Developing Guidelines for Collaborative Spaces Supporting Interdisciplinary Engineering Design Teams

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ABSTRACT

Communication deficiencies within interdisciplinary teams are known to reduce the effectiveness of those teams by causing erroneous behaviors (Alvarez & Coiera, 2006; Reader, Flin, & Cuthbertson, 2007). Also, many design defects have been attributed to communication breakdowns across disciplines (Chen & Lin, 2004). As the number of interdisciplinary teams in industry grows in order to adapt to dynamic business environments of the twenty-first century, providing an appropriate environment to improve interdisciplinary team effectiveness is critical for many organizations. In spite of its importance, little is known about what kind of environments support interdisciplinary team interactions.

There were three objectives of this dissertation: 1) to investigate the influence of physical environment on the effectiveness of interdisciplinary engineering design teams, 2) to investigate the influence of interaction strategy design support on the effectiveness of interdisciplinary engineering design teams, 3) to construct behavioral indicators of successful interdisciplinary teamwork to design testing and design guidelines for interdisciplinary team collaboration spaces.

To achieve these goals, the study was conducted in two phases. In Phase 1, the researcher conducted a direct observation of industry teams operating in the novel design space, the Kiva, at a design-consulting firm based in Pittsburgh, PA. The observation data provided 1) a list of significant participant behaviors to be examined and 2) interaction strategy design support (ISDS) procedures to be used during phase 2. Phase 2 was a laboratory-based 2x2 experimental study with physical room condition (Kiva vs. conference room) and interaction strategy design support (present vs. absent) as independent variables. The dependent variables were categorized as team process and output that measured team effectiveness. Overall, a significant interaction effect between the physical conditions and interaction strategy design support was found from all dependent measurements except for product evaluation. A significant main effect of physical conditions and interaction strategy support were found to a lesser extent. Based on the findings, testing methodology guidelines and design guidelines were developed.

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CHAPTER 1. INTRODUCTION

1. 1. Problem Statement

As dynamic business environments today require the completion of complex tasks, more organizations utilize the team as a common work unit (Salas, Cooke, & Rosen, 2008; Guzzo & Dickson, 1996; Cohen & Bailey, 1997). Especially in the field of engineering, organizations often use product development teams that bring together people from different departments. This allows those teams to have diverse areas of expertise. These teams that have members with different disciplinary backgrounds are called many different names, but for the purposes of this study will be referred to as interdisciplinary teams. The higher education community has already recognized the importance of the ability to function across disciplinary boundaries in the accreditation criteria for engineering programs (ABET, 2011).

Members of interdisciplinary teams face tougher barriers than those of single disciplinary teams (Lattuca, Voigt, & Faith, 2004; Borrego & Newswander, 2008). They have to overcome different views stemming from diverse disciplinary cultures in order to communicate and integrate expertise. Failure to overcome disciplinary barriers prohibits efficient communication among members, which harms the overall effectiveness of the team. For instance, members might have different priorities based on their backgrounds. If a mechanical engineer and an industrial designer work together to develop a product, the mechanical engineer is more likely to be concerned about the inter-workings of mechanical components whereas the industrial designer might be more concerned with the form factor of the product. If this difference is not resolved, these two members will be disruptive to the team dynamic.

As interdisciplinary teams are used in diverse areas, interdisciplinary communication failures have brought serious consequences in many different forms. For instance, communication deficiencies within interdisciplinary clinical teams have led to serious errors in clinical decisions (Alvarez & Coiera, 2006; Reader, Flin, & Cuthbertson, 2007). Other healthcare-related studies have linked poor team processes, such as lack of coordination, to less effective quality of care causing unnecessary hospital costs and increased mortality rates (Temkin-Greener, Gross, Kunitz, and Mukamel, 2004; Knaus, Draper, Wagner, & Zimmerman, 1986; Baggs, Ryan, Phelps, Richeson, & Johnson, 1992). The evidence is not limited to the healthcare sector. Ineffective communication between interdisciplinary teams in the National Aeronautics and Space Administration (NASA)'s space shuttle program is cited as one of the probable causes of the loss of the space shuttle Challenger, one of the worst aviation accidents in U.S. history (Rogers Commission Report, 1986). Engineers who were aware of potential technical failures due to inclement weather conditions failed to communicate these concerns to managers who did not possess equivalent technical expertise, which led to the wrongful decision to launch the shuttle (Vaughn, 1996).

In addition to medical and safety-related consequences, ineffective teamwork in interdisciplinary teams also leads to loss of productivity due to unsuccessful team processes (Hackman & Morris, 1983); this can translate to economic losses. This ineffectiveness of teams with functionally diverse members has been attributed to: an unwillingness of team members to share information (Lovelace, Shapiro, & Weingart, 2001); a lack of common expectations (Cronin & Weingart, 2007); and biases resulting from functional background differences (Bunderson & Sutcliffe, 2002).

In order to help members of interdisciplinary teams avoid these potential losses and achieve higher effectiveness, it is critical to provide an appropriate environment for improving interdisciplinary team effectiveness. In spite of the importance of interdisciplinary team collaboration, little is known about what kind of physical environment supports it.

1. 2. Background: Design Studios and the Kiva

Although it has not been common for engineering firms, architecture and industrial design studios have been using open and flexible spaces. Interdisciplinary design teams have begun to employ flexible studio environments. For example, Stanford University's Institute of Design, also known as the "D. School", is currently renovating the building with "open project spaces" and "spontaneous collaboration spaces" equipped with reconfigurable furniture that is easy to arrange as needed (Stanford University Institute of Design, 2009).

In industry, a growing number of companies are investigating designing effective workspaces to foster appropriate team interactions and consumer communications that could lead to innovative outcomes. For example, Royal Mail and Dutch Tax office dedicated spaces to support team innovations and Phillips Research provided a space where research staff could observe consumers interacting with new products (Moultrie et al., 2007).

Design consulting firms make strong claims about the positive impact of their flexible environment on innovative performance of their design teams. For example, MAYA Design uses a dedicated meeting space called the “Kiva”, a cylindrically shaped room covered with wall-mounted whiteboards, featuring modular furniture that can be easily reconfigured.

First, whiteboards that surround the entire premises of the space allow people to visualize ideas without being constrained to one whiteboard. Because the drawings and other written materials remain in the room, those ideas become part of the environment in which the team members are immersed.

Second, modular furniture allow people move about in the room, so they can change orientations to any direction they want to, which allows great flexibility in the use and reuse of the space. They claim that flexible use of space affords flexibility in interactions (See Figure 1 for possible arrangements).

Figure 1. Kiva in a brainstorming session (photographed by the researcher, used with permission of the participants)

Third, a cylindrically shaped room stimulates more parallel and active team interactions by removing the hierarchical affordance of the space. A rectangular conference room is typically arranged to direct the attention of the users (e.g., towards a speaker at the podium). A round space like the Kiva removes this affordance of directional orientation and distributes attention omni-directionally. Thus, it encourages people to take more initiative instead of depending on the people who are closer to the center of attention (e.g., front of the room).

Fourth, a set of activities designed to stimulate team interactions enhances the team effectiveness, when combined with the Kiva. It has been anecdotally noted that activities such as structured brainstorming sessions that require team members to use the features of the Kiva increased the level of team interactions and performance of the teams using the space.

