (2) with traditional multimedia technology-supported simulation; (3) with AR-supported simulation.

H2c: There are significant differences in using accumulations in face-to-face collaborative learning for physics across three conditions: (1) without simulation support; (2) with traditional multimedia technology-supported simulation; (3) with AR-supported simulation.

H2d: There are significant differences in using acceptances in face-to-face collaborative learning for physics across three conditions: (1) without simulation support; (2) with traditional multimedia technology-supported simulation; (3) with AR-supported simulation.

H2e: There are significant differences in using rejections/no response in face-to-face collaborative learning for physics across three conditions: (1) without simulation support; (2) with traditional multimedia technology-supported simulation; (3) with AR-supported simulation.

Chapter 3 Methodology

In this section, I start by presenting the overall research design of this research. Next, the background information of participants is described. The materials adopted in this research, including the system and the task, are introduced. Then, I outline the procedure of conducting experiments and the approach of analyzing data.

3.1 Research Design

This research seeks to investigate the influences of an AR-supported simulation on two primary dimensions of mutual engagement of social interaction in face-to-face collaborative learning for physics, equality and mutuality of engagement of social interaction.

The experimental design dominating the research tradition of CSCL was adopted in this research (Stahl et al., 2006). The single-factor between-subjects design with three conditions featured by different instructional media was used. Elastic collision, an important phenomenon in the instruction of conservation of momentum in physics of Junior College in Singapore, was chosen as the learning scenario of the collaboration. The collaboration was in the form of face-to-face dyadic discussion. The first condition was normal face-to-face collaborative learning without simulation support, and pairs of students in this condition discussed the question with the support of paper-based instructional material ("Paper-based condition"). In the second condition, a simulation system supported by 2D graphics technology was provided to facilitate the group discussion ("2D-based condition"). In the third condition, a simulation system supported by AR technology was offered to aid the discussion (“AR-based condition”). All participants were divided into two-member groups and then each group was randomly assigned to one of the three conditions. The requirement for being a participant was that he/she had no prior knowledge of elastic collision. Open-ended questions were adopted in the discussion since they could provide more opportunities for motivating collaborators to explore the knowledge.

Three main considerations were given for the experiment design. First, the capability of AR-supported simulation for fostering mutual engagement of social interaction in normal face-to-face collaborative learning for physics should be examined. Promoting the effectiveness of collaborative learning without simulation support is a basic requirement for a simulation tool to meet, so the comparison between the collaboration without simulation support and with the AR-supported simulation was made. Second, it is necessary to analyze the advantages of AR-supported simulation for supporting mutual engagement of social interaction in face-to-face collaborative learning compared to those of traditional technologies. Currently, traditional 2D graphics technology with low cost and low programming complexity is popularly used in simulating scientific phenomena in school instructions to aid students’ understanding of abstract concepts and principles, while AR technology is relatively new for simulating scientific phenomena. In order to promote the widespread use of AR-supported simulation, it is critical to identify the unique value of AR-supported simulation compared to traditional 2D-supported simulations. So, a 2D-based condition was designed to further compare the influences of AR-supported simulation and 2D-supported simulation on mutual engagement of social interaction in face-to-face collaborative learning. Third, experimenting with scientific simulations is commonly used at the initial stage of teaching new knowledge at school. So the participants were required to have little knowledge about the elastic collision and between-subjects design was applied to compare the impacts of different instructional media on mutual engagement of social interaction in collaborative learning.

The whole process of each group's collaboration was videotaped, and the video recordings served as the primary data source for analyzing the social process of collaborative learning. Both quantitative content analysis and conversation analysis of the social process in collaborative learning were adopted in the data analysis. And the influences of AR-supported simulation on mutual engagement of social interaction were investigated by comparing the equality and mutuality of engagement of social interaction in collaborative learning across three experimental conditions.

3.2 Participants

60 undergraduate students from the National University of Singapore participated in this research. The criterion for being a participant was that he/she must have taken Physics as a subject in Secondary School but not taken it in Junior College/Polytechnic. This ensured that the participants had basic knowledge of motion and energy, but did not know about linear momentum and elastic collision. The sample included 44 females and 16 males, whose age ranged from 21 to 27 years old (M=21.98, SD=1.36). All the participants had no experience of using AR technology before. 10 pairs of participants were assigned to each of the three conditions.

3.3 Materials

3.3.1 The systems

A mobile AR system was developed to simulate the phenomena of elastic collision in this research. The software prototype was implemented on HTC Nexus One phone running Android OS 2.2 with a supporting server program on a PC. In the system, computational intensive tasks like marker detection and physics simulation had been offloaded to the dedicated server and then the processed results would be sent back to the mobile phone for 3D graphic rendering and display. The physic engine had been built on the server side to detect the collision between the two virtual objects and response to occurring collision according to the principles of physics. Communication between the server and the client were facilitated by high speed Wi-Fi (IEEE802.11) network and the protocols to enable smooth information exchange.

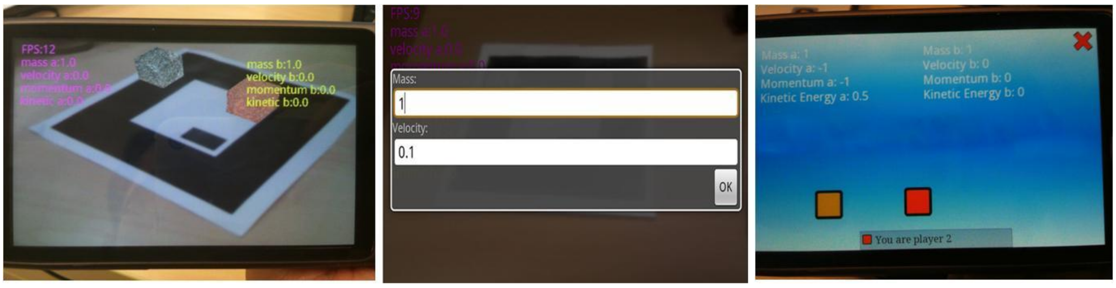
This system can visualize two 3D virtual cubes on a marker and has the capacity of simulating the phenomena of elastic collision in a shared virtual space with mobile phones. Each virtual cube is controlled by one user and the user can freely alter the mass and the initial velocity of the cube that he/she controls through the input surface. The simulation process only starts after receiving the data from both users. The whole collision process is visualized with real-time numerical data of mass, velocity, momentum and kinetic energy of the two objects, which are displayed on the two sides of the screen. In the collaboration process, the two users are free to choose when to use the system and they are allowed to run the simulations as many times as they may need to support their discussion.

In addition, a simulation supported by 2D graphics technology on the same HTC Nexus

One phone was built. To make it a similar architecture to the AR-based simulation, a server was also included in the design. Similarly, each object is controlled by one user and the user can set mass and initial velocity for the object he/she controls. After the program on the server received the information that both users had entered in mobile clients, the simulation would start. Real-time data of mass, velocity, momentum and kinetic energy are also displayed on the two sides of the screen.

In the figure 3.1, the view of the AR-supported simulation, the input interface of the AR-based simulation and the view of the 2D-based simulation were presented (from the left to the right).

Figure 3.1 The views of the AR-supported simulation, the input interface and the 2D-supported simulation



mass a:1.0
velocity a:0.0
momentum a:0.0
kinetic a:0.0

mass b:1.0
velocity b:0.0
momentum b:0.0
kinetic b:0.0

Mass: 1
Velocity: 0.1

Mass a: 1
Velocity a: -1
Momentum a: -1
Kinetic Energy a: 0.5

Mass b: 1
Velocity b: 0
Momentum b: 0
Kinetic Energy b: 0

3.3.2 The task

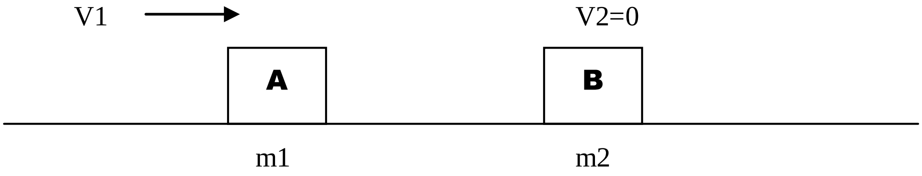
A discussion task related with elastic collision was designed for the two participants in a group to collaboratively work on the problem-solving. The goal of the group discussion was to reach shared understanding on the characteristics of phenomena of elastic collision and the physics principles underlying the mechanism of the phenomena within the group. The questions in the discussion task were as follows:

(1) Under the context that the object B is stationary and the object A moves towards B

(See Figure 3.2), how many kinds of subsequent motions can happen after the elastic collision? And how does the relationship between the masses of two objects influence the subsequent motions of the two objects after the elastic collision?

(2) How do you explain the change of motions of the two objects after elastic collision?

Figure 3.2 The learning scenario of the discussion task



3.4 Procedure

In the experiment, the two participants within a group were first asked to read a set of paper-based instructional material on elastic collision for 15 minutes independently. The material was extracted from the notes prepared by the physics department of a local Junior College. For the group assigned to the paper-based condition, the questions in the discussion task were introduced to the participants in the group right after the individual reading. And they were to discuss the questions only with the support of the instructional material. For the groups assigned to the AR-based or 2D-based condition, the participants were instructed the method of manipulating the systems after the reading. Each group practiced to use the system for several rounds to be familiar with the way of using it. Next, the discussion task was presented to them and they started collaboratively solving the problems required with the simulation support. In all the three experimental conditions, once the two participants in a group had reached an agreement on the answers to the questions, they would submit a discussion summary and the whole experiment ended. The scenarios of the experiments in the paper-based, the 2D-based and the AR-based conditions (from the left to the right) were showed in Figure 3.3.

Figure 3.3 The scenarios of experiments in the three conditions

3.5 Data Analysis

The video recordings of collaborative learning of 30 groups' were transcribed for the analyses of the influences of AR-supported simulation on mutual engagement of social interaction in face-to-face collaborative learning for physics. This research focused on the knowledge-based social interaction in the process of collaborative learning, while procedural interactions for organizing the discussion (e.g. dividing roles for running experiments, managing discussion flow between questions), asking and providing information on setting up the experiments (e.g. initiating a simulation, asking and offering information on setting values before experimenting the simulation) and off-task interactions (e.g. making comments on the technology, expressing personal affairs) were not included in the analyses of mutual engagement of social interaction in collaborative learning.

The data analysis was comprised of two stages. At the first stage, the quantitative content analysis based on the coding scheme was used to specify the general patterns and assess the quality of social interaction in collaborative learning across three conditions. At the second stage, the conversation analysis functioned as a more situated approach to further the illustration of the findings of the quantitative content analysis in the conversation contexts and deepen the understanding of opportunities created by AR-supported simulation to support mutual engagement of social interaction in collaborative learning.

3.5.1 Quantitative content analysis

3.5.1.1 Mutual engagement of social interaction

Interaction sequences, described as episodes of conversation with the same level of content focus in the social process of collaborative learning, functioned as contexts to examine mutual engagement of social interaction in collaborative learning in this research. In collaborative learning, the interaction sequence was formed when one person in the group initiates a new level of content focus in the conversation and the other person must give a response at the same level of focus. Then a subset of verbal exchanges might take place at the same level of content focus in the group, which in turn led to further development of the interaction sequence. The interaction sequence ended when one person in the group shifted the level of content focus by making a request for new information or presenting information at a new level of content focus instead of directly building on the prior statement. Therefore, each interaction sequence was comprised of an initiating statement that controlled the conversation direction and a series of development statements that extended the initiation at the same level of content focus. According to the conceptualization of mutual engagement of social interaction in peer collaboration proposed by Damon and Phelps (1989), the degree of variation of the number of initiating statements made by two collaborators and the approaches of constructing development statements following the initiating statement were primary indicators of the equality and mutuality of engagement of social interaction in collaborative learning.

In this research context, initiating statements referred to presenting a statement or asking a question at a new level of content focus in the process of collaborative learning, while development statements were those following up the initiating statement and extended the discussion centering upon the same content focus. The content focuses could be different aspects related with elastic collision, for example, describing one possible results of elastic collision, interpreting the mechanism underlying the elastic collision, predicting possible results of elastic collision, summarizing the findings, etc.

Measures of equality of engagement of social interaction

The equality of engagement of social interaction was examined based on the degree of equality on controlling over the direction of conversation for problem-solving. The number of initiating statements made by each participant in a group was counted, and the equality of engagement of social interaction was measured by the standard deviation of the amount of initiating statements engaged by each participant in the social process of collaborative learning to represent the degree of variation between the number of initiating statements expressed by the two collaborators (referring as “equality index”). The higher the standard deviation was, the lower level of the equality was (Jahng, Nielsen, & Chan, 2010). Then, the average equality index of all groups in each condition was calculated. One-way, between-groups ANOVA and post-hoc comparisons were used to test the differences in average equality index across three conditions to identify the impacts of AR-supported simulation on the equality of engagement of social interaction in collaborative learning.

Measures of mutuality of engagement of social interaction

In order to gain an insight into the characteristics of mutuality of engagement of social interaction in collaborative learning, communicative functions of development statements were analyzed on the basis of the coding scheme developed by Barron (2000) and modified for this research (See Table 3.1). Five mutually exclusive categories of development statements were defined, including elaborations, clarifications, accumulations, acceptances and rejections/no responses. They were analyzed at the level of utterance that was defined as the statement with single communicative function made by one person (Visschers-Pleijers, Dolmans, De Leng, Wolfhagen, & Van der Vleuten, 2006). These categories could facilitate to identify patterns of social interaction with different levels of mutuality, which were beneficial for assessing the effectiveness of AR-supported simulation for supporting mutual engagement of social interaction in face-to-face collaborative learning for physics.

Elaborations included developing the prior statement by offering an alternative explanation, disagreeing with the statement and providing logical justifications, modifying the prior statement with reasonable argumentation, or proposing a hypothesis to interpret the prior statement. They were perceived as the development statements with high mutuality to effectively construct mutual understanding. The person did not only positively build upon the prior statement expressed by the partner, but also presented critical viewpoints towards the prior statement for further meaning negotiation.

Clarifications referred to responses that requested for more information, explanation or verification in relation to the prior statement at the same level of content focus. They were also characterized by high mutuality. The person needed to actively seek to deepen the mutual understanding after integrating the meaning of the knowledge expressed by the partner with his/her prior understanding.

Accumulations were responses that accepted the prior statement and offered additional supportive information as warrant or took up the prior request and provided an answer to it. They played an important role in accumulating common grounds between the collaborators. But compared to elaborations and clarifications, the mutuality of accumulations was lower since less exploratory thinking was involved in the statements.