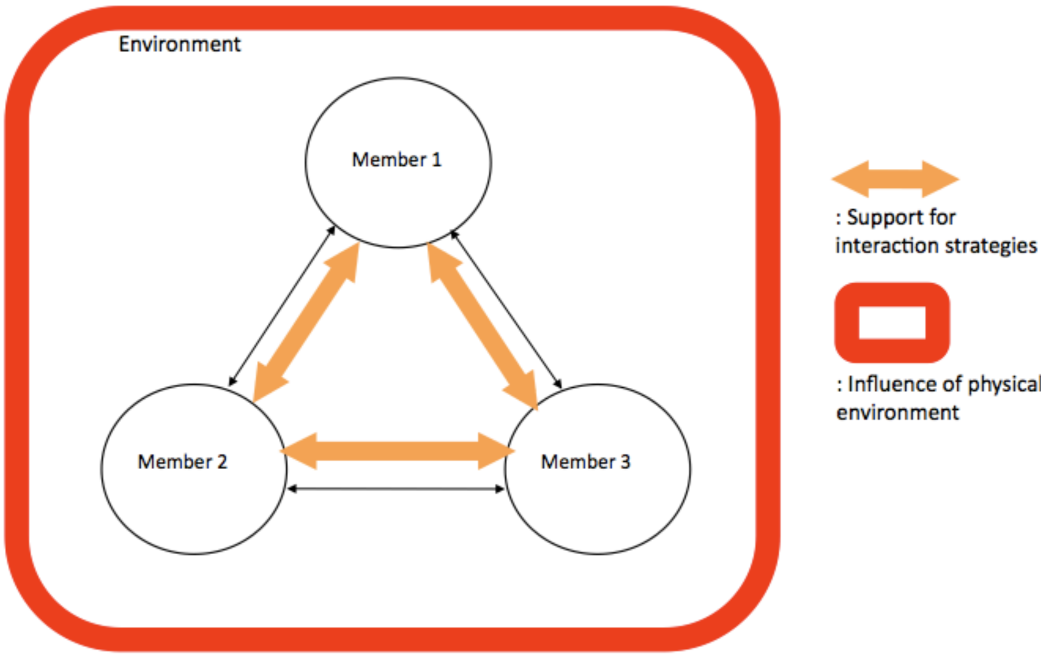

Figure 2. Conceptualization of the influence of environment and interaction strategy design support

The Kiva represents a workspace that affords social interactions among team members. Also, by providing reconfigurable furniture, teams can control the arrangement of the work environment. The interaction support (e.g., structured brainstorming sessions) represents the organizational level intervention that ensures effective use of physical environment.

It can be argued that when people work in a team, they need to communicate and interact with each other effectively. Hence, a physical workspace that could enhance the team's interaction would be desirable to enhance team effectiveness. In this context, it can be argued that having a cylindrically-shaped room with movable furniture affords parallel (as opposed to hierarchical) relationships among team members, which would lead to enhanced interactions and increased team effectiveness. First, a cylindrical room does not orient people towards any direction because there is no front of the room. As people sit around the perimeter, they possess equal amounts of directional attention as opposed to different levels of attention assigned to people in the 'front row' in a rectangular room. Also, having whiteboards that surround the wall space affords idea visualization by offering the users with opportunities for writing and drawing. It is assumed that the wall-mounted whiteboards will trigger participants to organize their ideas visually on the whiteboards. However, these claims have been made based on anecdotal evidence and the space was never systematically investigated using rigorous research methods.

1. 3. Research Objectives

There were three objectives of this study:

1) to investigate the influence of physical environment and interaction strategy design support on the effectiveness of interdisciplinary engineering design teams,

2) to investigate the influence of interaction strategy design support on the effectiveness of interdisciplinary student engineering design teams, and

3) to construct behavioral indicators of successful interdisciplinary teamwork to design testing and design guidelines for interdisciplinary team collaboration spaces and strategies.

1. 6. Research Model and Approach

In order to understand the concepts and phenomena related to how physical environment and interaction strategy design support (ISDS) impact team effectiveness, one should make use of a theoretical framework that conceptualizes these complex underlying processes. As Salas and his colleagues (Salas, Stagl, Burke, & Goodwin, 2007) summarized, many of the extant team effectiveness models were grounded in McGrath's classic Input-Process-Output framework (1984). Likewise, the research model for this study was based on the classic I-P-O framework with an additional feedback loop. There are two input variables (physical environment and team characteristics), two process variables (team interactions and team mental models), and one output variable (team effectiveness). Planned measurements including both quantitative and qualitative approaches for Phase 2 are laid out in the model depicted in Figure 4.

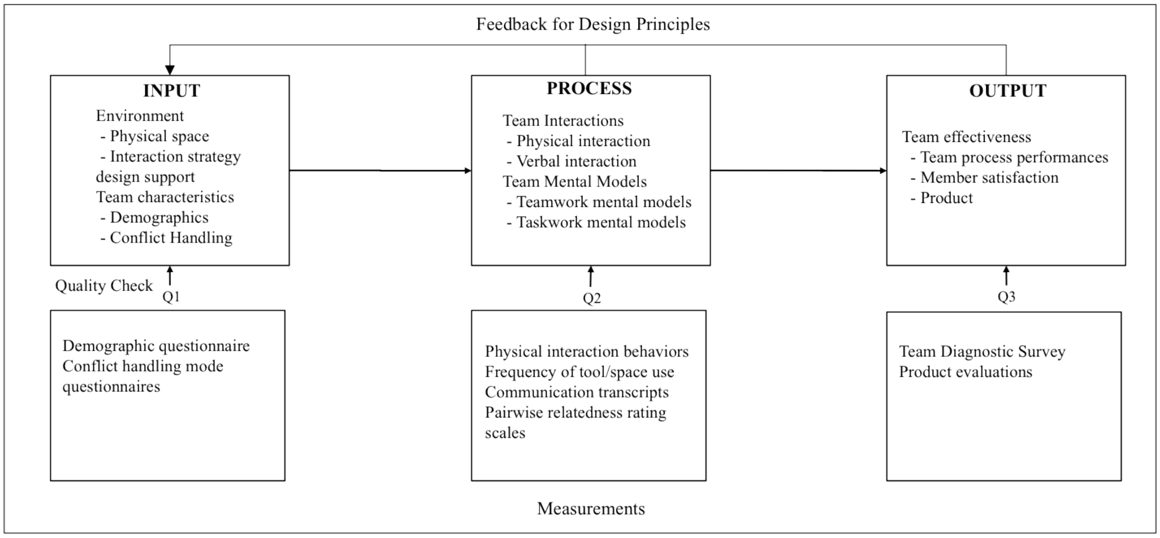

Figure 3. Conceptual model of the research (conceptualized using Ilgen et al., 2005; Kleiner, 1997; Hackman, 1987)

1. 5. Research Questions and Hypotheses

With the overarching goal of examining the impact of space and strategy, some specific research questions were addressed.

- RQ_1: To what extent do physical conditions affect team interaction patterns?
- RQ_2: To what extent do physical conditions affect the level of team mental model similarity?
- RQ_3: What are the relationships between team interaction patterns and team mental models?
- RQ_4: To what extent do physical conditions affect team effectiveness?
- RQ_5: To what extent does interaction strategy design support (ISDS) affect the level of team mental model similarity?
- RQ_6: To what extent does interaction strategy support affect team effectiveness?

- RQ_7: To what extent do the quantity and quality of team interactions affect team effectiveness?
- RQ_8: To what extent does the interaction between physical conditions and interaction strategy support impact team interaction patterns?
- RQ_9: To what extent does the interaction between physical conditions and interaction strategy support affect the level of team mental model similarity?
- RQ_{10}: To what extent does the interaction between physical conditions and interaction strategy support impact team effectiveness?
- RQ_{11}: What are the success indicators of interdisciplinary design teams?

The corresponding hypotheses are as follows.

- H_1: Teams operating in the Kiva condition will show greater quantity and quality of interdisciplinary team interactions.
- H_2: Teams operating in the Kiva condition will show higher levels of team mental model similarity.
- H_3: Teams operating in the Kiva condition will show higher levels of team effectiveness.
- H_4: Teams receiving interaction strategy support will show higher quantity and quality of interdisciplinary team interactions.
- H_5: Teams receiving interaction strategy support will show higher levels of team mental model similarity.
- H_6: Teams receiving interaction strategy support will show higher levels of team effectiveness.

- H_7: Teams showing higher levels of team interaction will show higher levels of team effectiveness.
- H_8: There will be a significant interaction effect of the physical conditions and interaction strategy support on the quantity and quality of interdisciplinary team interactions.
- H_9: There will be a significant interaction effect of the physical conditions and interaction strategy support on the levels of team mental model similarity.
- H_{10}: There will be a significant interaction effect of the physical conditions and interaction strategy support on the levels of team effectiveness.

These questions were answered using a two-phase mixed-methods research approach that included both quantitative and qualitative methods. In Phase 1, direct observations and semi-structured interviews of expert users in an industry setting provided the insights needed to generate the significant actions and design tasks used in Phase 2. In Phase 2, a laboratory-based experimental study was conducted with a sample of thirty-six participants. Questionnaire data as well as video data of team interaction behaviors and participant-created artifacts were collected from said study.

CHAPTER 2. LITERATURE REVIEW

2. 1. Team Effectiveness: Definition and Theoretical Frameworks

There are many suggested definitions of team effectiveness. Hackman (1990) contend that team effectiveness is comprised of team task output, team process, and individual growth. Many subsequent empirical studies followed this classification and supported the validity of this argument (Jarvenpaa, Shaw, & Staples, 2004). Many researchers agree that team effectiveness is measured by appraising outcomes of team activities. To date, many factors such as team composition, work structure, or task characteristics have been identified as factors that affect team effectiveness (Salas et al., 2008). To explain team-related phenomena while encompassing those factors and predict team behaviors, many researchers have attempted to suggest a comprehensive model of team effectiveness.

One of the most influential frameworks in driving empirical research was McGrath's (1984) classic Input-Process-Output (I-P-O) model. The I-P-O model argues that inputs (e.g., team composition) drive the team processes (e.g. interaction) that lead to outputs (e.g. team satisfaction). Although this model was the basis for many empirical studies, it is limited in capturing the complex nature of teamwork. It is criticized for misguiding many meditational factors to be considered as processes and implying a single-cycle path as well as linear progression in team developmental stages. To address these the limitations of the I-P-O framework, Ilgen et al. (2005) suggested the Input-Mediator-Output-Input (IMOI) model, which attempts to reflect the non-linear nature of teams and to add a feedback loop (Ilgen, Hollenbeck, Johnson, & Jundt, 2005).

Table 1

IMOI Framework and Team Constructs (Created based on Ilgen et al., 2005)

IMOI Indicator	IM Phase	MO Phase	OI Phase
Team developmental stage	Forming	Functioning	Finishing
Team constructs and behaviors	- Trusting: potency, safety - Planning: information gathering, strategy development - Structuring: shared mental models, transactive memory	- Bonding: managing diversity and conflict - Adapting: routine/novel performance, workload sharing - Learning: learning from minority members/ best members	- Decline and eventual disbanding of members

Salas and his colleagues recently reviewed eleven existing team effectiveness models and frameworks (Salas et al., 2007). After reviewing various definitions of key constructs (team, teamwork, team performance, team effectiveness) and several theoretical frameworks that attempt to model team effectiveness from the previous studies, Salas et al. suggested that most of the existing models and frameworks of team effectiveness acknowledges that inputs, processes, and outputs as essential part of team phenomenon that drives a holistic understanding of team effectiveness. They found that existing frameworks had differing primary constructs and mediators (e.g., organizational characteristics), as well as varying degrees of consideration of dynamic task cycles and team life span. This review led to the development of a multilevel, integrative framework of team effectiveness. This integrative framework differs from previous frameworks in that it integrated cognitive aspects such as shared cognitions. The impact of shared cognition of team members is recognized by the team research community as one of the factors that are affected by organizational environments as well as team leadership and coaching strategy.

2. 2. Influence of Physical Environment on Team Effectiveness

2. 2. 1. Affordance of Physical Space

When considering the impact of physical space on human behaviors, an oft-asked question is how space can afford certain activities. An environment or object "affords" an activity if, when a user encounters said environment object, she is led to act in a certain way. For example, a flat surface that is at the height of an adults' knee affords "sit-on-ability" for most of adults (Gibson, 1977). Environments shape activities because humans exist within the environment and use artifacts within the environment to execute tasks. Among the many dimensions of work environments, physical space is particularly interesting because it includes all of the elements of a work system. Previous studies have shown that space affects activities and posited that certain types of space afford certain types of activities (Fayard & Weeks, 2007; Kim et al., 2007; Moher, Hussain, Halter, & Kilb, 2005; Nova, 2005; Pepper, 2008). For example, the concepts of space and its affordance have been traditionally studied in the context of virtual spaces. In virtual spaces, people associate social connotations with various types of spaces because spaces have certain meanings attached to them. These connotations trigger expectations of proper behavior and also influence dominant communication patterns. For instance, in a virtual lecture hall, a formal information transfer from a teacher to students is expected. Thus, it can be argued that social activity is rooted in a space (Dieberger, 2003). sA longitudinal empirical study found that groups left notes to provide “shared persistent reference” for members, and it was also discovered that interdisciplinary teams preferred large surfaces that were readily available for group visualization (Ju, Lee, & Klemmer, 2007). Hence, it could be argued that providing the same visual reference such as a whiteboard for all members to refer to could help teams to maintain the same mental imagery that is physically embodied in the space.

2. 2. 2. Physical Environment and Team Effectiveness

The usability guide of the ISO standards provides widely accepted definitions of usability related concepts. Part 11 of ISO 9241 defines an ‘environment’ to be those relevant characteristics of the physical and social context used in a system, including attributes of the wider technical environment, the physical environment (e.g. workplace, furniture, etc.), the ambient environment, and the social and cultural environment (ISO, 1998). In this perspective, attention needs to be directed to spatial layout of a workplace as well as the tools and furnishings included in the environment. Despite the rise of team-related studies, little is known about how physical space impacts team effectiveness. In a study that examined the relationship between physical environment and individual cognitive aspects, Shelton and McNamara contend that human spatial memory is attributable to the effect of environment (Shelton & McNamara, 2001). If that is the case, it may be argued that the environmental factor will invoke differences in each individual's cognitive behavior, which may lead to differences in team cognition (e.g. team mental models).

Regarding environmental effects on human cognitive behaviors, effects of perspective elevation and environmental geometry were studied in a virtual reality setting recently, and the authors found that participants showed faster directional judgment in a cylindrical room than a rectangular room (Luo & Duh, 2009). Similarly, another study showed a positive correlation between users' proximity to a whiteboard and their implicit interactions (Ju et al., 2007). On the other hand, Adamczyk and Twidale suggest that design principles intended for designing collaborative tools that support nominal (not interdisciplinary) teams might not effectively support interdisciplinary team effectiveness (Adamczyk & Twidale, 2007). Observations of industry practices found the potential of physical environments supporting the design process through provisioning of appropriate tools (Moultrie et al., 2007). Additional evidence of this potential is presented in a case study of an engineering design team using a design studio with flexible features at a pharmaceutical company (Kristensen, 2004). These observations reinforce the idea of possible environmental, especially spatial, effects on the cognitive ability of an individual. Considering that each individual's cognition is the basis for team level cognition and interactions, it can be hypothesized that physical space will have an impact on team effectiveness.