Acceptances included showing simple agreements with the prior statement, such as “Yea.”, “Ok.”, “Yes, I think it’s right.”, or just repeating the prior statement expressed by his/her partner. Although they contributed to reaching agreement rapidly, they were low in meaning richness, which made the development of mutual understanding less constructive. Hence, the mutuality of acceptances was lower than accumulations.

Rejections/no response included simply rejecting the prior statement without giving any reasons or ignoring the other’s initiating statement or the prior clarification. The responses that made no substantive contribution to the conversation such as “I don’t know” and “I’m not sure” also fell into this category. Featured by less reciprocity, this type of statements hindered the construction of mutual understanding and was the lowest in mutuality of engagement of social interaction.

Table 3.1 Coding scheme for knowledge-based social interaction

Category	**Description**
Initiating statements	Initiated a new level of content focus in the conversation to direct the interaction flow, including requesting for information and presenting a statement at a new level of content focus
Development statements	A person's response to the prior statement at the same level of content focus
Elaborations	Developed the prior statement by providing an alternative explanation; disagreed with or modified the prior statement with rationales; proposed a hypothesis to interpret the prior statement
Clarifications	Requested for more information, explanation, verification in relation to the prior statement
Accumulations	Accepted the prior statement and offer additional information as warrant; took up the prior request and provide an answer to it
Acceptances	Simply agreed with the prior statement; repeat the prior statement
Rejections/no responses	Rejected the prior statement without giving any reasons; ignored the prior initiating statement or the clarification within an interaction sequence; non-substantive responses

Regarding the evaluation of the mutuality of engagement of social interaction in collaborative learning, the occurrences of five categories of development statements within a group were firstly counted. Then, the proportion of each category of development statements in the group was derived by dividing the frequency of each category of development statements by the overall amount of development statements in the social process of collaborative learning. The average percentage of each category of development statements of all groups in each condition was calculated. The assumption of one-way ANOVA was not met when comparing the percentage with different denominators. So, to identify the impacts of AR-supported simulation on the mutuality of engagement of social interaction in collaborative learning, nonparametric Kruskall-Wallis tests were used to test the differences in the average percentage of each category of development statements across three experimental conditions and Mann-Whitney tests were applied for pairwise comparisons.

3.5.1.2 Inter-coder reliability

The inter-coder reliability of classifying communicative functions of knowledge-based social interaction was tested in this research. 12 transcripts (40% of all transcripts) were randomly selected from the overall 30 transcripts, and two independent coders identified the communicative functions of knowledge-based social interaction in each transcript according to the coding scheme. The inter-coder reliability (Cohen’s kappa) was 0.793, which showed a substantial agreement.

3.5.2 Conversation analysis

Conversation analysis of social interaction in collaborative learning is identified as a useful way to better interpret the reasons that result in the variability of patterns of social interaction across different situations found in the quantitative analysis (Barron, 2003). In this research, in addition to comparing mutual engagement of social interaction on the basis of quantitative content analysis, the conversation analysis of the social process in collaborative learning was applied. Through contextualizing the situations when collaborators initiated a new focus in the conversation and adopted patterns of social interaction with different levels of mutuality, it helped to explore the reasons that related to the differences in the equality and mutuality of engagement of social interaction across three conditions.

In the conversation analysis, interaction sequences maintained the contexts for evaluating the influences of AR-supported simulation on mutual engagement of social interaction in face-to-face collaborative learning. Initiating statements and development statements with different levels of mutuality proposed in the quantitative content analysis served as primary discourse events when analyzing sequential evolution of collaborators' negotiation of meaning. Also, the content of knowledge-based social interaction for constructing shared understanding of elastic collision was examined. Two main categories of content were identified. One was describing the surface phenomena of elastic collision, such as the masses of the two objects and the velocities of the two objects before and after elastic collision. The other was explaining the underlying mechanism underlying the phenomena, mainly including applying the concepts and principles in the instructional material or life experience to illustrate the change of motions before and after the collision. Specifically, the attention was paid to the way that collaborators integrated the experience of manipulating simulations with the social process in the 2D-based and AR-based conditions for building mutual understanding, which included the language used to describe and reflect on the simulation scenarios during the discussion.

By situating the occurrences of initiating statements and development statements featured by different levels of mutuality in the context of interaction flow and using simulation support, I attempted to examine how the differences in mutual engagement social interaction emerged during meaning negotiation among three conditions and capture typical examples to interpret the challenges and opportunities that resulted in different levels of mutual engagement of social interaction to build mutual understanding in collaborative learning.

Chapter 4 Results

The results of data analyses are presented in the following two sections. In the first section, the differences of the equality and mutuality of engagement of social interaction in collaborative learning across three experimental conditions in the quantitative analysis are compared through testing the hypotheses proposed in this research. Based on those significant influences exerted by the AR-supported simulation in the first section, in the second section, representative episodes of conversation in three conditions are analyzed to provide more detailed evidence on how the AR-supported simulation impacts mutual engagement of social interaction in face-to-face collaborative learning for physics.

4.1 Quantitative Analyses of the Influences of AR Technology on Social Interaction

In this part, the influences of AR-supported simulation on the equality of engagement of social interaction are quantitatively analyzed at first. Then I focus on the mutuality of engagement of social interaction and compare patterns of social interaction across three experimental conditions.

4.1.1 Equality of engagement of social interaction

The equality of engagement of social interaction was measured by the level of equality on controlling over the direction of social interaction flow. Initiating statements indicated the change of direction of social interaction in collaborative learning, and the number of initiating statements made by each person represented his/her control of the direction. Equality index, the standard deviation of the amount of initiating statements generated by each person in a group, was used to assess the degree of variation between the amounts of initiating statements made by two collaborators, which represented the level of equality on controlling over the task. Then the average equality index of groups in each condition was gotten for further comparison across three conditions. The equality index with a bigger number meant that there was a large variation between the amounts of initiating statements made by two collaborators, indicating the level of equality of engagement of social interaction was lower.

The average equality index of two students within the groups in the paper-based condition (5.59) was much bigger than those in the 2D-based condition (2.12) and the AR-based condition (1.56) (See Table 4.1). Thus, the equality of engagement of social interaction in the AR-based condition was the highest, which was followed by those in the 2D-based condition and the paper-based condition.

The difference in the level of the equality of engagement of social interaction in collaborative learning across three conditions was significant ($F(2, 27) = 5.733$, $p<0.01$). The post-hoc comparisons showed that the differences between the paper-based condition and the other two conditions were significant. However, there was no significant difference between the AR-based and the 2D-based conditions. Therefore, H1 about the differences in the equality of engagement of social interaction in collaborative learning for physics across three conditions was partially supported.

The AR-supported simulation had the capacity of significantly increasing the equality of engagement of social interaction in face-to-face collaborative learning only with the support of paper-based instructional materials, but no significant enhancement was found by comparing the levels of the equality in collaboration with the AR-supported simulation and the 2D-supported simulation.

Table 4.1 Mean (SD) results for equality index

	Paper-based (SD)	2D-based (SD)	AR-based (SD)
Equality	5.59 (4.74)	2.12 (1.15)	1.56 (1.04)

4.1.2 Mutuality of engagement of social interaction

The patterns of development statements with different levels of mutuality were analyzed to characterize the mutuality of engagement of social interaction in collaborative learning. They were classified into five categories, including elaborations, clarifications, accumulations, acceptances and rejections/no response. The average percentage of each category of development statement in each condition was gained to provide an overview of the distribution of five categories of development statements in three experimental conditions. Furthermore, the difference in the average percentage of each category of statements across three conditions was tested to assess the influences of AR-supported simulation on patterns of social interaction with different levels of mutuality (See Table 4.2).

In the paper-based condition, the average percentage of acceptances (40.0%) was the highest one, which was followed by those of accumulations (26.5%), clarifications (17.5%), rejections/no response (9.2%) and elaborations (6.8%).

In the 2D-based condition, the average percentage of accumulations was 40.7%, ranking the first place among five categories of development statements. The second one was acceptances, with an average percentage of 29.0%. The average percentages of clarifications, elaborations and rejections/no response were 15.4%, 12.0% and 2.9%.

In the AR-based condition, the average percentage of accumulations (43.3%) ranked first among five categories of development statements, followed by those of acceptances (20.4%), elaborations (18.5%) and clarifications (17.0%). The average percentage of rejections/no response was 0.8%.

Table 4.2 Average percentages of five categories of development statements

	Paper-based	2D-based	AR-based
Elaborations	6.8%	12.0%	18.5%
Clarifications	17.5%	15.4%	17.0%
Accumulations	26.5%	40.7%	43.3%
Acceptances	40.0%	29.0%	20.4%
Rejections/no response	9.2%	2.9%	0.8%
Total	100.0%	100.0%	100.0%

Comparisons of five categories of development statements among three conditions were made to illustrate the influences of AR-supported simulation on the mutuality of engagement of social interaction in face-to-face collaborative learning for physics.

As for elaborations, the average percentage was 18.5% in the AR-based condition, followed by those in the 2D-based condition (12.0%) and the paper-based condition (6.8%). The difference in the average percentage of elaborations in the social process of collaborative learning across three conditions was significant (df=2, H=17.255, $p<0.001$). The Mann-Whitney tests also showed all three conditions were significantly different. So, the hypothesis about the significant differences in the average percentage of elaborations in face-to-face collaborative learning for physics across three conditions was supported. With the assistance of AR-supported simulation, the collaborators engaged in more critical but constructive elaborations when building shared understanding of the knowledge compared with those in the 2D-based condition, and groups in both AR-based and 2D-based conditions engaged in more elaborations than those in the paper-based condition.

The average percentages of clarifications were 17.5%, 15.4% and 17.0% in the paper-based, the 2D-based and the AR-based conditions. No significant difference was found in the average percentage of clarifications in the social process of collaborative learning across three conditions. Thus, H2b about the significant differences in the average percentage of clarifications in face-to-face collaborative learning for physics across three conditions was not supported.

The average percentages of accumulations were 40.7% and 43.3% in the 2D-based and the AR-based conditions respectively, whereas it was relatively lower in the paper-based condition (26.5%). There were significant differences in the average percentage of accumulations in social interaction in collaborative learning across three conditions (df=2, H=17.950, $p<0.001$). The Mann-Whitney tests revealed that significant differences between the paper-based condition and the other two conditions, but no difference was found between the 2D-based and the AR-based conditions. H2c about the significant differences in the average percentage of accumulations in face-to-face collaborative learning across three conditions was partially supported. The collaborators with the support of simulation tools were inclined to offer additional information when positively building upon the prior statement compared to those in the paper-based condition, but the impacts between the AR-supported and the 2D-supported simulations were relatively similar.

The average percentage of acceptances in the paper-based condition was 40.0%, which was much higher than that in the 2D-based condition (29.0%) and the AR-based condition (20.4%). The average percentages of acceptances in the social interaction in collaborative learning across three conditions were statistically different (df=2, H=15.522, p<0.001). The Mann-Whitney tests demonstrated that all three conditions were significantly different. H2d about the significant differences in the average percentage of acceptances in face-to-face collaborative learning for physics across three conditions was supported. The collaborators in the paper-based condition tended to use more minimal positive acknowledgements or simple repetitions in collaborative learning, whereas the technology-based simulations enabled to significantly reduce the percentage of acceptances and the influence of the AR-supported simulation was significantly greater than those of the 2D-supported simulation.

The average percentage of rejections/no response was 9.2% in the paper-based condition, which was much higher than those in the 2D-based condition (2.9%) and the AR-based condition (0.8%). There were significant differences in the average percentage of rejections/no responses in the social process across three conditions (df=2, H=16.630, p<0.001). The Mann-Whitney tests showed that the average percentage of rejections/no responses in the paper-based condition was significantly higher than those in the AR-based and the 2D-based conditions, but there was no difference between the AR-based and the 2D-based conditions. So, H2e about the significant differences in the average percentage of rejections/no response in face-to-face collaborative learning for physics across three conditions was partially supported. The AR-supported simulation had the capacity of encouraging collaborators constructively negotiating meaning with each other instead of simply rejecting or ignoring the prior statement in collaborative learning, however, it was quite similar with the capacity of the 2D-supported simulation.

In sum, the AR-supported simulation could significantly foster the equality of engagement of social interaction in face-to-face collaborative learning for physics without simulation support, but its influence was not significantly different from that of 2D-supported simulation. Both AR-supported simulation and 2D-supported simulation had significant effects on increasing the use of elaborations and accumulations and reducing the use of acceptances and rejections/no response in face-to-face collaborative learning for physics without simulation support, and the AR-supported simulation could significantly enhance the effects on elaborations and acceptances compared to the 2D-supported simulation. But the influence of AR-supported simulation on accumulations and rejections/no response was not significantly different from that of 2D-supported simulation. And there were no differences in the use of clarifications among collaborative learning without simulation support, with the 2D-supported simulation and with the AR-supported simulation. So, the AR-supported simulation did not only keep the affordances of 2D-supported simulation for promoting the equality of engagement of social interaction and increasing accumulations and elaborations, and decreasing simple acceptances and rejections/no response in face-to-face collaborative learning for physics, but also possessed capabilities for furthering the enhancements of the 2D-supported simulation in some aspects of mutuality of engagement of social interaction in collaboration, including elaborations and acceptances.

4.2 Qualitative Analyses of the Influences of AR technology on Social Interaction

In this section, the qualitative analysis of selected episodes from conversations in collaborative learning are presented to exemplify the features of social interaction across three conditions and contextualize the opportunities provided by AR-supported simulation to enhance mutual engagement of social interaction in face-to-face collaborative learning for physics. At the beginning, the challenges for mutual engagement of social interaction in collaborative learning without simulation support are presented to explain the reasons that result in low level of equality and mutuality of engagement of social interaction. Next, I analyze the characteristics of mutual engagement of social interaction in the 2D-based condition to address the capabilities and challenges of 2D-supported simulation for strengthening mutual engagement of social interaction. Third, I present the unique opportunities created by AR-supported simulation for promoting mutual engagement of social interaction in collaborative learning.

4.2.1 Challenges for mutual engagement of social interaction in collaboration without simulation support

In order to address the opportunities provided by AR-supported simulation for supporting mutual engagement of social interaction in collaborative learning, it is significant to firstly identify the challenges for the collaborators' mutual engagement in learning activities without simulation support. The differences in the approach of building shared understanding of knowledge in the social process could be found between collaborations with and without the support of technology-based simulation. Within the context of collaborative learning without simulation support, less reciprocal efforts in co-constructing knowledge negatively affected the joint problem-solving in collaborative learning.

Compared with the groups in the AR-based and the 2D-based conditions, those in the paper-based condition were lower in the equality and mutuality of engagement of social interaction in collaborative learning. The imbalance in controlling over the discussion direction between the two collaborators and less engagement of building upon each other's ideas posted challenges for the group to negotiate meaning together for building shared understanding of the knowledge in collaborative learning.

"Initiating statement-acceptance/no response-initiating statement" was a typical pattern of conversation in the paper-based condition that deterred the level of mutual engagement of social interaction. One person raised a content focus in the conversation, and the other person usually acknowledged the statement without giving more constructive information to the discussion or just ignored the statement. Then, the first person was forced to generate a statement to invite his/her partner to join the conversation. The new initiative could be either at a different level of the previous focus in his/her last turn or a completely new focus, which marked the beginning of a new interaction sequence. So, one person took the leading role in controlling over the task, whilst the other was passively involved with the conversation. Meanwhile, the interaction sequence was characterized with short length due to the lack of commitment of building upon what the other had said. The following episode from a group in the paper-based condition could reflect this pattern of interaction in collaborative learning. The two collaborators, Gladys and Lin, engaged in predicting the number of subsequent motions of the two objects after elastic collision at the beginning of the discussion.

1. Gladys: They move together or A moves back [after the elastic collision].
2. Lin: Uh-huh.
3. Gladys: We can assume the mass.
4. Lin: Ok.
5. Gladys: Move back or move together?
6. Lin: I think they will move together.
7. Gladys: Ok.
8. Lin: [What about the] Direction and speed [of the two objects]?
9. Gladys: The kinetic energy is the same and we can calculate the velocity.
10. Lin: Uh-huh.
11. Gladys: I think [the speed of] A will decrease.
12. Lin: Uh-huh.
13. Gladys: Can it be faster?
14. Lin: No.
15. Gladys: Speed of B increases?
16. Lin: Yes.

Gladys opened the conversation through presenting two possibilities of subsequent motions of the two objects, and Lin minimally acknowledged her partner’s proposal. Then Gladys introduced a new focus on exploring the impacts of mass on the change of motion after elastic collision, but it was still simply responded by her partner. Next, Gladys made a request to elicit Lin’s idea on the possibility of the subsequent motions. Lin took up the proposal and gave an option without explaining more about it. In turn 8, Lin generated her first initiating statement in the conversation to ask more details on the change of motions of the two objects. Gladys showed her idea, and Lin simply agreed with it. In the rest of the episode, Gladys generated three initiating statements on predicting the change of speeds of the two objects at different levels of focus (turns 11, 13, 15). But Lin gave minimal responses to these three initiatives. In this context, Gladys played a dominant role in leading the discussion, while Lin passively performed. Although the acceptances allowed collaborators to reach consensus in a quick way, the insufficient meaning negotiation caused by the lack of mutual commitment made it difficult for them to jointly constructing shared understanding of the knowledge at a high level.

This pattern of interaction was more obvious when explaining the underlying mechanism resulting in the change of motions of the two objects after elastic collision in the discussion. The two collaborators of another group in the paper-based condition, Chong and Alice, attempted to interpret the principles underlying the phenomenon after predicting three possible outcomes of elastic collision in the following episode.

1. Chong: The kinetic energy of A is transferred to B.
2. Alice: Yes.
3. Chong: So A is not moving.
4. Alice: Yes.
5. Chong: Total kinetic energy?
6. Alice: Yes, all energy.
7. Chong: In the second scenario, partially transferred? They are still moving [after the collision].
8. Alice: Yea, both moving.
9. Chong: Then the third scenario will be not transferred, isn't it?
(No response from Alice)
10. Chong: The second one is partially, right?
11. Alice: Yes, it is partially.
12. Chong: The third one is no transfer of energy because B doesn't move and A is

moving back.

13. Alice: Uh-huh.

14. Chong: Something else?

15. Alice: No.

Chong explained the underlying principle of the first possible outcome after elastic collision characterized by the object A stopping and object B moving forward from the perspective of energy transfer in the initiating statement, and Alice simply accepted Chong's explanation. Chong then added the result of the first scenario as a warrant to support the interpretation based on the energy transfer and Alice positively acknowledged it. In the next turn, Chong initiated a statement through requesting verification from Alice, and Alice still simply responded to it without providing more explanations to support her position. In turns 9-11, Chong adopted similar strategies to make initiating statements, presenting her own explanations on different possible outcomes in questions to ask for Alice's ideas. However, Alice gave simple acknowledgement to the questions or ignored it. At the end, Chong posed an open question to check whether her partner expected to elaborate more on the problem, but Alice directly rejected it.

In the above two examples, the dominant people tried to invite the partners to be involved in the conversation and the asymmetric interaction was caused by less effort spent in engaging exploratory activities of the passive partners. The conversation was characterized by high frequency of simple acceptances since the passive person mostly responded to the other's statement by minimal positive acknowledgements. No response to the previous question also occasionally occurred in the course of conversation.

Without simulation support, another style of asymmetric talk featured with low equality and mutuality could be generated as one person concentrated on expressing his/her ideas and there were few chances for the other to claim his/her opinion. In the following episode, the two collaborators in the paper-based condition, Ling and Sim, attempted to explain the reasons for the change of motions of the two objects after elastic collision.

(Ling wrote down the equation of conservation of momentum)

1. Sim: Could you explain these?

2. Ling: Ok. This is the equation of conservation of momentum. V1 and v2 are initial velocity, and u1 and u2 are velocity after the collision.

3. Sim: Ok.

4. Ling: If the right direction is positive, then we can get this equation. I make some rearrangements and get these equations. So if m1 is bigger than m2, I guess the velocity after the collision should be bigger than v1.

5. Sim: Uh-huh.

6. Ling: A should move to the right and B should also move to the right.

7. Sim: Also, I think the kinetic energy should be the same.

(Ling wrote down equations and did calculations by herself, while Sim read the instructional material.)

8. Ling: So anyway we have v1+u1=u2+v2. Can you follow me?

(Sim continued reading the instructional material herself and did not respond to Ling’s question)

9. Ling: So we’ve already got this one. This is the equation of conservation of kinetic energy. I made some rearrangements and got this.

(Ling explained the equations while continued calculating.)

10. Sim: I think since A moves to this direction and B is at rest [at first], the force of collision makes some energy of A be transferred to B.

11. Ling: Yeah.

12. Sim: So B will move forwards and A will also move in the same direction.

13. Ling: Anyway, it can be proved by equations.

After reading the question 2 in the discussion task, Ling wrote down the formula of conservation of momentum on the paper without communicating with Sim. Sim opened the conversation through requesting for an explanation of the formula from Ling. Ling explained the variables in the formula to Sim. After Sim acknowledged her explanation, Ling started clarifying her understanding of the formula and tried to use it to interpret the change of motion after the collision based on her mathematical calculations, and Sim minimally accepted Ling's explanation (turns 4-5). Through turns 6-7, Ling did some calculations on the basis of the formulas and stated her thoughts at the same time, but Sim began reading the instructional material herself without reacting to Ling's proposals. At the end of turn 8, Ling asked "can you follow me?" to confirm whether Sim understood her idea instead of inviting her partner to explain the phenomena in a collaborative manner. Sim did not respond. Then Ling continued working on her calculations and attempted to explain the calculation process to Sim. In turn 10, rather than build thoughts on Ling's statement, Sim expressed her understanding for interpreting the change of motions of the two objects after the elastic collision from the perspective of energy transfer. Ling simply agreed with it. Then Sim took up Ling's agreement and added some supportive information to complete her explanation. Instead of furthering Sim's statement, Ling showed little concern to it and insisted that her explanation based on the calculation better served for solving the problem and closed the whole discussion. In a summary, Ling focused the attention on explaining her understanding of the knowledge and made fewer attempts to jointly negotiate meaning with her partner. At the same time, the dominant role took by Ling made Sim become passive-oriented in the process of collaboration, which had detrimental effects on mutual engagement of social interaction in collaborative learning. Generally, the social process was low in equality and mutuality of engagement of social interaction.

Meanwhile, instead of collaboratively negotiating the contradictory understanding of the knowledge for developing consensus, the collaborators tended to use negative answers or ignore the conflicts in the social process. The collaborators in another group, Khanh and Amylia, in the following episode engaged in explaining why elastic collision took place. Before this, Khanh and Amylia had predicted three possibilities of elastic collision to answer the question 1, and Amylia set values of mass and initial velocity for two objects (m1=m2=2, u1=0.2, u2=0) and obtained the velocities of two objects after the collision through calculations (v1=0, v2=0.2).

1. Amylia: The total momentum before and after [the collision] is the same.
2. Khanh: Uh-huh.
3. Amylia: So it means that this one totally transferred the momentum to this one.
4. Khanh: No, it can’t be totally transferred.
5. Amylia: In this case, it is totally transferred.
6. Khanh: Because this is a special case.
7. Amylia: What do you mean “special”? Because masses are same?
8. Khanh: I have no idea.

(There was a silence for about 10 seconds)

9. Amylia: This is the value of v1 and this is v2.
10. Khanh: So there are three scenarios because we don’t have exact numbers.
11. Amylia: Um…In this case, v2 equals to 0.2.
12. Khanh: Hmm?
13. Amylia: Because we set u1 0.2 and u2 0.
14. Khanh: But this is a very special case because masses are equal.
15. Amylia: I think the equal mass will affect…If we don’t know v1, how we can

know/

16. Khanh: //But what do you want to know now?

17. Amylia: I want to know why this one totally stops and the momentum is totally transferred to this object.

18. Khanh: In this formula, [it is] the conservation of momentum.

19. Amylia: But we only have this one.

20. Khanh: Yea, never mind.

21. Amylia: Our case is the perfect collision, right?

22. Khanh: Uh-huh.

23. Amylia: So we can use these numbers.

24. Khanh: But you just put the number in the formula.

25. Amylia: Actually, if it likes that, we still don't have the answer.

26. Khanh: So what is your answer?

27. Amylia: The answer is v2 equals 0.2.

28. Khanh: But it is a very specific number, and this question asks us to explain something general based on principles.

(Khanh started writing something on the paper, while Amylia read the material.)

29. Khanh: This means that there will be a reduction in the momentum of A compared to before collision. It causes A to move slower to the right, to stop or to move in the opposite direction.

30. Amylia: But the total momentum is still conserved?

31. Khanh: Correct.

Amylia initiated the conversation by stating the conservation of momentum in elastic collision. After Khanh minimally acknowledged it, Amylia took up the agreement and came to a conclusion that all the momentum of the object A was transferred to the object B after the elastic collision based on her previous calculation under the condition that two objects had the same mass. Then Khanh directly rejected it and contended that it was a "special" case, but Amylia insisted that her idea be suitable for answering to the question. Instead of trying to reach shared understanding on the meaning of “special”, Khanh closed this interaction sequence with “I have no idea”. After a silence for about 10 seconds, Amylia continued attempting to explain her case to Khanh, while Khanh still persisted that it was inappropriate to apply that case to interpret the phenomenon (turns 9-14). The conflict between them became more and more salient as the conversation progressed. Amylia highlighted that the equal mass could be a factor influencing the change of motions and tried to argue the importance of knowing the value of v2. Without waiting for Amylia to complete her sentence, Khanh interrupted her and posed a rhetorical question: “but what do you want to know now?” in an unfriendly way. Amylia responded to Khanh’s query but Khanh ignored it and raised a new level of focus to point out that the formula itself could reveal the conservation of momentum. Amylia thought that it was not enough to use a single formula to explain the phenomenon but Khanh did not care about Amylia’s idea through saying “never mind” (turns 19-20). While Amylia continued carrying out her explanation (turns 21-25), Khanh presented a rhetorical question again to request Amylia to interpret the meaning of “answer” in her statement (turns 26-28). Rather than communicate her thoughts with Amylia, Khanh gave up the negotiation and started writing down her explanation on the paper, whilst Amylia read the instructional material herself. After Khanh finished writing her explanation, she read it to Amylia (turn 29). Amylia made a request on the conversation of momentum based on Khanh’s statement. Khanh agreed with it and ended the discussion. In the whole episode, the two collaborators persisted in holding their own viewpoints and showed few mutual concerns in further exploring each other’s understanding and resolving the discrepancies in their viewpoints.

To summarize, under the condition without simulation support, the challenges for mutual engagement of social interaction in collaborative physics learning could be evidenced by the lack of establishment and development of shared focus in the process of meaning negotiation. The unequal participation in generating statements to direct the conversation and insufficient initiatives in mutually engaging in each other’s statement needed to be addressed in order to promote the effectiveness of face-to-face collaborative learning.

4.2.2 Traditional technology-supported simulations and the characteristics of mutual engagement of social interaction

The 2D-supported simulation provided opportunities for enhancing mutual engagement of social interaction in face-to-face collaborative learning for physics without simulation support. The process of collaboratively running simulations of elastic collision facilitated the collaborators to develop shared understanding of scientific phenomenon. But limited willingness of sharing simulation outcomes after running a round of simulation hindered the collaborators to engage in critical elaborations in the 2D-based condition.

In the following episode, the collaborators with the simulation supported by 2D graphics technology jointly explored the possibilities of subsequent motions of elastic collision through setting different values for the masses of the two objects and the initial velocity of the object A.

1. Ang: We can set the same mass.
2. Dasen: It never says we have to assume the relationship between masses. The first one is that both of them have equal mass, and another one is that they have different masses.
3. Ang: Ok.

4. Dasen: We put [the same] mass 5. And your velocity is 0. My velocity is 3.

(Observe the simulation)

5. Dasen: When they have the same mass, after A hits B, A will be stationary and B continues to move at a specific velocity.

6. Ang: Ok. A moves at first, right?

7. Dasen: Yes, then A stops and B continues to move because of the momentum. So let’s see we have different mass.

8. Ang: Ok.

9. Dasen: Just now we were 5 and 5. So now mine is 5 and you can put something larger.

10. Ang: Ok.

11. Dasen: My velocity is still 3.

12. Ang: Mine is still 0.

(Observe the simulation)

13. Ang: It still moves in the same direction. A bounces and then goes backwards. Just now it didn’t move.

14. Dasen: I don’t think so. Maybe not as much…

15. Ang: Not as much as this one?

(No response from Dasen)

16. Ang: It means that because my object is heavier than yours, so that is another kind/

17. Dasen: //Do you want to try double mass?

18. Ang: Ok.

(Observe the simulation)

19. Ang: It’s the same, right? If A is heavier, the result is the same.

20. Dasen: Yea, but the distances they move are different.

21. Ang: Subsequent motions…So motion is either/

22. Dasen: //When A hits B, B continues moving if masses are equal. B moves in the direction of A and A will be stationary.

23. Ang: Uh-huh. Is it possible that this thing is so heavier that it remains stationary

and A bounces back?