2. 2. 3. Design Principles for Team Supportive Environment

While there are workstation design guidelines concerning the ergonomic aspect of a work environment, little is known about whether the physical layout of a work environment may support collaboration. Thus, no definitive design principles have been published for designing a meeting space that supports collaboration among collocated team members. Still, some design heuristics have been provided for optimizing configurations of a video-mediated team-meeting environment (Grenville, 2001). Although the heuristics Grenville developed were specific to video-mediated distributed meeting rooms, some were suggested for collocated teams.

A recent investigation of six organizationally similar but spatially different university corporate research centers revealed that several space-related factors (e.g., visibility and connectivity) predicted face-to-face consultation among researchers based on their investigation of relationships among physical layouts, collaboration patterns, and innovative outcomes (Toker & Gray, 2008). Interestingly, some of the principles derived from the three studies were very similar. Similar findings included:

- Conference style including a circular shaped design is recommended for collocated teams as it increases the visibility among team members.
- Include adaptive features such as movable and flexible furniture.
- Include a presentation station (i.e. overhead, whiteboards).

These principles suggest that the design of the Kiva aligns with the facility design principles for fostering team collaboration, which were identified from the previous studies.

2. 3. Team Interactions: Scope

The term “team interaction” entails a wide range of activities from verbal communications to implicit interactions. Therefore, it is necessary to limit the scope of team interaction in this particular context. For the purposes of this study, the scope of team interaction shall be limited to verbal communications among team members and physical interactions between team members and features (whiteboards, furniture, artifacts, etc) of the space.

2. 3. 1. Verbal Communication and Interdisciplinary Team Interactions

Traditionally, the literature has divided team interactions into two categories: explicit interactions and implicit interactions (MacMillan, Entin, & Serfaty, 2004). More effective teams will not require as many explicit interactions as ineffective teams. This argument stands especially well when a team is placed under limited resources such as time (e.g. flight crew under an emergency situation). When a time constraint is so critical that its importance outweighs the benefits of overt communication, implicit interaction becomes more important. Accordingly, empirical studies supporting this argument of communication overhead mostly involved time-critical contexts such as a flight mission (MacMillan et al., 2004). Thus, this argument may not be applicable to the context of interdisciplinary engineering design teams; overt communication will have more importance for such teams.

Boix, Mansilla, and Duraisingh name three stages that an interdisciplinary team experiences: individual understanding grounded in a discipline, expansion of understanding, and integration towards a new epistemology (Boix Mansilla & Duraisingh, 2007). One might argue that communication would play a key role in the second and third stages. Communication is a mechanism that team members utilize in order to exchange information, which in turn shapes shared understanding. Hence, it is necessary for the members to communicate information to each other in order to develop a shared understanding of and respect for all of the disciplines. Therefore overt communication should be necessary, perhaps even critical, for interdisciplinary engineering design teams, especially during the second stage when team members are building shared mental models.

2. 3. 2. Physical Interactions of Design Teams

In the context of engineering design, the design process may be considered situated and distributed (Le Dantec, 2009). In other words, the design process is influenced by presence of others as well as physical environments. Physical interactions can manifest as interactions between humans and artifacts or other types of physical surroundings, and they are analyzed in many different ways. For example, one study investigated designers' utilization of drawing surfaces for actions (drawing, writing, and gesturing) and uses (illustrating, emphasizing, noting, and referencing) (Bly, 1988). Similarly, an ethnographic study exploring the situated aspect of architectural design meetings. The author focused on significant actions such as sketching or using artifacts (e.g. architect's scale) as well as physical configuration of the artifacts in the meeting space (Le Dantec, 2009). In other cases, users' proximity to the physical artifact (e.g. whiteboard) was measured to examine the physical interactions between human and physical design environment (Ju et al., 2007). Chiu (2002) traced the use of communication tools (e.g., drawings being transmitted via fax) to analyze interactions that are mediated by artifacts among geographically distributed team members. It is evident that interactions between humans and surrounding physical environments and or artifacts are important part of design process.

2. 4. Team Mental Models

2. 4. 1. Definitions and Context

Again referring to the Boix Mansilla and Duraisingh definition of interdisciplinary team experiences (Boix Mansilla & Duraisingh, 2007), it is apparent that seamless collaborations and expertise integrations are important for an interdisciplinary team to function effectively. Hence, it seems necessary to understand the underlying phenomena of the collaborations among team members. As the concept of a team in the human factors domain has grown in research interest, many theorists have attempted to explain what makes teams perform successfully and how the process occurs.

The construct of team mental models was originally proposed as an explanatory framework for team behaviors (Cannon-Bowers, Salas, & Converse, 1993). This concept was built upon the concept of individual mental models, which are mechanisms whereby humans describe a system's purpose, explain its current state and functioning, and predict its future states (Rouse & Morris, 1986). Therefore, team mental models can be understood as an organized knowledge structure that is shared by team members, which allows them to describe the purpose, explain the current behavior, and predict future states of the team. Since 1993, theorists have attempted to support the explanatory and possibly predictive power of team mental models by reviewing existing team literature and capturing the evidence of team mental models (Blickensderfer, Cannon-Bowers, & Salas, 1997; Cooke, Salas, Cannon-Bowers, & Stout, 2000; Cooke, Salas, Kiekel, & Bell, 2004; Salas & Fiore, 2004; Mohammed, Ferzandi, & Hamilton, 2010). However, few empirical studies have been published that validate this notion.

Team-related research focuses on conceptualizing how team members share knowledge and how this sharing affects the performance and effectiveness of the team (Salas & Fiore, 2004). That shared knowledge among team members has been referred to as shared mental models, shared cognition, team cognition, team knowledge and many other terms in team literature. According to the conceptual structure of team mental models proposed by Cannon-Bowers et al. (1993), a team may have multiple mental models in four different areas: equipment, task, team interaction, and teammates. Mathieu et al. later suggested that the first two areas represented task-work mental models and the last two represented teamwork mental models (Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000).

2. 4. 2. Team Mental Model and Team Performance: Empirical Evidence

It has also been suggested that team performance could be enhanced when team members share similar and accurate task-work and teamwork mental models in the original framework. To this date, only a few empirical studies have been published supporting this argument. In Mathieu et al. (2000), dyads of undergraduate students executed flight simulation missions designed to yield data on the level of coordination. Findings indicated that teams with higher levels of team mental models (measured by a relatedness matrix on task-work and teamwork mental models) exhibited higher success rates on the mission. This study was able to confirm the notion that a higher level of team mental models enhances team performance. This study also showed that the accuracy of team mental models was correlated with higher team performance. A more recent study conducted by the same research team, however, failed to confirm the correlation between higher teamwork mental models and better team performance (Mathieu, Heffner, Goodwin, Cannon-Bowers, & Salas, 2005).

Another recent laboratory-based study conducted on undergraduate student action teams examined the performance implications of task-work mental models and teamwork mental models. The purpose of this study was to investigate the impact that leader briefings and team-interaction training have on team adaptation to novel environments. The authors argued that team mental models of team members were influenced by briefing quality as well as team-interaction training that the team received before the mission. The quality of leader briefing could also lead to changes in the communication processes of the team during the mission, which would yield differences in team performance. Findings suggested that the higher quality of leader briefing and team-interaction training positively influenced development of mental models, which led to better communication processes and higher team performance (Marks, Zaccaro, & Mathieu, 2000).

While Mathieu and others conducted laboratory-based research, another study took this theory of team mental models to the field setting. Lim and Klein (2006) studied seventy-one combat teams in the Singapore military in order to investigate the relationship between similarity and accuracy of team mental models (both teamwork and task-work mental models) and team performance. Ten weeks after teams were formed, a survey was administered that consisted of fourteen statements describing team procedures, equipment and task for task-work mental models and fourteen statements describing team interaction processes and member characteristics for teamwork mental models. Also, subject matter experts were given the same survey in order to obtain accuracy measurements. After the data were collected, a social network analysis algorithm that calculates network similarity, Pathfinder, was used to compute the similarity and accuracy scores. These scores were used to conduct a series of correlation and hierarchical regression analyses. Results showed that both team mental model similarity and accuracy were predictive of team performance. Although a limited number of studies were located, one can confirm that shared mental models, both task-work and teamwork models, positively impact team performance from these empirical studies.