24. Dasen: Maybe we can try.

(Observe the simulation)

25. Ang: Still moves.

26. Dasen: It still moves, but I think if it is really really heavy, it won't move at all.

27. Ang: Can we try 1000?

28. Dasen: Yea.

(Observe the simulation)

29. Dasen: It's a bit.

30. Ang: Just a bit.

31. Dasen: So there are probably two motions.

32. Ang: One is what?

33. Dasen: They have equal mass, B will move in the direction A travels in. Then A will remain stationary. It doesn't move, right?

34. Ang: It didn't, right? Try again.

35. Dasen: So mass is 5.

(Observe the simulation)

36. Ang: It doesn't move, ok. It means A hits B, A stops and B continues moving.

37. Dasen: Yea. Another is B's mass is higher, B will move and A will bounce back.

38. Ang: Yea.

39. Dasen: But we haven't tried A's mass is higher.

(Observe the simulation)

40. Dasen: So if A's mass is larger than B, then B will continue moving and A will slow down but still travel in the same direction after the collision.

41. Ang: Uh-huh.

42. Dasen: So there are three kinds [of subsequent motions].

43. Ang: Yea, three kinds.

At the beginning of the collaborative learning, Ang and Dasen set the same masses for the two objects, described the outcome together and decided to set different masses (turns

1-8). Then they executed several simulations through hypothesizing that mass B was larger than mass A, mass B was much larger than mass A and mass B was smaller than mass A, and eventually obtained three possible subsequent motions after the elastic collision. The interaction was characterized with constructive meaning making by building upon each other's statements. On the one hand, Ang and Dasen used acceptances to acknowledge the prior statement on the description of simulation results (turns 30, 38, 41), and they accepted the prior statement and offered supportive information to develop mutual understanding (turns 7, 36). On the other hand, they sometimes positively but critically elaborated on the other's statement by linking a new hypothesis to the previous one (turn 26) and correcting the prior statement (turn 20). Regarding the equality, running simulations created more opportunities to generate new initiating statements for the two collaborators. After each round of simulation, the collaborators started the discussion at a new level of content focus to share their own understanding of the simulation. At the same time, the initiating statements were coherent, and the distribution was relatively equal. The collaborators mostly acknowledged the other's statement first and then initiated their statements at a different level of content focus. For instance, in turn 6, Ang agreed with Dasen's explanation of the outcome and then asked a question to verify her puzzle. In turn 23, Ang reacted to the prior statement first and proposed her own understanding in a question to invite her partner to join the conversation. Also, Dasen introduced an initiating statement on summarizing the findings based on previous simulations in turn 31. In the end, Dasen made a conclusion about the number of possibilities they had explored to seek a common ground, and then Ang agreed with it and the common ground was achieved (turns 42-43).

The common ground accumulated based on the shared experience of investigating different possible results of elastic collision with technology-based simulation did contribute to further negotiation of the underlying mechanism of the phenomenon. The following episode was also from the conversation between Ang and Dasen. They attempted to integrate their experience of running simulations with the knowledge in the instructional material to interpret the change of motions of the two objects after elastic collision for answering the question 2 in the discussion task.

1. Ang: Since it is elastic collision, then the total energy remains the same, but there is probably energy transfer from one to another [after the collision]. If the mass is lighter, it gains smaller momentum because of the fact that the kinetic energy is the same.
2. Dasen: I think so. The total momentum is also conserved, and we can change the value.
3. Ang: Yea, so if the value of one is lighter, it will give more velocity.
4. Dasen: Because the mass doesn’t change [in the process of collision].
5. Ang: Yea, the momentum is conserved.
6. Dasen: The total momentum [is conserved].
7. Ang: Yea. So when the stationary object is lighter than the moving object, the subsequent velocity of the stationary one will be greater than the initial velocity of the moving object.
8. Dasen: Uh-huh. Explain the change of motions…Try what?
9. Ang: We try two masses are equal.

(Observe the simulation)

10. Dasen: The momentum is the same, and the total kinetic energy before and after are also the same…For this one when A collides with B, I assume that kinetic energy is transferred to B and B moves at the same velocity.
11. Ang: When the masses are same, ok.

12. Dasen: Yes, the total kinetic energy and momentum maintain the same.

13. Ang: Ok.

Ang and Dasen discussed the explanation of the change of motions after elastic collision based on the view of energy transfer. In turns 1-8, accumulations and elaborations were frequently used to construct shared understanding of the underlying principles. Apart from accepting the prior statements, they tended to provide more related information to enrich the explanations (turns 2, 4, 5, 8). For example, in turn 2, after acknowledging the prior statement, Dasen added another feature of elastic collision. In turn 4, Dasen accepted Ang's idea and gave a reason to support his idea as well. Also, they elaborated on each other's ideas by presenting an assumption based on the prior statement (turn 3), offering alternative explanation through associating the simulation result (turn 7) or giving a more accurate explanation (turn 6). To facilitate further explanations, Ang and Dasen ran another simulation under the two objects with the same mass. Compared to the simulation with two same mass objects they manipulated just now, they added more information on the change of speed of the two objects this time. In turn 5 of the last episode, they just used "specific" to describe the speed of the object B, and they found the speed of the object B was the same as the initial speed of the object A in this new round of simulation. Then Dasen explained the principle underlying the change of motions of the two objects based on the result of simulation (turn 10). Ang accepted it and highlighted the relationship between the masses of two objects in this explanation. At last, Dasen pointed out the basic principles in elastic collision again to complete the explanation.

Although the two collaborators actively engaged in refining mutual knowledge on the phenomenon of elastic collision, the shortage of elaborations between the intervals of two experimentations was a challenge for mutual engagement of social interaction. For example, through the turns of 5-8, 13-16, 25-28 in the first episode of Dasen and Ang, they tended to simply describe the simulation results and rapidly moved to a new round of experimentation. Another episode from the conservation in the 2D-based condition was chosen to further address the limitations in mutual engagement of social interaction in collaborative learning with the simulation supported by traditional 2D graphics technology. The two collaborators, Liang and Jessica, tried to find out possible results of elastic collision in order to answer the question 1 in the discussion task.

(Observe the simulation)

1. Liang: Object B moves towards the right.
2. Jessica: And A will stop.
3. Liang: Yes, A will stop. So this is one kind of motion…Let's see mass of B is twice of A.
4. Jessica: Ok.
5. Liang: [Let's] see what will happen. So you'll be 20. I still put 10 for the velocity.

(Observe the simulation)

6. Liang: So A moves towards the left.
7. Jessica: Yes.
8. Liang: Mass B is more than A, so mass A can affect the motion…So if mass of B is more than that of A, A will move in the opposite direction.
9. Jessica: Yes.
10. Liang: Because the total energy of two colliding objects is conserved, I guess since the mass of B is higher than A, A must move back to balance the energy, isn't it?

(No response from Jassica)

11. Liang: So there are two kinds of motions.
12. Jessica: If A is larger than B?

13. Liang: I think B will move faster, but we can try. Let’s put mass A is more than
B.I put 20.
14. Jessica: I put 10.
(Observe the simulation)
15. Jessica: Both move to one direction.
16. Liang: A goes to the same direction also.
17. Jessica: And B is faster.
18. Liang: Uh-huh.

At the beginning, Liang depicted the movement of the object B after the collision under the condition that the two objects had the same masses, and Jessica added more information on the change of motion of the object A. Liang acknowledged it by repeating Jessica’s statement. Their conversation on talking about the result of the first round of simulation quickly closed with a short conclusion and a suggestion about a new simulation by Liang (turn 3). After the second round of simulation, Liang attempted to associate the relationship between masses of the two objects and the result (turn 8) and explain the underlying principles for the result (turn 10) besides simply describing the phenomenon itself (turn 6). However, Jessica did not actively participate in the discussion, and she just showed a brief agreement (turn 9) or ignored Liang’s question (turn 10). Then Liang sought the understanding on the number of possible results of elastic collision from Jessica. Jessica proposed a new suggestion and they started a new round of simulation. After the simulation, they also shortly described the results without engaging in much elaboration on it (turns 15-18). In the process, Liang and Jessica tended to quickly share the simulation results, and then started the next simulation rather than further explain the result. In some groups under the 2D-based condition, the collaborators even did not communicate with each other on the result or simply said “ok” to acknowledge it and then ran the next simulation. Meanwhile, the collaborators exhibited little mutual engagement on further elaborating on the results of the phenomenon. Sometimes one student tried to extend the description of the results to a deeper explanation on the relationship or principles underlying the phenomena, but the other student did not spend coordinated efforts in building upon it (turns 8-10). Also, the collaborators were more likely to directly accept simulation outcomes and rarely verbalized the outcomes that contradicted their prior understanding. Hence, less exploratory interaction made it difficult for collaborators to establish and sustain mutual understanding on deep knowledge of elastic collision. In general, the lack of mutual engagement of social interaction in collaborative learning after implementing a round of simulation was common in the 2D-based condition.

In a brief, by taking advantage of the knowledge resources provided by the 2D-supported simulation, the collaborators exhibited a higher level of mutual engagement of social interaction for solving the problem compared with those without simulation support. On the one hand, running simulations stimulated both collaborators to come up with new initiating statements by offering new ideas about the topic. On the other hand, they made more commitments to engage in the other’s contribution. They increased the use of accumulations to develop common grounds instead of simple acceptances, and seldom used rejections/no response in the conversation. And the use of elaborations was more frequent compared with face-to-face collaborative learning without simulation support. However, the lack of joint commitments in social interaction after each round of simulation was a challenge for the collaborative learning with the 2D-supported simulation.

4.2.3 AR-supported simulation and the characteristics of mutual engagement of social interaction

Building upon the features of scientific simulation supported by traditional multimedia technologies, the AR-supported simulation also offered some unique opportunities for the collaborators to foster mutual commitments in jointly solving the problem. In this part, the capability of AR-supported simulation for enhancing personal experience was illustrated first, and then the characteristics of mutual engagement of social interaction in collaborative learning with the AR-supported simulation were analyzed in detail.

4.2.3.1 Strengthened personal experience in learning scenarios

Before analyzing the mutual engagement of social interaction in collaborative learning with the AR-supported simulation, the differences of personal involvement in learning scenarios were compared across three experimental conditions.

Traditionally, individuals take a third-person perspective towards the knowledge in school instructions. They usually talk about the representations of knowledge from textbooks in an impersonal way. The following episode was the collaborators in the paper-based condition engaged in predicting the subsequent motions of the two objects after elastic collision. They adopted impersonal pronouns such as “they”, “object A” and “B” as referents to speculate the change of motions of the two objects in each possible scenario of elastic collision. The bolded words signaled the use of pronouns in the conversation. For example:

1. Yau: **They** both move to this direction.
2. Kaven: Yea, **object A** will slow down and **B** will move forward.
3. Yau: Can **A** stop and **B** move?
4. Kaven: Maybe.

5. Yau: **A** will rebound?

6. Kaven: You mean the opposite direction?

7. Yau: Uh-huh.

The application of technologies has potential for expanding learning experiences. Under the condition with the AR-supported simulation, individuals could get involved in richer learning experience that was evaluated by their verbal exchanges right after collaboratively experimenting simulations of elastic collision. They tended to treat the process of running simulation from a first-person perspective and felt as if they were agents of the simulations rather than just watching it. The following episode was chosen from the conversation of the collaborators in the AR-based condition to highlight the different learning experience delivered by the AR technology. It took place after Estella and Tian running a simulation, and they discussed the outcome of the simulation.

1. Estella: Why **I** move faster? **I**'m stationary.

2. Tian: Because **I** moved towards **you**, then **you** shift away.

3. Estella: Just now **you** hit **me** and make **me** move, right?

4. Tian: Yea!

Estella and Tian talked about the simulation scenario by using many personal pronouns such as “I”, “you” and “me” to describe the change of motions of the two objects after the elastic collision. For the above simulation, Estella controlled the object B that was initially stationary while Tian chose the object A that moved towards the object B before the elastic collision. They set the same mass to the two objects. After the collision, the object A became stationary, while the object B moved forward. The use of language in their social interaction showed that they embedded their physical selves into the scientific simulation. When Estella said “Why I move so faster?”, she thought she acted as the block in the simulation and her motions was changed after the collision. Tian further explained the process of collision by assuming that they played the roles in the simulation. The collaborators revealed strengthened connection with the simulation context and their deeply involvements in the simulation could be displayed by the referential pronouns used in the conversation. Similar referential strategies reflecting collaborators' first-person perspective towards the learning scenario such as "I bounce back", "I push you away", "we both move to the same direction", "You hit me, and then I flew away and you became stationary", "How come we go to different ways?", "I move out of the screen." were frequently used in the AR-based condition when the collaborators referred to the scenarios right after running the simulation. The frequency of using this kind of metaphorical references in the discussion decreased as the time went by after a round of simulation, but it would increase again after the collaborators implemented a new simulation. Sometimes, although the collaborators did not fully view the simulation scenario from the first-person perspective, they also revealed strengthened personal experience in their description of the simulations. They tended to add the possessive adjectives and referred the objects as "my one" and "yours" instead of directly using the impersonal pronouns like "one" and "object A".

However, not all technologies have the capacity of delivering the first-person experience in learning activities. In the groups with the 2D-supported simulation, the collaborators preferred to stick to take a third-person perspective towards the simulation scenarios. After running a round of simulation, they preferred to use impersonal pronouns to refer to the simulation result as follows:

1. Tammy: **One** stops and **one** moves on.
2. Wen: **Object A** stops moving, and **B** moves to the right in the same velocity.

3. Tammy: Uh-huh.

In the above setting, Tammy controlled the object A and Wen controlled the object B respectively. They set the same value for the masses of the two objects and then observed the outcome of elastic collision. After the simulation, they described the change of motions of the two objects and used “one”, “object A” and “B” to refer to the objects in the simulation. Tammy claimed “One stops and the other moves on” to illustrate the directions of the two objects after the collision, and then Wen responded to her by adding information on the change of speed of the two objects. Similarly, the collaborators in the 2D-based condition usually referred to the simulations in a third-person way through using series of impersonal pronouns, such as “object B is kicked out”, “A stops”, “It’s still moving”, “they move in the same direction”, etc. Thus, different strategies of referential uses were adopted in the 2D-based and the AR-based conditions.

Based on the prominent role of AR-supported simulation in enriching personal learning experience and prompting involvement in simulation activities, more evidence was presented in the next part to clarify the influences of AR-supported simulation on mutual engagement of social interaction in the process of pursuing shared understanding of the knowledge on elastic collision in face-to-face collaborative learning.

4.2.3.2 Strengthened mutual engagement of social interaction in learning scenarios

In the AR-based condition, the stronger link between personal experience and simulation activities contributed to promoting mutual engagement of social interaction after running simulations. Compared to the simulation supported by 2D graphics technology, AR technology created more opportunities to enhance the reciprocity of social interaction in collaborative learning. The collaborators with the AR-supported simulation displayed higher interests in interacting with each other after running each round of simulation. Also, they mutually got involved with elaborations and invested more attempts to develop shared understanding on the knowledge together.

So as to illustrate the reciprocal interaction engaged by the collaborators, the social processes of two groups with the AR-supported simulation were segmented into a number of episodes and analyzed successively. The first four episodes were the whole process of the two collaborators, Gwyneth and Mark, solving the questions in the discussion task with the AR-supported simulation. In each episode, the salient features of mutual engagement of social interaction were presented.

The following episode was that Gwyneth and Mark explained the simulation outcome after the first simulation by setting same masses for the two objects. They sought to capture as many as features of the phenomena by identifying the change of motions of the two objects after the simulation.

1. Gwyneth: Elastic collision means that kinetic energy is conserved, right?
2. Mark: Yea.
3. Gwyneth: So they can’t stop.
4. Mark: Cannot stop?
5. Gwyneth: Unless…No, A can stop and B continues moving.
6. Mark: Perhaps we can try this.
7. Gwyneth: Ok.
8. Mark: I’m B, so velocity is 0.
9. Gwyneth: Same mass?
10. Mark: Ok.
(Observe the simulation)

11. Gwyneth: Wow!
12. Mark: My one moves away.
13. Gwyneth: I'm stationary.
14. Mark: Yea, you're stationary.
15. Gwyneth: So one of the situations is that A will stop moving and then B will move.
16. Mark: Yea.
17. Gwyneth: The speed will be the same speed as A moves in.
18. Mark: So B will move at the same speed?
19. Gwyneth: Yea, you moved away at the same speed.
20. Mark: Then opposite direction? Only two, right?
21 Gwyneth: This will be if the masses are the same.
22. Mark: So we can try different mass.
23. Gwyneth: Yea…just now supposed to be the same mass, yea.
24. Mark: So let's try different mass.
25. Gwyneth: You are bigger mass or smaller mass?
26. Mark: I'm 2 and you're 1. My velocity is 0.
(Observe the simulation)

After briefly making some preliminary assumption (turns 1-10), Gwyneth and Mark set up the experiment and observed the simulation result to explore possible outcomes of elastic collision. They talked about the change of motions of the two objects as if they were agents in the simulation activity through using "I" and "you" (turns 11-14). Then they stepped back from the simulation scenario and started examining the simulation. They explained the exact changes of direction and speed of the two objects after the collision (turns 15-19). Sometimes they still referred to the previous simulation from a first-person perspective to support their explanation (turn 19). After building the common ground on the simulation result, Mark made an initiating statement to seek the understanding on other possible results from Gwyneth (turn 20). Then Gwyneth expressed her justification based on Mark's idea. Mark extended Gwyneth's statement and proposed a suggestion for running the next simulation. The collaborators showed high willingness to share the result of the simulation from a first-person perspective right after running the simulation. They mutually engaged in explaining the result through building on each other's idea and smoothly transited to the next round of simulation. After observing a new round of simulation through setting a bigger mass for the object B, they communicated the results with each other and further elaborated it to explore more possibilities in the next episode.

1. Mark: Wow! You hit me and move backwards.
2. Gwyneth: So you took the same direction but I rebounded.
3. Mark: Yea, ok.
4. Gwyneth: Your velocity is 0, right?
5. Mark: Yes, my velocity is 0.
6. Gwyneth: If your mass is smaller, then?
7. Mark: Yea, if B's mass is smaller…
8. Gwyneth: Actually, it's the same.
9. Mark: Yea, I think it is the same and they still move to different direction.
10. Gwyneth: Yea, just the speed will be different. Because for this one, A has more speed than B, but for the other one, if B's mass is smaller, then A will have less speed than B.
11. Mark: Yea.
12. Gwyneth: Is it possible if A hits B and then A moves in the same direction?
13. Mark: As B?
14. Gwyneth: Because just now we moved to the opposite direction.
15. Mark: Yea, either stopped or went to the opposite direction.
16. Gwyneth: Yea. Let's try.
17. Mark: Ok.

18. Gwyneth: Just now your mass is bigger, right?
19. Mark: Yea, if my mass is smaller, then?
20. Gwyneth: Now you keep your mass smaller.
21. Mark: Ok. My mass is 1 and velocity is 0.
(Observe the simulation)

At the beginning, Gwyneth and Mark talked about the change of motions of the two objects through imaging they were players in the scenario, which was evidenced by using series of personal pronouns such as “you”, “me” and “I”. Moving back from the simulation scenario, Gwyneth initiated an assumption after reflecting on the relationship of the masses of the two objects. In turns 8-11, they discussed the results when the object B had a smaller mass by providing more explanations to support their assumption. Then Gwyneth introduced another initiating statement based on the previous simulation result, and posed a question on a new possible outcome after the collision. Gwyneth and Mark accepted each other’s statement, provided more information to verify them and at last proposed to start a new simulation to test their prediction (turns 14-15). In the following episode, Gwyneth and Mark collaboratively got involved with exploratory interaction to analyze the simulation results and attempted to integrate them with the principles in the instructional material to explain the underlying mechanism of the phenomenon.

1. Gwyneth: Oh, it’s possible.
2. Mark: Uh-huh. Your velocity is also 1, isn’t it?
3. Gwyneth: Yes.
4. Mark: Your mass is 5, isn’t?
5. Gwyneth: Yes, because the energy is conserved…So it’s possible. Correct correct!
6. Mark: So if your mass is higher than mine, and your velocity is bigger than mine, then they will move in the same direction.

7. Gwyneth: It means that mass relates with…Actually, p=mv.

8. Mark: Uh-huh.

9. Gwyneth: So that means that…If the masses are the same…

10. Mark: A has different momentums [when the mass increases]…So the momentum will be higher.

11. Gwyneth: Yea, the higher the mass, the higher the momentum is. If mass A is bigger than mass B, it continues moving to the right.

12. Mark: We can use the formula p=mv. For object A, the momentum is 5. For B, the momentum is 0. So if your momentum is higher than my momentum, then basically we move in the same direction.

13. Gwyneth: Correct.

14. Mark: So we conclude if momentum of A is higher than momentum of B, then both move in the same direction.

15. Gwyneth: Yes, the direction of A will not change…But then it is given mass of A is larger than mass of B. The initial momentum of A is always larger than B because B is 0.

16. Mark: Uh-huh. Direction of A is the same as the direction of B...

17. Gwyneth: It continues but slower. How to explain the reason? Based on observation and based on theory?

18. Mark: Observation.

19. Gwyneth: Because in the observation we saw it was possible.

20. Mark: Yea, can we say using the formula? Mathematically it makes sense.

21. Gwyneth: Yea, the formula is ok, but how it happens?

22. Mark: We increase the mass of object A, and make smaller of object B, and then they move in the same direction. So based on the formula and the observation, we know how the mass influences it.

23. Gwyneth: Basically we observed it and then use the mass to explain…For all collisions, momentum is conserved. Total momentum is conserved.

24. Mark: How to explain when total momentum is conserved?

25. Gwyneth: It helps to explain when B moves and how far…Partially help to

explain when and how A will move or stop moving. We know B will always move?

26. Mark: Uh-huh.

27. Gwyneth: But we don’t know how far. A is harder to predict because you don’t know when it stops moving, and if it moves, which direction it goes in, and what the speed is.

28. Mark: Uh-huh. B will always move, right?

29. Gwyneth: Yea, but we only know it is based on the conservation of momentum. After A hits B, B will goes to somewhere.

30. Mark: Uh-huh. The total energy is also conserved.

31. Gwyneth: There is relationship between p and m because v is the only one stays fixed.

32. Mark: Uh-huh.

33. Gwyneth: We only changed m, and then the momentum is changed.

34. Mark: So mass affects the motion.

35. Gwyneth: So m changes p because the change in p, the resultant effect is different for A and B.

36. Mark: M changes p…v is constant?

37. Gwyneth: We can keep it constant, but actually we can use different velocities.

38. Mark: If the velocity is the same, but the mass is different, what will happen? Let’s try.

39. Gwyneth: Velocities were different in the last three scenarios.

40. Mark: Just now do you change the velocity?

41. Gwyneth: We changed the mass.

42. Mark: Velocity was the same?

43. Gwyneth: No, my velocity was different.

44. Mark: What if velocity is the same but the mass is different?

45. Gwyneth: So I set the velocity 1.

46. Mark: Yes. I put 0.

47. Gwyneth: Mass is five?

48. Mark: Yes.

(Observe the simulation)

Gwyneth and Mark found that it was possible for the two objects to move in the same direction after the elastic collision according to the simulation results. Gwyneth felt excited when the prediction was proved to be true and Mark summarized the relationship between the masses of the two objects and the subsequent motion (turn 6). Then Gwyneth linked the formula of momentum with Mark's statement in an effort to explore the reasons for it (turn 7). After Mark acknowledged it, Gwyneth tried to continue her explanation about the influence of the mass on the subsequent motion. Mark further elaborated on the impacts of the mass to complement Gwyneth's statement. Gwyneth took up her partner's explanation and summarized it by adding more details. Then Mark generated a new level of focus through using the number in the simulation they ran to explain the change of motions, but Gwyneth found Mark's explanation was problematic and provided a logical reason through pointing out that momentum of A was always larger than B, and this relationship could not be applied to explain the change of motions after the collision (turn 12-15). Mark realized it and initiated a new statement by describing the direction of the two objects after the collision, and Gwyneth modified it by offering information on the change of the velocity first and then introduced a new level of focus by proposing an alternative path to explain it (turns 16-17). The two collaborators reached mutual consensus on the importance of the observation. Mark also proposed that they could use the formula to interpret it at the same time, and Gwyneth presented a clarification for Mark to further explain how to apply the formula with the phenomenon. Mark took up Gwyneth's statement and presented his understanding on it, and Gwyneth accepted it and put forward a new level of focus by mentioning the principle of conservation of momentum. Mark made a follow-up query to ask for more explanations, and Gwyneth explained the role of the principle in interpreting the change of motions of the two objects (turns 24-27). Mark agreed to her and posed a question to verify his puzzle. Gwyneth answered it from the perspective of momentum and Mark added the conservation of energy to it. In order to further analyze the role of mass in the change of the motion, Gwyneth established the relationship between the mass and the momentum after controlling the variable of velocity in her new initiating statement, and then the two collaborators expanded this focus by building the relationship among mass, momentum and subsequent motions in their explanation (turns 31-35). In turn 36, Mark made a clarification by asking the function of velocity in the formula. He proposed a hypothesis based on Gwyneth's answer and suggested that they should keep the velocity constant in the simulation to evaluate the effects of mass in elastic collision. Then they jointly reflected on the velocity setting in the previous simulations and obtained a consensus on running new simulations by controlling the initial velocity of the object A (turns 39-44). After some interaction on the value setting, they started implementing a new simulation to investigate the role of mass in the elastic collision (turns 45-48).

This episode was characterized with the collaborators' high mutual engagement of social interaction in collaborative learning. Gwyneth and Mark coordinated with each other in the social process by constructively building shared understanding on the knowledge. They exhibited great willingness to take up the partner's statement and gave further extensions to enrich the meaning construction of both simulation results and underlying principles. And they actively elaborated on each other's idea by linking new explanations, refining the explanation and providing justifications, and proposing related assumptions. Clarifications were also frequently used to elicit more explanations of the prior ideas. Meanwhile, the flow of the interaction was coherent and both of them displayed interests in introducing initiating statements. Experimenting simulations provided resources for initiating more new ideas. Also, rather than completely change the previous content focus in the conversation, they usually gave a response to the partner's statement first and then generated a proposal at a different level of the prior focus, which contributed to the evolving explanations for the development of mutual understanding on the phenomenon.

In the last episode, Gwyneth and Mark implemented their idea by manipulating the system and further refined the shared understanding of the knowledge.

1. Gwyneth: Ok, same conclusion. Then if my mass is bigger yours but the velocity remains. What is your mass?
2. Mark: My mass is still 5.

(Observe the simulation)

3. Gwyneth: Still the same.
4. Mark: Your velocity is?
5. Gwyneth: 1, I didn't change it. So the change of mass will change everything.
6. Mark: So the change of mass will change the momentum, and it will affect the direction after the collision.
7. Gwyneth: Yes, [it] affects the direction, and in turn alters the motion of the objects.

After controlling the variable of initial velocity of the object A in the simulations, Gwyneth and Mark found that the outcomes were constant. Gwyneth confirmed that the significant role of mass in affecting the subsequent motions of elastic collision, and then Mark offered a clearer explanation by associating mass, momentum and change of motions the two objects. Eventually, they came to their shared conclusion for the discussion.

So manipulating the AR-supported simulation in face-to-face collaboration made the collaborators experience the first-person perspective towards the learning scenario and transform the personal experience to mutual engagement in analyzing the simulation activities. The mutual commitments did lead to intensive exploratory interaction in the process of constructing the meaning of both surface phenomenon and deep principles in collaborative learning.

The AR-supported simulation also stimulated the collaborators to collaboratively interpret the discrepancy between the simulation outcome and the previous conceptual understanding of the phenomenon. They were more motivated to share their confusion when describing the simulation scenarios. The following four episodes from another group, Shane and Maria, were analyzed to highlight the features of social interaction after running each round of simulation. In the first episode, Shane and Maria talked about the result of the simulation when setting the same masses for the two objects.

(Observe the simulation)

1. Shane: Did you see what happens?
2. Maria: Oh, yours went out of paper! What happened?
3. Shane: Also, yours stopped completely.
4. Maria: Oh, no, mine moved. Now it becomes stationary, right?
5. Shane: Yes.
6. Maria: How come it happens? Where is yours?
7. Shane: I'm out of the screen. I think because the energy or the velocity, according to the theory, transfer to here. 0.5 entirely transfers to this. So this becomes 0, this becomes 0.5.
8. Maria: Oh, some transfers happen! Where is the final velocity?
9. Shane: It's there, -0.5.

10. Maria: Oh, -0.5, it's for you. Then you go out of the picture.

11. Shane: You are 0. You're 0.5 and become 0.

12. Maria: I'm stationary, but if I pass energy to you, how come you become minors?

13. Shane: It's velocity. This direction is positive and this is negative. You go this way, so it was minors.

14. Maria: Oh, I see. I want to ask you does the distance matter?

15. Shane: We cannot change the distance, so I do not think so.

16. Maria: Ok, it's a fixed distance.

17. Shane: So we already have one case.

After the first round of the simulation, Shane and Maria vividly depicted the scenario of the simulation by using the expressions such as "yours went out of paper" and "I'm out of the screen". Their strengthened personal experience could be obviously reflected by the language use in the social process. In the whole episode, either personal pronouns or possessive adjectives were adopted. Especially for the use of personal pronouns such as "you" and "I", it indicated that they completely viewed the simulation from a first-person perspective and deeply got involved in the shared learning scenario. Also, the two collaborators revealed a high degree of engagement with each other's statement to jointly develop mutual understanding of the knowledge. Maria expressed her puzzle through asking series of questions "How come it happens? Where is yours?", and Shane not only provided the answer at the phenomena level but also tried to explain the phenomena based on his understanding of the principle (turns 6-7). Maria posed a new level of content focus on the number of the velocity to the conversation after accepting Shane's explanation (turn 12). After reaching shared understanding of it, they solved another problem related with the impacts of the distance, and then prepared for trying a new simulation under different masses of the two objects. In the next episode, Shane and Maria described the simulation result and developed a new assumption on the basis of the result.