2. 4. 3. Team Mental Models and Interdisciplinary Teams

The construct of shared mental models suggests that 1) behaviors specifically related to team functioning are important to task outcomes, 2) effective teamwork behaviors appear to be consistent across domains, and 3) team process variables (e.g. communication) influence team effectiveness (Cannon-Bowers et al., 1993). These findings are important for understanding the behavior of interdisciplinary teams. Interdisciplinary teams inherently require synthesis of expertise from each discipline represented by a team member. It is apparent that interdisciplinary teams will encounter tougher barriers than will non-interdisciplinary teams, as members are expected to exhibit little compatibility in terms of expertise. In order to overcome the barrier and proceed to truly interdisciplinary collaborations, Borrego and Newswander suggested that team members should 1) know their own field with recognition of the strengths and weaknesses, 2) realize and learn enough about other members and their domains to respect them, and 3) integrate a new epistemology (Borrego & Newswander, 2008).

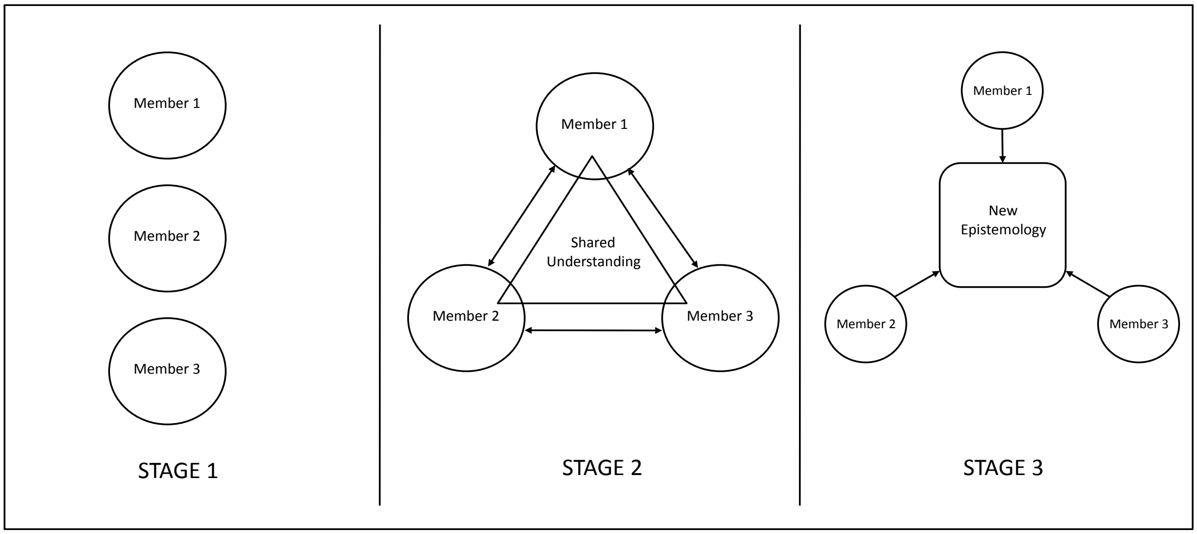

Figure 4. Conceptual model of interdisciplinary team collaboration

(Conceptualized from Borrego & Neswander, 2008; Boix Mansilla & Duraisingh, 2007)

The knowledge accumulated in human factors research and cognitive psychology research should be useful in order to understand the underlying process that interdisciplinary team members' experience. Hence, it can be argued that using the framework of shared mental models in order to explain the behavior of interdisciplinary teams would lead to understanding of underlying processes of interdisciplinary team interactions; and further allow for identifying factors that predict better performance of those teams.

2. 4. 4. Analyzing Shared Mental Models with Social Network Analysis

Social network analysis (SNA) mathematically quantifies the structure of society or even cognitive concepts. A comprehensive review paper by Butts sheds light on how SNA applies mathematical procedures to transform social concepts into simplified networks (Butts, 2008). According to Butts, SNA has wide application in many domains ranging from management to cognitive psychology. The techniques developed in SNA literature were adopted by computer science researchers in 1990 in order to develop an automated tool for eliciting team related knowledge (Schvaneveldt, 1990). The resultant PC-based software, UCINET with Pathfinder algorithm, uses SNA to yield similarity ratings and graphically represented networks. Since its conception, Pathfinder has been widely used among team mental model researchers to efficiently elicit mental model data. The benefit of using Pathfinder is that it provides numerical representation of relatedness between concepts so that it can be used for statistical inferences. Also, it allows researchers to obtain similarity ratings for a different unit of analysis such as NETSIM-team ratings representing the similarity of mental models shared by team members (Langan-Fox, Code, & Langfield-Smith, 2000). For the purpose of this study, 'NETSIM values' refer to the similarity rating of shared mental models for each team.

2. 5. Interdisciplinary Collaborations

2. 5. 1. Multidisciplinary vs. Interdisciplinary Teams

Even though some domains do not emphasize the difference between multidisciplinarity and interdisciplinarity, the two terms need to be distinguished. Before delving into the discussion of multi- versus interdisciplinary teams, it is important to revisit the term “team.” There are numerous definitions of a team, and several researchers have attempted to establish the distinction between the terms “group” and “team.” For the purpose of this study, a team is defined as “a distinguished set of two or more individuals who work interdependently, dynamically, and adaptively in order to achieve a common goal (Salas, Dickinson, Converse, & Tannebaum, 1992).”

Recently, (Borrego & Newswander, 2008) made a clear distinction between “multidisciplinary collaboration” and “truly interdisciplinary collaboration.” They characterized multidisciplinary collaborations as having limited exchange of information, with collaborators being left unchanged by the experience. Conversely, truly interdisciplinary collaboration shows integration of expertise by combining knowledge from each discipline. For example, if a student project team including two mechanical engineering students and two industrial design students who evenly divides the project work based on their disciplines, this team is a multidisciplinary team. Although the membership of this team involves more than one discipline, the expertise is not being integrated, which is an essential condition for an interdisciplinary team. In contrast, if the same student project team integrates their disciplinary expertise and collaborates in order to complete the project, this team now can be viewed as an interdisciplinary team.

An interesting analogy can be made to the distinction between groups and teams. As a group lacks shared value among team members compared to a team, a multidisciplinary team lacks shared and integrated expertise among members compared to an interdisciplinary team. As industry emphasizes integration of different expertise that covers several disciplines, it is important for engineering students to benefit from interdisciplinary education. Therefore, it could be argued that engineering students benefit from an interdisciplinary approach rather than a multidisciplinary approach.

Kim and McNair (2009) found similar evidence supporting interdiscipinarity in a semester-long case study of a senior-level interdisciplinary design class offered at the Department of Engineering Education at Virginia Polytechnic Institute. Twenty-one students participated in the class that consisted of five interdisciplinary teams covering computer engineering, marketing, communication, and industrial design. Students were tasked with designing various features of a “Smart Dorm Room” that uses pervasive computing technology to assist students with special needs while they live on-campus in their freshman year. Each team was asked to design one ‘smart’ feature (e.g., interactive furniture) of a Smart Dorm Room, and they were asked to produce a final design report at the end of the semester. To encourage socialization in the team, students were encouraged to self-organize into interdisciplinary teams. These teams then cooperatively conceptualized team projects within the configuration of a Smart Dorm Room. During interviews, students expressed that they were benefiting from the “real-world” setting of the class, which included students across several disciplines (Kim & McNair, 2009).