(Observe the simulation)

1. Maria: Where is mine?

2. Shane: So it continues moving. I can see what's happening!

3. Maria: I didn't see what was happening. Wait wait! How come we move out of the picture? Must we be within the picture? Why move out after the collision?...Let's do again.

(Observe the simulation)

4. Maria: When I am heavier than you, we both move in the same direction, but you move faster.

5. Shane: More momentum is put to the smaller one.

6. Maria: So you move faster. Velocity is faster. I move slower because I'm heavier than you.

7. Shane: Yes.

8. Maria: Then what happens when it reverses? Will be the same thing except going to the right and then we go to the left?

9. Shane: If this one is lighter, yes, it might be like this.

10. Maria: Yes.

After observing the second round of simulation, Maria addressed the scenario from the first-person perspective by using "we" to indicate the objects and expressed great surprise towards the result of the simulation through posing series of questions (turn 3). She suggested repeating the simulation and after running the simulation, they jointly interpreted the phenomena based on the simulation results. Stepping back from the simulation scenario, Maria described the direction and speed of the two objects after the collision (turn 4). Shane accepted it and added the concept of momentum to it, and Maria further explained Shane's statement to illustrate the relationship between the mass and the velocity. After that, Maria initiated a new statement to explore more possibilities of the phenomenon by suggesting setting bigger mass to the object B. She also predicted that both objects would move to another direction since the masses were reversed. In the next episode, they found that the prediction was wrong and expressed the conflict between the simulation results and the prior conceptual understanding.

(Observe the simulation)

1. Maria: I mean…I'm not right.
2. Shane: How come that one move so fast?
3. Maria: I first thought everybody should move to the left. Why move in opposite direction? Remember, just now I was heavier than you, all moved to the right. Then we hypothesized that when the mass reverse we will move to the reversed direction. So why move apart?
4. Shane: They should move apart but I didn't know it is so fast. Because after you hit this, this one still moves. This one is lighter, so you bounce back. That's what I thought. But I did not expect this one moved so fast.
5. Maria: For me, I just expected everybody moved here. Like just now. You know.
6. Shane: Yes, the reverse way.
7. Maria: Totally reverse. I supposed it.
8. Shane: So there are three ways in total.
9. Maria: What are three?
10. Shane: When A equals with B, then A stops, and B moves. Or A hits B and both continue moving. Or A goes backwards and B continues moving. B will always move but move in different velocity, depending on the mass.

Maria initiated the conversation and realized that her prediction was wrong. Shane also expressed his confusion towards the simulation from the first-person perspective. Then Maria started introducing her prediction process that related to the last round of simulation, and Shane took up her statement and pointed out that the mass did affect the subsequent motions. In turns 5-7, they continued reflecting on the reason for making such a prediction together and built a common ground on it. At last, they summarized their findings based on the three rounds of simulations. Then, in the following episode, Shane and Maria attempted to elaborate on the whole process to explain their wrong prediction.

1. Shane: The object with more mass has more influence.
2. Maria: Yes, the heavier object has more influence, so weight is important. Mass or weight?
3. Shane: Weight is gravitational, while mass is constant, right?
4. Maria: So the variable is mass. Just use mass.
5. Shane: So mass has more influence on the direction and velocity of motion.
6. Maria: What is the change of motion?
7. Shane: I realize that we are supposed to guess what will happen before [the simulation], and then this is what happens after.
8. Maria: So I thought they moved to the same direction. Why I guess wrongly?
9. Shane: Initially we hypothesized that if mass of A was less than B, A would move in the opposite direction. But we thought B would not move or move along with A.
10. Maria: Yea, just the same direction.
11. Shane: However, we see that B will also move in the same direction as A, but A moves backwards. So there is still transfer of force.
12. Maria: Yes. No transfer of mass, so there may be some external force factors.
13. Shane: But there is no external force. [There is] only internal force.
14. Maria: Ok.

Shane initiated a statement by asserting that the object with a bigger mass played an important role in affecting the subsequent motion based on the prior simulations. Maria agreed with Shane’s statement and questioned on the conceptions of mass and weight. Shane answered the question and provided his argument, and they attained mutual understanding on using mass as the antecedent to explain the mechanism underlying the change of motion after elastic collision (turns 2-5). Next, they began interpreting the wrong prediction together. After reflecting on the prediction process and the simulation result in turns 9-11, Shane tried to use the transfer of force to explain the reason that made the object B moved forward instead of moving backwards with the object A. On the basis of Shane's statement, Maria offered an alternative reason, the external force, for influencing the subsequent motions since mass could not be transferred. But Shane corrected Maria's statement by changing the external force to internal force according to the features of elastic collision. In this episode, the common ground developed in the process of running simulations offered shared resources for Shane and Maria to seek the principles underlying the phenomenon, which enhanced their mutual concerns and facilitated them to find out the explanation for solving the confusion together.

In sum, the AR-supported simulation had the capacity of allowing the collaborators to obtain rich personal experience in learning activities. Not only did it offer shared referential resources for students to jointly explore knowledge and refine their understanding along the learning process as simulations supported by the traditional technology, but also enhanced their connection with learning scenarios and the partner, which thereby contributed to fostering the joint commitments in co-constructing meaning and dealing with confusions of the knowledge in collaborative learning. The descriptive analyses of the conversation in collaborative learning demonstrated that more elaborations could emerge in this evolving process, which also gave complementary evidence for the results in quantitative content analysis. In order to associate the phenomenon with the abstract principles in the textbook or interpret the discrepancy between the phenomena and the prior misunderstanding, the collaborators made more attempts to link an alternative perspective to the prior explanation, propose a new hypothesis in relation to the prior statement or modify the previous idea by offering justifications. Indeed, the shared resources and the enriched learning experience provided by the AR-supported simulation stimulated the collaborators to make more contributions to the conversation rather than simply expressing acceptances to respond his/her partner. Meanwhile, the transitions between content focuses of conversation were more coherent. The collaborators in the group held more equal control over the task, and they usually gave their responses to the prior statement first and then started initiating a statement at a new level of content focus. After negotiating the meaning based on a round of simulation, the collaborators would move on to the next simulation to explore more knowledge on elastic collision.

Chapter 5 Discussion and Conclusions

The objective of this research is to examine the influences of an AR-supported simulation on mutual engagement of social interaction in face-to-face collaborative learning for physics. The equality and mutuality of engagement of social interaction serve as two indicators to assess mutual engagement in collaborative learning. The single-factor between-subjects experiments are designed to compare the equality and mutuality of engagement of social interaction across three experimental conditions, including the paper-based, the 2D-based and the AR-based conditions. Both quantitative content analysis and conversation analysis are applied to analyze the data. The results reveal that the AR-supported simulation does not only share the capability of 2D-supported simulation for enhancing equality and mutuality of engagement of social interaction, but also further the enhancements of mutuality by increasing critical elaborations and reducing simple acceptances in face-to-face collaborative learning for physics.

In this section, based on quantitative content analysis and conversation analysis, the results of the influences of AR-supported simulation on the equality and mutuality of engagement of social interaction are discussed. Then, the significance of mutual engagement of social interaction as a relational aspect in the social context of CSCL is presented. Next, both theoretical and practical implications of this study are described. Limitations and future research are addressed. This section ends with the conclusion of the whole study.

5.1 The Influence of AR-supported Simulation on the Equality of Engagement of Social Interaction

The first research question of this study is to investigate the influence of AR-supported simulation on the equality of engagement of social interaction in face-to-face collaborative learning for physics. To answer this question, the quantitative content analysis is applied to identify the initiating statements in the social process of collaborative learning, and the degree of variation between the amounts of initiating statements made by two collaborators in the group is measured to represent the equality of engagement of social interaction. The hypothesis predicts that there are significant differences in the equality of engagement of social interaction across the paper-based, the 2D-based and the AR-based conditions. Apart from quantitatively comparing the level of equality of engagement of social interaction among three conditions, the conversation analysis is used to examine the occurrences of initiating statements in the setting of interaction flow to contextualize the finding in the quantitative content analysis.

According to the result of quantitative content analysis and hypothesis testing, the equality index of collaborative learning without simulation support is significantly lower than those in the 2D-based condition and the AR-based condition. Both AR-supported and 2D-supported simulations significantly promote the equality of engagement of social interaction in collaborative learning without simulation support, however, no significant difference in the enhancement of equality of engagement of social interaction is found between the AR-based and the 2D-based conditions. So, the AR-supported simulation has similar facilitation effects as the 2D-supported simulation on increasing the equality of controlling over the direction of conversation. In the collaboration without simulation support, asymmetric participation in generating initiating statements is common in the social process of collaborative learning. Two types of asymmetric participations emerge in the collaborative learning. One situation is a person just passively accepts the ideas made by his/her partner and makes little effort in initiating a new focus to the conversation. The other situation is one person dominates the conversation by continuously expressing his/her ideas, and fewer chances are given to the other party to state the thoughts. The conversation analysis from the 2D-based and the AR-based conditions indicates that the use of technology-based simulations can address this problematic issue and enhance equal participation in directing the conversation. As Suthers and Hundhausen (2003) claimed, external representations of knowledge entail the potential for prompting the initiation of meaning negotiation. Presenting unshared meaning is the first step to negotiate the meaning for achieving mutual understanding in conversation. Being a form of disciplinary representation, the AR-supported simulation provides shared referential resources for both collaborators to actively exercise control over the task flow by initiating negotiations at different levels of content focuses. The collaborators hold stronger obligation of seeking shared understanding in the group with the support of technology-based simulation. Such effects show that shared interactive simulation does not only afford the collaborators equal opportunities for manipulating the simulation of scientific phenomenon, but also leads to more equal controls over the collaboration between the two people. It gives evidence that visible and manipulative representations of knowledge have positive effects on collaborators' engagement for pursuing mutual understanding pointed out by Crook (1998).

5.2 The Influence of AR-supported Simulation on the Mutuality of Engagement of Social Interaction

The second research question of this study concentrates on the influences of AR-supported simulation on the mutuality of engagement of social interaction in face-to-face collaborative learning for physics. Five categories of development statements with different levels of mutuality for reaching mutual understanding in the development statements are identified, including elaborations, clarifications, accumulations, acceptances and rejections/no response, to facilitate to quantitatively measure the effects of AR-supported simulation on the mutuality of engagement of social interaction in collaborative learning. According to Mercer's (1996) classification of talks in collaborative learning, elaborations and clarifications fall into exploratory talk, accumulations and acceptances belong to cumulative talk and rejections/no response are disputational talk. Among these, elaborations and clarifications are featured with the highest mutuality of engagement of social interaction since the person needs to critically and constructively build on the prior statement presented by his/her partner. Accumulations and acceptances are also beneficial for developing common grounds between collaborators since they have to engage with each other's idea in a supportive way. But the lack of meaning negotiation makes acceptances have limited effects on increasing mutual understanding of the knowledge compared with accumulations. And rejections/no responses are the lowest in mutuality. Five hypotheses are proposed as guidance to examine the differences in elaborations, clarifications, accumulations, acceptances and rejections/no response across the paper-based, the 2D-based and the AR-based conditions. Furthermore, the conversation analysis is integrated to interpret the variability of mutuality of engagement found in the quantitative content analysis in a broader context through taking the interaction flow and experience of manipulating simulations into consideration.

As Clark and Brennan (1991) argued, the meaning initiation is just the starting point of establishing mutual understanding and the negotiation process requires joint commitments of people involved in the conversation to achieve mutual understanding. In general, the findings in the present research demonstrate that the AR-supported simulation could enhance the mutuality of engagement of social interaction by encouraging the collaborators building upon each other's statements. Among the three conditions, the level of mutuality of engagement of social interaction is relatively low in face-to-face collaborative learning without simulation support. Lack mutual commitments in co-constructing shared meaning of the knowledge is a main challenge for the effectiveness of joint problem-solving in collaboration. Rather than work on the group task in a collaborative manner, poor reciprocity in social interaction is obvious in collaborative learning without simulation support. After one person initiates a statement at a new level of content focus, the other person tends to simply agree with it without adding more supportive information or giving some critical viewpoints. Also, rejections and no response are used more frequently than those in the conditions with simulation tools. In the 2D-based and the AR-based conditions, the reciprocity between the two collaborators is much enhanced in the social process. The average percentages of elaborations and accumulations significantly increase, while those of acceptances and rejections/no response reduce. Additionally, the AR-supported simulation does not only share the capacity of the 2D-supported simulation for strengthening the mutuality by increasing the use of elaborations and accumulations, and reducing the use of acceptances and rejections/no response in the conversation, but also shows more advantages in furthering the influences on the aspects of elaborations and acceptances in face-to-face collaborative learning. However, neither AR-supported nor 2D-supported simulations have significant effects on using clarifications in the social process of collaborative learning. In the collaboration without simulation support, the collaborators are also motivated to ask for clarifications of the prior statement made by their partners.

As an emerging technology, AR creates opportunities for fostering the mutuality of engagement of social interaction in face-to-face collaborative learning for physics. Particularly, the AR-supported simulation enables collaborators to become involved in more elaborative interaction compared with the 2D-supported simulation, which is conceived as a valuable means for enriching the process of meaning negotiation and in turn deepening the conceptual understanding of knowledge in extant literatures (Mercer, 1996; Wegerif, 1996). The AR-supported simulation does not only play the role of shared referential resources as traditional technology-supported simulation, but also serve as a facilitator for enhancing collaborators' subjective participatory sense in collaborative learning. In traditional scenarios, technology-based simulations have been perceived as referential anchors that provide shared knowledge resources to strengthen meaning negotiation in collaborative learning (Suthers, 2006). The technology-based simulation provides shared referential resources for meaning negotiation, which opens up more possibilities for increasing mutual understanding of the knowledge between the collaborators throughout learning activities. Compared to those without simulation support, the collaborators with simulation supports exhibit a higher level of mutual engagement of social interaction for making predictions and explaining the underlying mechanism of elastic collision. The functions of external representations in strengthening the richness of meaning negotiation documented by Suthers and Hundhausen (2003) are also supported by the findings in this research. The collaborators with the simulation prefer to continuously negotiate and modify the understanding of the knowledge by constructively building on each other's statement. However, in the 2D-based condition, the issue of mutual efforts still presents challenges for collaborators to take active roles in meaning negotiation to build shared understanding of knowledge. Frequently, the collaborators in the 2D-based condition just simply talk to each other about the simulation results and quickly start the next round of simulation. At the interval of two rounds of simulations, they seldom jointly get involved with exploratory interaction to expand their conversation or propose inquiries on the inconsistency between the simulation result and their prior conceptual understanding. For the AR-supported simulation, the results in this research demonstrate that it enables to augment the basic capacity of traditional applications as shared referential resources and further promote the potential of meaning negotiation in collaborative learning by strengthening the collaborators' subjective tie with the simulation scenario. Indeed, this affordance named "reflector of subjectivity" is highly appreciated for constructing more effective CSCL environments to foster the richness of meaning negotiation of knowledge (Suthers, 2006, p.328).

With the AR-supported simulation, the collaborators obtain rich personal experience by viewing the simulation activities from the first-person perspective. After running a round of simulation, they prefer to explain the change of motions of the two objects after the elastic collision by using personal pronouns such as "I", "you" and "we" to refer the objects. Moving beyond simply watching the simulation, the collaborators develop strong connection between personal experience and simulation scenarios and feel like they are agents in the simulation. Previous research has analyzed some similar phenomenon in their simulation-based projects and used this kind of first-person experience to indicate a high level of personal involvement in face-to-face CSCL environments (Andrews et al., 2003; Colella, 2000). In comparison, the participants tend to hold the third-person perspective towards the 2D-supported simulation in collaborative learning by using impersonal pronouns to describe simulations. The influences of AR-supported simulation on the change of collaborators' perspective towards learning activities can be attributed to the virtual components embedded in AR technology. Avradinis et al. (2000) brought forward that scientific simulations supported by traditional multimedia technologies function as "media-rich electronic books" for references, while the immersive quality of virtual reality technology can establish a more engaging context for physics education by delivering enriched personal experience. Based on the results, AR technology entails great promises for creating a hybrid learning setting and enriching individuals' sense of involvement through integrating immersive experience of virtual reality with real world activities as Dieterle, Dede and Schrier (2007) have asserted.

The valuable benefits of rich personal experience supported by the AR technology lie in the coherent evolution from collaborators' personal to interpersonal involvement, which result in growing mutual engagement of social interaction in collaborative learning. In comparison with the collaborators in the 2D-based condition, the collaborators in the AR-based condition exhibit greater willingness to communicate with each other after running each round of simulation. At the beginning, they describe the simulation outcomes together to capture the features of elastic collision with frequent use of personal pronouns as if they were agents in the simulation scenario. Meanwhile, situated in a face-to-face context, the collaborators can easily move back from the prior strengthened personal experience and start analyzing the phenomenon reflectively. The enhanced personal experience motivates them to spend greater mutual efforts in jointly interpreting the meaning of the knowledge, which is helpful for promoting the development of shared understanding. Instead of merely depicting the scientific facts presented by simulation results, the collaborators prefer to engage in more explorations based on the surface phenomenon and seek deeper understanding of the knowledge. They display strong initiatives for building upon each other’s idea and making constructive statements to extend the meaning negotiation of both concrete phenomenon and abstract underlying mechanisms. These findings provide supports for the impacts of the interplay between medium characteristics and learning activities on the effectiveness of collaboration stressed by Lai and his colleagues (2007). Characterized with affordances of providing shared referential resources and delivering richer personal experience, the AR-supported simulation is able to shape the patterns of verbal exchanges in the process of collaboration and motivate the collaborators to mutually engage in more exploratory interaction for problem-solving. Additionally, the interactional opportunity offered by AR-supported simulation promotes the construction of shared understanding of both scientific facts and underlying principles at the interval of running two simulations. The effectiveness of transforming learning experience into reflective meaning negotiation of the knowledge is identified as an important criterion for evaluating the success of a simulation-based collaborative learning environment (Chee & Hooi, 2002). Colella (2000) also placed high emphasis on productive communicative activities followed with the strengthened personal experience in simulation-based collaborative learning. He clarified that the fundamental objective of creating rich personal experience is to realize its potential for stimulating active exploratory activities to seek deep understanding of the knowledge. In the present research, the successful transition of rich personal experience to a high level of mutual engagement of social interaction demonstrates the strengths of AR technology in supporting face-to-face collaborative learning for physics.

Combining the findings on equality and mutuality of engagement of social interaction in collaborative learning, the positive effects of AR-supported simulation on mutual engagement of social interaction support the role of ICTs as important resources for enhancing reciprocal interaction in the process of collaborative learning (Järvelä, et al., 1999). Instead of being isolated from the social process of collaborative learning, the AR-supported simulation enables to promote mutual engagement in negotiating the meaning of abstract physics knowledge through stimulating the collaborators' engagements to jointly construct the understanding of scientific phenomena and underlying principles.

5.3 Enhancement of Mutual Engagement of Social Interaction in CSCL

In this study, by contextualizing the construction of mutual understanding of knowledge among collaborators as a communication issue, the findings provide evidence that collaborative relation reflected by mutual engagement of social interaction functions as an important aspect in developing mutual understanding in collaborative learning. Recognized that collaborators might form different social relationships in learning activities, some researchers have highlighted the significance of taking collaborators' communicative behaviors towards mutual understanding into consideration when investigating group functioning in collaborative learning (Barron, 2003; Storch, 2002). The results show the feature of mutual engagement of social interaction in collaborative learning for making mutual understanding and how it can be shaped by technologies from the lens of joint commitments in social interaction. They together support the perspective of viewing collaborative relational aspects as an integral part of collaborative learning and analyzing the relational aspect in the social context of collaborative learning to interpret the difference in the effectiveness of constructing mutual understanding (Barron, 2003). Different levels of equality of directing the interaction in collaborative learning can represent the relationship formed in the social process of collaborative learning. Collaborators might demonstrate various initiatives for seeking mutual understanding from each other in different conditions. And the variability in using elaborations, accumulations, acceptances, and rejections/no response across conditions indicates that collaborators display different reciprocal engagements in each other's contribution. Rather than rely on co-construction as a general concept to capture the process underlying the development of mutual understanding in collaborative learning, categorizing patterns of social interaction with different levels of mutuality is beneficial for specifying relational aspects in the social process of constructing knowledge. Also, it helps to measure the quality of social interaction in collaborative learning.

Additionally, the effects of technology-based simulation on supporting mutual engagement of social interaction reveal that AR technology can assist the development of collaborative relation for constructing mutual understanding of knowledge. The ways of the collaborators relating themselves with each other are diverse when negotiating the meaning of knowledge. The collaborators in the AR-based condition show the highest level of mutual engagement of social interaction among three conditions. Particularly, the AR-supported simulation stimulates the collaborators to involve in more elaborations, which require people to positively and critically orient their understanding to each other's statements in conversation. The results suggest that technologies can augment social interaction collaborative learning by introducing new possibilities for fostering collaborative relation in social interaction. And the impacts of simulations on social interaction differ from medium to medium. It provides evidence for supporting the mediating role of external circumstances on collaborators' behaviors to construct mutual understanding in collaborative learning (Järvelä et al., 1999). Compared to traditional multimedia-supported simulation, the AR-supported simulation is more capable of addressing the relational issue in collaborative learning. Serving as shared referential resources and the reflector of subjectivity, the AR-supported simulation motivates people to spend more mutual efforts in developing shared understanding of knowledge. Better collaborative relation established in the AR-based condition makes step forward for constructing more effective CSCL contexts with interactive socio-culture.

5.4 Implications

In this section, the theoretical implications of this study for investigating social interaction in CSCL are firstly discussed. Then, I present the practical implications for applying emerging technologies for supporting collaborative learning.

5.4.1 Theoretical implications

This study addresses the consideration of taking social process and the mediating role of technologies in constructing understanding of knowledge into account in CSCL. The socio-cultural perspective in traditional collaborative learning stresses the social context for constructing knowledge and the function of tools in mediating social interaction in collaborative learning. Not all groups work in a collaborative manner for building mutual understanding. Different levels of mutual engagement of social interaction across three conditions indicate that relational aspects in the social context of collaborative learning should be considered when examining the construction of mutual understanding. The findings also provide evidence for supporting the mediating function of technology in influencing the social process of collaborative learning. The AR-supported simulation can enhance mutual engagement of social interaction in collaborative learning by offering shared referential resources and strengthening personal experience. This study adds to the understanding of how the social context in collaborative learning can be enhanced by technologies.

This study also has implications for identifying the mechanism that affects the efficacy of constructing mutual understanding in the social process of CSCL. Moving beyond simply characterizing patterns of social interaction, this study focuses the attention on the quality of social interaction to assess the capability of AR-supported simulation for supporting social interaction in collaborative learning. By incorporating joint commitments in social interaction in theory of grounding, mutual engagement of social interaction serves as a lens to investigate the impacts of AR-supported simulation on the efficacy of social interaction for building mutual understanding of knowledge in collaborative learning. The findings suggest that the AR-supported simulation does not only entail the capability of the 2D-supported simulation for promoting mutual engagement of social interaction, but also furthers the enhancements in the uses of more elaborations and less acceptances. The integration of joint commitments in social interaction with collaborative learning gives insight into the underlying mechanism of the efficacy of social interaction and the opportunities of technologies for fostering social interaction in collaborative learning.

5.4.2 Practical implications

As more and more emerging technologies are developed for enhancing the effectiveness of collaborative learning, this research has several practical implications for applying CSCL technologies in physics education.

The findings imply that the sociability issue of CSCL environments should be stressed in the future design in order to enhance the effectiveness of collaborative learning. In this research setting, collaborative use of technology-based simulation is capable of enhancing face-to-face interaction for solving physics problems, and the effects are various from medium to medium. Thus, it is significant to identify the affordances of technologies for promoting social interaction when designing CSCL environments.

The present research also provides evidence for supporting the value of AR technology in face-to-face collaborative learning for physics. The AR-supported simulation entails great possibilities for enriching personal experience of collaborators and motivating their mutual commitments in establishing and maintaining shared understanding of knowledge. Characterized with both attributes of virtual reality and the real world, AR technology opens up new opportunities for constructing a more engaging face-to-face CSCL environment to strengthen mutual engagement of social interaction in collaborative learning for physics compared to traditional 2D graphics technology.

Furthermore, the computing power and wireless connection of handheld devices enable them to be suitable platforms to extend the functions of conventional computers and display devices of AR for knowledge delivery in this research. The AR-supported simulation implemented by handheld devices makes AR technology more accessible in school environments, which contributes to fulfilling the potential of AR for supporting collaborative learning activities in the future.

5.5 Limitations and Future Research

This research mainly controls the prior knowledge of elastic collision in the experiment design to examine the influences of AR-supported simulation on mutual engagement of social interaction in collaborative learning at the introductory stage of learning physics knowledge. Actually, there are other factors like the relationship between collaborators, habits of using mobile phones and one’s attitude towards new technologies that might have impacts on communicative behaviors in collaborative learning. Therefore, the limitation on controlling participant variables in the present research needs to be addressed in future studies.

This research focuses the attention on the process of collaborative learning at the group level and examines the impacts of AR-supported simulation on face-to-face collaborative learning from the perspective of mutual engagement of social interaction. The social process and learning outcomes are two primary dimensions of collaborative learning activities. Therefore, for the next step, it is necessary to associate the social process with the learning achievement to investigate the relationship between mutual engagement of social interaction and individuals' knowledge gain in collaborative learning.

Technologies enable to affect the effectiveness of collaborative learning in multiple ways, and the influences can be diverse from context to context. To fully understand the benefits of AR technology for supporting collaborative learning, more research are needed to analyze the social impacts of AR technology on the effectiveness of collaborative learning in the future.

5.6 Conclusions

The advancements of ICTs offer more opportunities for enhancing the effectiveness of learning practices. In the field of CSCL, the sociability issue of CSCL environments has received growing attention recently and a range of researchers suggested that it is necessary to examine the mediating functions of technologies in supporting the social process of CSCL (Stahl et al., 2006; Suthers, 2006).

Mutual understanding is emphasized for socially constructing knowledge in collaborative learning. The development of mutual understanding is a communication issue, and joint commitments in social interaction are needed to effectively establish and sustain mutual understanding of knowledge during the collaboration (Clark & Brennan, 1991). Building on the theoretical perspective of joint commitments in social interaction for grounding, mutual engagement of social interaction serves as a significant relational aspect in the social context of collaborative learning for measuring the efficacy of coordinating the social process to develop mutual understanding.

Featured with a combination of attributes of virtual reality and real world, AR technology demonstrates great potential for augmenting learning experience. In order to identify the mediating role of AR technology in enhancing the efficacy of social interaction in building mutual understanding, this research investigates the influences of an AR-supported simulation on mutual engagement of social interaction in face-to-face collaborative learning for physics. The results suggest that the AR-supported simulation has the capacity of strengthening meaning negotiation potential beyond traditional 2D-supported simulation to address the challenges for mutual engagement of social interaction in face-to-face collaborative learning for physics. Apart from functioning as shared referential resources, the AR-supported simulation has facilitation effects on offering first-person experience in collaborative learning activities. This affordance further prompts collaborators' personal involvements within simulation scenarios and their mutual efforts in engaging in exploratory interaction to seek shared understanding of the knowledge. In particular, with the AR-supported simulation, the collaborators display higher level of joint commitments and get involved in more elaborations and less simple acceptances compared to those with the simulation supported by traditional 2D graphics technology. Therefore, AR technology can afford more unique opportunities for fostering mutual engagement of social interaction in face-to-face collaborative learning.

The findings enrich the understanding of the communicative mechanism underlying the efficacy of building mutual understanding of knowledge and the mediating functions of technologies in enhancing collaborative relation in the social process of collaborative learning. All of them have theoretical implications for the research on social interaction in CSCL. Additionally, this study provides evidence for supporting the potential of AR technology for promoting face-to-face collaborative learning for physics, which contribute to designing more effective CSCL environments in the future.

References

Alavi, M. (1994). Computer-mediated collaborative learning: An empirical evaluation. *MIS Quarterly, 18*(2), 159-174.

Andrews, G., Woodruff, E., MacKinnon, K. A., & Yoon, S. (2003). Concept development for kindergarten children through a health simulation. *Journal of Computer Assisted Learning, 19*(2), 209-219.

Arvaja, M. (2007a). Contextual perspective in analysing collaborative knowledge construction of two small groups in web-based discussion. *Computer-Supported Collaborative Learning, 2*(2-3), 133-148.