2. 5. 2. Cultural Perspective of Interdisciplinary Teams

It has been shown that being able to communicate expertise and establish effective working relationships are key to a successful interdisciplinary collaboration (Chen & Lin, 2004). Culture is a collective perspective that reflects the way a certain group of people perceive, appraise, and experience the world (Hofstede & McCrae, 2004). People view the world through their own cultural lenses (Klein, 2004), which shapes their experience and sometimes causes cross-cultural problems. By the same reasoning, it can be argued that disciplinary culture also is a cultural lens that affects the interactions of team members. A recent study indicates that disciplinary culture challenges students when communicating across disciplines (Dannels & Gaffney, 2009). It has been shown that different occupations possess different cultures. For instance, engineering culture is identified with preference of linear and quantitative thinking (Schein, 1996) whereas designers prefer flexibility and innovation (Cross, 2001; Julier, 2006). These studies further suggest that a discipline is a culture that shapes people's way of thinking and communicating.

2. 5. 3. Benefits of Interdisciplinary Team Settings: Empirical Evidence

As mentioned earlier, a few studies have established benefits of interdisciplinary team settings in engineering education. For example, Borrego and Newswander (2008) interviewed engineer-nonengineer pairs of authors who published their work in the Journal of Engineering Education for the last four years in order to capture patterns and benefits of interdisciplinary collaborations among researchers. They found that while some authors took a multidisciplinary approach, the majority took an interdisciplinary approach. In the interviews, the researchers who indicated truly interdisciplinary collaboration patterns suggested that this type of collaboration allowed for expansion of personal development as well as research productivity. Some stated that they saw "different ways of thinking and stretched their own limits of cognition." One of the interviewees elaborated that, during the collaboration process, he realized a new, non-engineering-based approach to solving a problem that he never knew before this collaboration. The results yielded a model of truly interdisciplinary collaboration in engineering education research. Although this study interviewed engineering and non-engineering researchers (mostly faculty members) who worked together, the inherent nature of collaboration that crosses disciplinary boundaries is the same with the student teams that include both engineers and non-engineers. Therefore, the findings from this study should be transferrable to interdisciplinary student teams. In that context, engineering students may benefit from interdisciplinary collaborations by learning new approaches and broadening their views to solving a problem.

2. 6. Engineering Design Teams: Characteristics and Tasks

2. 6. 1. Characteristics of Engineering Design Teams

A design process in an engineering context differs from a design process in an artistic context. (Suh, 1990) defined an engineering design process as an iterative process of problem definition, creative process of design generation, and analytic evaluation of the design to meet the initial goal. In this perspective, an engineering design team can be characterized by its specific goals, design processes, and constrained schedule for outcome delivery. From the properties of each design stage, one might assume creative members and innovative members will play different roles in different stages. In order to determine the ideal composition of the team that will result in the ideal performance, it is imperative to understand what affects the performance of a team in general.

Several team characteristics such as size, structure, or decision-making processes can impact the effectiveness of a team. Although there is not one definitive, most desirable team configuration, several principles have been derived. For example, Medsker and Campion suggest that a team should be large enough to accomplish work assigned to them yet small enough to avoid heightened coordination needs or disorganization (Medsker & Campion, 1997). They also suggest that a heterogeneous team with horizontal decision-making process shows higher effectiveness. Additionally, autonomous teams with a flexible task structure exhibited higher performance.

Guzzo and Dickson state similar findings in their comprehensive review of team related literature (Guzzo & Dickson, 1996). They reported mixed evidence on the impact of group sizes and confirmed the positive influence of member heterogeneity. In a more recent review on factors affecting team performance, Salas et al. suggest that adaptability of a team's structure is important for teams that need to perform an innovative task (Salas, Sims, & Burke, 2005).

There are other characteristics of a team that might affect its performance. An engineering design team's creativity is significant regarding performance. Thus, reviewing the factors that affect a team's creativity may yield more information for determining the ideal team composition. Especially regarding the impact of verbal communication, researchers found mixed evidence of its influence on team creativity. Some studies suggested that verbal communication among team members interfered with collaboration during creative idea generation processes (Mullen, Johnson, & Salas, 1991; Park-Gates, 2001). Meanwhile, others contend that interaction did not interfere with team creativity (Hargadon & Bechky, 2006; Tiwana & McLean, 2005). Most of the studies that confirmed negative impact used a brainstorming task for measuring team creativity. However, idea generation tasks are only a part of the engineering design process. Thus, despite the mixed evidence, one might argue that throughout the entire process of engineering design, more active communication would have its benefits by allowing members to understand the process and each other more effectively.

2. 6. 2. Process of Engineering Design

Engineering design is an iterative process of defining problem, developing concepts or solutions, evaluating solutions, and implementation of the design (Bilen, 2001). During the concept development stage, brainstorming is an especially important task because the ideas the team generate during this stage decides the direction which rest of the project will take. Many researchers have researched brainstorming tasks due to its pronounced importance, and mixed evidence has been found whether or not team interaction helps or hinders the brainstorming process. Some studies found overt verbal communication hindered idea generation resulting in production losses (Mullen et al., 1991; Paulus, Dugosh, Dzindolet, Coskun, & Putman, 2002; Paulus, Larey, Putman, Leggett, & Roland, 1996) and poorer quality of ideas (Dornburg, Stevens, Hendrickson, & Davidson, 2009; Park-Gates, 2001), whereas others found team interaction resulted in higher performances (DeRosa, Smith, & Hantula, 2007; Hilliges et al., 2007; Nemeth & Ormiston, 2007). DeRosa et al. (2007) suggest that group interactions are beneficial for idea generation if an effective intervention were used. When Dornburg et al. (2009) tested the web-based electronic brainstorming system they developed, the participants in the group brainstorming setting were able to see the list of ideas that others generated and were allowed to build on others' ideas. However, Dornburg et al. found no interaction among members in the group brainstorming conditions to aid positive group processes. Hence, it can be argued that when group interaction is not facilitated with an intervention, it is possible for individual brainstorming to generate more and better ideas. Also, the use of structured procedures to help teams participate more and interact in a way that can stimulate idea generation will be beneficial.

2. 6. 3. Evaluation of Engineering Design Products

One final way of evaluating team effectiveness of an engineering design team is assessing the product generated as a result of design processes. Considering the purpose of engineering design teams is to produce innovative engineering product, the evaluation criteria must consider innovativeness. The evaluation criteria for innovativeness of engineering design products can be informed by studies of creativity and innovation. In the early years of creativity research, Guilford (1967) identified four basic characteristics of creative products: originality, fluency, flexibility and elaboration (Baer & Kaufman, 2006). Many researchers used these categories to evaluate creative products. However, measuring the level of creativity or innovativeness of an engineering product still remains a difficult process. With the recent increasing emphasis on creative idea generation involved in engineering design processes, a group brainstorming task has emerged as an appropriate tool for studying creativity; and the ideas generated from the brainstorming session are considered to be creative output. Some researchers focused on the quantity of the ideas to measure the level of group creativity (Hilliges et al., 2007), while others took a further step and assessed the creative quality of those ideas (Nemeth & Ormiston, 2007; Park-Gates, 2001). For instance, Park-Gates (2001) asked judges who were recruited from professional interior design firms to rate novelty and appropriateness on a 9-point rating scale to determine the creativity of interior design students' ideas portrayed in their design report. Nemeth and Ormiston (2007) asked coders to rate the level of creativity of participants' ideas, but did not provide the coders any detailed categories such as novelty or appropriateness that were used in Park-Gates' study. From these studies, authors who used more detailed criteria were able to provide richer and more convincing data. Hence, clearly defining detailed categories seems necessary when evaluating creative products.

For engineering creativity, a unique perspective of functionality comes into play for the assessment of a creative product. That is, a creative engineering product should be evaluated differently from a creative music piece or artwork. In that sense, many creativity researchers agreed that a creative product should not only be novel but also useful (Amabile, 1996). One singular property of creative engineering products is that they must go through the product lifecycle. While novelty might be important, other aspects such as functionality, feasibility, or marketability are even more significant and necessary for the products to be realized and used. Cropley and Cropley propose four dimensions specific for engineering creativity: relevance, novelty, elegance, and generalizability (Cropley & Cropley, 2005). The authors emphasized that a creative engineering product should not only offer a mechanical solution but also be aesthetically pleasing. Contemporary evidence supporting this hypothesis can be found in the recent success of design-oriented products in the market (e.g. iPod). Nonetheless, the authors stressed the importance of functional creativity in the explanation of the framework. In sum, it was clear that functionality should have greater emphasis when evaluating creative engineering products.

CHAPTER 3. METHODS

3. 0. OPERATIONAL DEFINITIONS

Interdisciplinary Team. According to the most commonly accepted definition by Salas, Dickinson, Converse, and Tannenbaum (1992, p. 4), a team is a unit consisting of two or more individuals "who interact, dynamically, interdependently, and adaptively toward a common goal, who have each been assigned specific roles to perform, and who have a limited time-span of membership." In contrast, a group is defined as a collection of individuals who exist for a certain period of time and convene for a particular purpose but may not have collective goals (O'Neil, Baker, & Kazlauskas, 1992, p. 155). The key difference between a team and a group is interdependency of members (Salas et al., 1992, p. 4). In the context of this study, a collection of participants shares a common goal (designing a product), exists for a limited time period (3 sessions), has certain performance roles (idea producer, note-taker, etc.). Furthermore, the members of the collection are interdependent on one another other; hence, the collection constitutes a team.

There are varying degrees of collaboration that cross disciplinary boundaries. Different researchers have used different labels to categorize such collaboration, including interdisciplinarity, multidisciplinarity, transdisciplinarity, and cross-disciplinarity (Huutoniemi, Klein, Bruun, & Hukkinen, 2010). Multidisciplinarity indicates the type of collaboration that simply brings expertise from more than one discipline without integration, whereas interdisciplinarity demonstrates integration and synthesis of expertise across disciplines (Borrego & Newswander, 2008; Klein, 2004; Lattuca, 2001;

National Academies of Science, 2005). Transdisciplinarity is defined as a process wherein a novel and transcendent theoretical framework is developed as a result of collaboration across disciplines over extended periods of time (Rosenfield, 1992 as cited in Klein, 2008). Cross-disciplinarity is sometimes used interchangeably with interdisciplinarity (Crowley, Eigenbrode, O'rourke, & Wulfhorst, 2010). In other cases, it takes on a more generic definition that can include any type of collaboration involving members or methods from more than one discipline (Klein, 2008; National Academies of Science, 2005; Salmons & Wilson, 2007).

The context of this study requires integration of knowledge across disciplines, or interdisciplinarity. Therefore, three individuals were recruited from three different academic disciplines (Electronic & Computer Engineering, Industrial Design, and Marketing) to form an interdisciplinary team. To control the familiarity of team members, the participants were limited to students who had no prior history of collaboration with one another.

<u>Team Effectiveness</u>. Based on the classic work of Hackman (1987) as well as the conceptualization by Salas et al. (2007), for the purpose of this study, team effectiveness is understood to have three different facets: team process performance, team-produced product, and members' satisfaction with the teamwork and other members. Team process performances were measured in terms of team interactions (physical and verbal) and team mental models (taskwork and teamwork). The team-produced products were analyzed using the design rubric, and other team effectiveness

constructs such as satisfaction were measured using questionnaires and content analysis of team communications.

Kiva. The Kiva is a cylindrically-shaped meeting space especially designed to stimulate team interaction. The walls are covered with curved whiteboards, and the space features wheeled chairs that are modular and movable to allow for flexible room arrangements. The Kiva used in this study was located in Cowgil Hall at Virginia Polytechnic Institute.

Conventional Conference Room. For the purpose of this study, a 'conventional conference room' is a rectangular room with a rectangular table in the middle of the room. Chairs with no wheels were provided around the table. One whiteboard was provided and was located approximately one foot from one end of the table.

Interaction Strategy Design Support. Based on previous research on interdisciplinary design teams (Adamczyk & Twidale, 2007; Chiu, 2002) and exemplary industry practices of leading design consulting firms such as IDEO (Simsarian, 2003) and MAYA Design, interaction strategy design support (ISDS) is defined as a set of activities intended to stimulate teams' verbal and physical interactions. The participants under the ISDS-present condition received two structured brainstorming sessions designed based on the industry practice observed during the Phase 1 of this study. In the structured brainstorming, the participants were asked to brainstorm individually for ten minutes, in order to generate—on sticky notes—as many ideas as possible, then use whiteboards to post and categorize their ideas as a team. Once all of the ideas were posted, each member was asked to vote for the two best ideas from the board. For each upvoted idea, each participant who voted for the idea was then asked to explain her choice. The person who posted said idea was then asked to explain the idea in further details.

The purpose of this process was to encourage the discussion and negotiation among team members while generating many ideas as individuals. Also, voting and explanation encouraged members to produce higher quality ideas. The structured brainstorming process was used twice during the session for exploring design opportunities (problems) as well as seeking design solutions to solve the problems.

3. 1. PHASE 1: FIELD-BASED PILOT STUDY

3. 1. 1. Purpose of Phase 1

Phase 1 had two purposes: 1) obtaining expert insights on the relationship between the physical design environment and interdisciplinary design, and 2) observing professional teams in an industry setting to investigate how the spatial arrangement and interaction strategy design support were used. Information obtained from this phase was used to construct the behavioral types and to refine Phase 2 experimental procedures.

3. 1. 2. Methods

Phase 1 used an ethnographic research approach, with direct observations and semi-structured interviews. The study procedures were approved by Virginia Tech's Institutional Review Board.

3. 1. 2. 1. Observation Sessions

Two interdisciplinary team meetings occurring in the Kiva at MAYA Design Inc. were observed and video-recorded. The participants were clients of MAYA Design Inc. using the Kiva facility and received ISDS from expert facilitators at MAYA Design Inc. The researcher obtained participant permission to observe and record sessions via MAYA administrative staff, and then traveled to the company site to conduct the sessions. The participants signed the informed consent forms before the beginning of the session, and then the researcher explained the purpose of the observation. After the informed consent procedure, the researcher retreated to an observation room to watch a video-feed showing the aerial view of the Kiva. The sessions were video-recorded, and the experimenter took observation notes during the session. After each session ended, the video recordings were transcribed verbatim by the researcher to reconstruct the ISDS procedures. The researcher also obtained internal documents explaining ISDS procedures used at the company. Facilitator remarks from the video transcripts were summarized and integrated with information obtained from the internal documents to create a step-by-step activity protocol. For the physical interactions of participants within the space, the video-recordings from the top-down view (shown in Figure 7) were coded to create a list of important behaviors of participants.

Figure 5. Top-down view of a design session in the Kiva at MAYA Design Inc.
(photographed by the researcher, used with permission of the participants)

3. 1. 2. 2. Semi-structured Interviews

In addition to observing the participants, the researcher interviewed two subject matter experts from MAYA Design Inc. (See Appendix B for interview questions). Participant A was the founder of the MAYA Design Inc. Participant B was the president and CEO of MAYA Design Inc. Both participants had been working in the field of interdisciplinary design as industrial designers for more than 20 years. They had also been engaged in developing environments and strategies to support interdisciplinary product design teams since 2000.