Arvaja, M. (2007b). Contextual resources in meaning negotiations of a student pair in a web-based history project. *International Journal of Educational Research, 46*(3-4), 215-228.

Avradinis, N., Vosinakis, S., & Panayiotopoulos, T. (2000). *Using virtual reality techniques for the simulation of physics experiments*. Paper presented at the Proceedings of the 4th World Multi-Conference on Systemics, Cybernetics and Informatics.

Baker, M., Hansen, T., Joiner, R., & Traum, D. (1999). The role of grounding in collaborative learning tasks. In P. Dillenbourg (Ed.), *Collaborative learning: Cognitive and computational approaches* (pp. 31-63). Oxford, U.K.: Pergamon.

Barnes, D., & Todd, F. (1977). *Communication and learning in small groups*. London: Routledge and Kegan Paul.

Barron, B. (2000). Achieving coordination in collaborative problem-solving groups. *Journal of the Learning Sciences, 9*(4), 403-436.

Barron, B. (2003). When smart groups fail. *Journal of the Learning Sciences, 12*(3), 307-359.

Billinghurst, M. (2008). *Usability testing of augmented/mixed reality systems.* Paper presented at the Proceedings of ACM SIGGRAPH ASIA.

Bossche, P. V., Gijselaers, W. H., Segers, M., & Kirschner, P. A. (2006). Social and cognitive factors driving teamwork in collaborative learning environments: Team learning beliefs and behaviors. *Small Group Research, 37*(5), 490-521.

Chee, Y. S., & Hooi, C. M. (2002). *C-VISions: Socialized learning through collaborative, virtual, interactive simulations*. Paper presented at the Proceedings of the Conference on Computer Support for Collaborative Learning: Foundations for a CSCL Community.

Chin, C., & Brown, D. E. (2000). Learning in science: A comparison of deep and surface approaches. *Journal of Research in Science Teaching, 37*(2), 109-138.

Chiu, C.-H. (2003). Exploring how primary school students function in computer supported collaborative learning. *International Journal of Continuing Engineering Education and Life Long Learning, 13*(3-4), 258-267.

Clark, H. H. (1996). *Using language*. Cambridge MA: Cambridge University Press.

Clark, H. H., & Brennan, S. E. (1991). Grounding in communication. In L. B. Resnick, J. M. Levine, & S. D. Teasley (Eds.), *Perspectives on socially shared cognition* (pp. 127-148). Washington, DC: American Psychological Association.

Cole, H., & Stanton, D. (2003). Designing mobile technologies to support co-present collaboration. *Personal and Ubiquitous Computing, 7*(6), 365-371.

Colella, V. (2000). Participatory simulations: Building collaborative understanding through immersive dynamic modeling. *Journal of the Learning Sciences, 9*(4), 471-500.

Costabile, M. F., De Angeli, A., Lanzilotti, R., Ardito, C., Buono., P., Pederson, T. (2008). *Explore! Possibilities and challenges of mobile learning*. Paper presented at the Proceedings of Conference on Human Factors in Computing Systems.

Crook, C. (1998). Children as computer users: the case of collaborative learning. *Computers & Education, 30*(3-4), 237-247.

Damon, W., & Phelps, E. (1989). Critical distinctions among three approaches to peer education. *International Journal of Educational Research, 1*3(1), 9-19.

Dede, C. (2008). Theoretical perspectives influencing the use of information technology in teaching and learning. In J. Voogt & G. Knezek (Eds.). *International handbook of information technology in primary and secondary education*. New York: Springer.

Dieterle, E., Dede, C., & Schrier, K. (2007). “Neomillennial” learning styles propagated by wireless handheld devices. In M. Lytras & A. Naeve (Eds.), *Ubiquitous and pervasive knowledge and learning management: Semantics, social networking and new media to their full potential* (pp. 35–66). Hershey, PA: Idea Group, Inc.

Dillenbourg, P., & Fischer, F. (2007). Basics of computer-supported collaborative learning. *Zeitschrift für Berufs- und Wirtschaftspädagogik, 21*, 111-130.

Dillenbourg, P., Baker, M., Blaye, A., & O’Malley, C. (1996). The evolution of research on collaborative learning. In E. Spada & P. Reiman (Eds.), *Learning in humans and machine: Towards an interdisciplinary learning science* (pp. 189-211). Oxford, UK:

Elsevier.

Erkens, G. (2004). Dynamics of coordination in collaboration. In J. Linden & P. Renshaw (Eds.), *Dialogic Learning* (pp. 191-216): Springer Netherlands.

Fischer, F., Bruhn, J., Gräsel, C., & Mandl, H. (2002). Fostering collaborative knowledge construction with visualization tools. *Learning and Instruction*, *12*(2), 213-232.

Fischer, F., & Mandl, H. (2005). Knowledge convergence in computer-supported collaborative learning: The role of external representation tools. *Journal of the Learning Sciences*, *14*(3), 405-441.

Galaczi, E. (2004). Peer-peer interaction in a paired speaking test: the case of the First Certificate in English. Doctoral dissertation, Teachers College, Columbia University.

Gijlers, H., Saab, N., Van Joolingen, W. R., De Jong, T., & Van Hout-Wolters, B. H. A. M. (2009). Interaction between tool and talk: How instruction and tools support consensus building in collaborative inquiry-learning environments. *Journal of Computer Assisted Learning*, *25*(3), 252-267.

Hogan, K., Nastasi, B. K., & Pressley, M. (1999). Discourse patterns and collaborative scientific reasoning in peer and teacher-guided discussion. *Cognition and Instruction*, *17*(4), 379-432.

Jahng, N., Nielsen, W. S., & Chan, E. K. H. (2010). Collaborative learning in an online course: A comparison of communication patterns in small and whole group activities. *Journal of Distance Education*, *24*(2), 39-58.

Järvelä, S., Bonk, C. J., Lehtinen, E., & Lehti, S. (1999). A theoretical analysis of social interactions in computer-based learning environments: Evidence for reciprocal understandings. *Journal of Educational Computing Research, 21*(3), 359-384.

Kaptelinin, V. (1999). Learning together: Educational benefits and prospects for computer support. *Journal of the Learning Sciences, 8*(3), 499-508.

Kaufmann, H., & Dünser, A. (2007). Summary of usability evaluations of an educational augmented reality application. In R. Shumaker (Ed.), *Virtual Reality, HCI International Conference* (pp. 660-669), LNCS 4563, Springer-Verlag Berlin Heidelberg.

Kaufmann, H., Schmalstieg, D., & Wagner, M. (2000) Construct3D: A virtual reality application for mathematics and geometry education. *Education and Information Technologies, 5*(4), 263-276.

Kirschner, P. A., & Kreijns, K. (2005). Enhancing sociability of computer-supported collaborative learning environments. In R. Bromme, F. W. Hesse, & H. Spada (Eds.), *Barriers and biases in computer-mediated knowledge communication* (Vol. 5, pp. 169-191): Springer US.

Klopfer, E., Perry, J., Squire, K., & Jan, M.-F. (2005). *Collaborative learning through augmented reality role playing*. Paper presented at the Proceedings of the 2005 Conference on Computer Support for Collaborative Learning: Learning 2005: the next 10 years!

Koschmann, T. (2002). *Dewey's contribution to the foundations of CSCL research*. Paper presented at the Proceedings of the Conference on Computer Support for Collaborative Learning: Foundations for a CSCL Community.

Kreijns, K., Kirschner, P. A., & Jochems, W. (2002). The sociability of computer-supported collaborative learning environments. *Journal of Education Technology & Society, 5*(1), 8-25.

Kumpulainen, K., & Kaartinen, S. (2000). Situational mechanisms of peer group interaction in collaborative meaning-making: Processes and conditions for learning. *European Journal of Psychology of Education, XV*(4), 431-454.

Kumpulainen, K., & Kaartinen, S. (2003). The interpersonal dynamics of collaborative reasoning in peer interactive dyads. *The Journal of Experimental Education, 71*(4), 333-370.

Kumpulainen, K., & Mutanen, M. (1999). The situated dynamics of peer group interaction: an introduction to an analytic framework. *Learning and Instruction, 9*(5), 449-473.

Lai, C.-H., Yang, J.-C., Chen, F.-C., Ho, C.-W., & Chan, T.-W. (2007). Affordances of mobile technologies for experiential learning: the interplay of technology and pedagogical practices. *Journal of Computer Assisted Learning, 23*(4), 326-337.

Linell, P. (1998). *Approaching dialogue: Talk, interaction and contexts in dialogical perspectives*. Amsterdam: John Benjamins.

Liu, C.-C., Chung, C. W., Chen, N.-S., & Liu, B.-J. (2009). Analysis of peer interaction in learning activities with personal handhelds and shared displays. *Educational Technology & Society, 12*(3), 127–142.

Mercer, N. (1996). The quality of talk in children’s collaborative activity in classroom. *Learning and Instruction, 6*(4), 359-377.

Pauchet, A., Coldefy, F., Lefebvre, L., Picard, S. L. D., Bouguet, A., Perron, L., Guerin, J., Corvaisier, D., & Collobert, M. (2007). *Mutual awareness in collocated and distant* *collaborative tasks using shared interfaces*. Paper presented at the Proceedings of the 11th IFIP TC 13 International Conference on Human-computer interaction.

Reamon, D. T., & Sheppard, S. D. (1997). *The role of simulation software in an ideal learning environment*. Paper presented at the ASME Design Engineering Technical Conferences.

Roschelle, J. (1992). Learning by collaborating: Convergent conceptual change. *Journal of the Learning Sciences, 2*(3), 235-276.

Roschelle, J., & Teasley, S. D. (1995). The construction of shared knowledge in collaborative problem solving. In C. O'Malley (Ed.), *Computer supported collaborative learning* (pp. 67-97). Berlin, Germany: Springer.

Russell, D. W., Lucas, K. B., & McRobbie, C. J. (2004). Role of the microcomputer-based laboratory display in supporting the construction of new understandings in thermal physics. *Journal of Research in Science Teaching, 41*(2), 165-185.

Sangin, M., Dillenbourg, P., Rebetez, C., Bétrancourt, M., & Molinari, G. (2008). The effects of animations on verbal interaction in computer supported collaborative learning. *Journal of Computer Assisted Learning, 24*(5), 394-406.

Shaer, O., Kol, G., Strait, M., Fan, C., Grevet, C., & Elfenbein, S. (2010). *G-nome surfer: A tabletop interface for collaborative exploration of genomic data*. Paper presented at the Proceedings of the 28th International Conference on Human Factors in Computing Systems.

Shelton, B. E., & Hedley, N. R. (2004). Exploring a cognitive basis for learning spatial relationships with augmented reality. *Technology, Instruction, Cognition and*

Learning, 1(4), 323-357.

Staarman, J. K., De Laat, M., & Van der Meijden, H (2002). *Seeking attunement in collaborative learning.* Paper presented at the Proceedings of the International Standing Conference for Research, on Activity Theory.

Stahl, G., Koschmann, T., & Suthers, D. (2006). Computer-supported collaborative learning: An historical perspective. In R. K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 409-426). Cambridge, UK: Cambridge University Press.

Storch, N. (2002). Patterns of interaction in ESL pair work. *Language Learning, 52*(1), 119-158.

Sun, P.-C., & Cheng, H. K. (2007). The design of instructional multimedia in e-learning: a media richness theory-based approach. *Computers & Education, 49*(3), 662-676.

Suthers, D. D. (2001). Towards a systematic study of representational guidance for collaborative learning discourse. *Journal of Universal Computer Science, 7*(3), 254-277.

Suthers, D. D. (2006). Technology affordances for intersubjective mean making: A research agenda for CSCL. *International Journal of Computer-supported Collaborative Learning, 1*(3), 315-337.

Suthers, D. D., & Hundhausen, C. D. (2003). An experimental study of the effects of representational guidance on collaborative learning processes. *Journal of the Learning Sciences, 12*(2), 183-218.

Tao, P.-K. (1999). Conceptual change in science through collaborative learning at a computer. *International Journal of Science Education, 21*(1), 39-57.

Visschers-Pleijers, A. J. S. F., Dolmans, D. H. J. M., De Leng, B. A., Wolfhagen, I. H. A. P., & Van der Vleuten, C. P. M. (2006). Analysis of verbal interactions in tutorial groups: A process study. *Medical Education, 40*(2), 129-137.

Visschers-Pleijers, A. J. S. F., Dolmans, D. H. J. M.,Wolfhagen, I. H. A. P., & Van der Vleuten, C. P. M. (2005). Development and validation of a questionnaire to identify interactions that promote deep learning in PBL. *Medical Teacher, 27*(4), 375-381.

Vygotsky, L. (1978). *Mind and society*. Cambridge, MA: Harward University Press.

Wagner, D., Schmalstieg, D., & Billinghurst, M. (2006). Handheld AR for collaborative edutainment. In Z. Pan, A. Cheok, M. Haller, R. Lau, H. Saito & R. Liang (Eds.), *Advances in Artificial Reality and Tele-Existence* (Vol. 4282, pp. 85-96): Springer Berlin / Heidelberg.

Webb, M. (2008). Impact of IT on science education. In J. Voogt & G. Knezek (Eds.), *International Handbook of Information Technology in Primary and Secondary Education* (Vol. 20, pp. 133-148): Springer US.

Wegerif, R. (1996). Using computers to help coach exploratory talk across the curriculum. *Computers & Education, 26*(1-3), 51-60.

Weghorst, S. (2003). *Augmenting tangible molecular models*. Paper presented at the Proceedings of International Conference on Artificial Reality and Telexistence.

Whitelock, D., Taylor, J., O'Shea, T., Scanlon, E., Sellman, R., Clark, P., & O'malley, C. (1993). Challenging models of elastic collisions with a computer simulation. *Computers in Education, 20*(1), 1-9.

Winn, W. (1993). A conceptual basis for educational applications of virtual reality. Technical

Report TR-93-9, Human Interface Technology Laboratory, University of Washington.

Zurita, G., & Nussbaum, M. (2004a). A constructivist mobile learning environment supported by a wireless handheld network. *Journal of Computer Assisted Learning, 20*(4), 235-243.

Zurita, G., & Nussbaum, M. (2004b). Computer supported collaborative learning using wirelessly interconnected handheld computers. *Computers & Education, 42*(3), 289-314.

Appendix

Transcription conventions

…	A short pause in an utterance lasting between 1 and 3 seconds
[ ]	Words appearing in square parentheses are added after transcribing for facilitating the understanding of the conversation.
( )	Words appearing in parentheses represent non-verbal behaviors, such as observing the simulation, reading the instructional material, etc.
/	A single slash represents the point where one person’s statement is interrupted by the other’s in a group
//	Double slashes represents the beginning of the interrupting statement