One interview took place at Virginia Polytechnic Institute in Blacksburg, VA, and the other interview took place at MAYA Design Inc. in Pittsburgh, PA. Before the interview, the interviewees were given informed consent forms. After reviewing the consent form with the researcher, they signed the form. The experimenter asked the participants questions related to factors that affect interdisciplinary design processes, including success indicators of interdisciplinary teams and in-Kiva activities. In addition, the participants were asked to review the preliminary design task for the Phase 2 and provide feedback. Each interview took approximately forty minutes and was audio-recorded. The researcher transcribed verbatim the audio recordings of both interviews for content analysis.

3. 2. PHASE 2: LABORATORY-BASED STUDY ON THE INFLUENCE OF SPACE AND INTERACTION STRATEGY SUPPORT

3. 2. 1. Purpose of Phase 2

Phase 2 was conducted as a laboratory-based experimental study that investigated the impact of physical environment and interaction strategy design support (ISDS) on the effectiveness of interdisciplinary engineering design teams. The purpose of Phase 2 was to investigate the influence of physical space and interaction strategy design support on the effectiveness of interdisciplinary engineering design teams.

3. 2. 2. Methods

This study took the form of a 2 x 2 factorial design with physical space and interaction strategy design support (ISDS) as two main factors. The physical space factor had two levels: the Kiva and conventional conference room (CCR). The Interaction strategy design support factor also had two levels: existence and absence.

Table 2

Experimental Design

		Interaction Strategy Design Support (ISDS)	
		Present	Absent
Physical Space	Kiva	Kiva + ISDS Present	Kiva + ISDS Absent
	Conventional Conference Room (CCR)	CCR + ISDS Present	CCR + ISDS Absent

3. 2. 1. 1. Variables

Independent Variables. Two independent variables were considered: physical environment (room) and interaction strategy design support (ISDS). For their experimental sessions, Half of the participants were placed in conventional conference rooms that were set up in the Macroergonomics and Group Decision Systems Laboratory in Whittemore Hall at Virginia Polytechnic Institute (settings shown in Figure 6), and the other half were placed in the Kiva, which was set up in Cowgil Hall at Virginia Tech (settings shown in Figure 7). Additionally, half of the teams were given interaction strategy support while the other half was not. Table 3 summarizes the different experimental conditions.

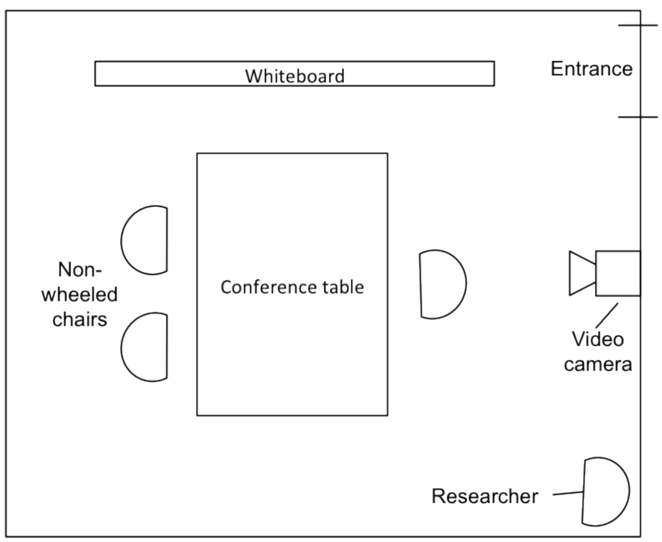

Figure 6. Schematic diagram of conference room setting

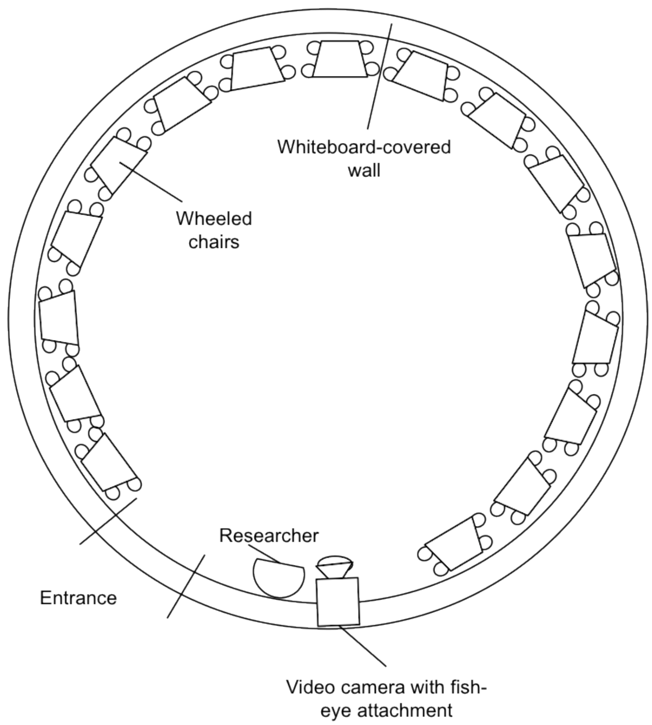

Figure 7. Schematic diagram of Kiva setting

Table 3

Description of Four Experimental Conditions

Experimental Conditions	Description
Conference room + ISDS support absent	Participants meet in a conference room. The room has a conference table in the middle of the room, three chairs around the table, and one whiteboard on the side of the room. The researcher does not provide facilitation during sessions. The instruction sheet is given and read by the researcher for the participants in the beginning of the concept generation session.
Conference room + ISDS support present	Participants meet in a conference room. The room has a conference table in the middle of the room, three chairs around the table, and one whiteboard on the side of the room. During the concept generation session, the researcher provides two facilitated brainstorming exercises that incorporate features of interaction strategies that industry experts use. The pre-written instructions are read to the participants during the facilitation.
Kiva + ISDS support absent	Participants meet in the Kiva. The room is cylindrically shaped and has whiteboards around the perimeter of the

	room. Twelve wheeled chairs are provided around the perimeter. One wheeled desk was placed next to the entrance. The researcher does not provide facilitation during sessions. The instruction sheet is given and read by the researcher for the participants in the beginning of the concept generation session.
Kiva + ISDS support present	Participants meet in the Kiva. The room is cylindrically shaped and has whiteboards around the perimeter of the room. Twelve wheeled chairs are provided around the perimeter. One wheeled desk was placed next to the entrance. During the concept generation session, the researcher provides two facilitated brainstorming exercises that incorporate features of interaction strategies that industry experts use. The pre-written instructions are read to the participants during the facilitation.

Dependent Variables. Five dependent variables in two categories, team process and output, were examined: 1) verbal interactions (rate and quality), 2) physical interactions (rate and quality), 3) team effectiveness scores (measured using the Team Diagnostic Survey, measuring both team processes and outcomes), 4) similarity of team mental models (task work & teamwork mental models), and 5) quality of the team-produced products.

3. 2. 1. 2. Participants

A total of thirty-six participants grouped into twelve interdisciplinary teams (three teams per each experimental condition) recruited from the senior-level (4^{th} year or beyond) undergraduate students at Virginia Tech participated in the study. The students majored in either Electrical and Computer Engineering (ECE), Industrial Design (ID), or Marketing (MKT). The age of the participants ranged from 19 to 24 (M = 21.50, SD = 1.03), and gender of the participants were mixed with more females (64%) than males (36%). Age and gender were not explored as a factor in this study. The participants were recruited using emails disseminated via departmental listservs, flyers posted on bulletin boards in various locations on campus, and recruiting emails sent to various senior level classes in all three academic departments. To balance team composition, each team included one student from each discipline. Members of each team were required to have no prior collaboration history with each other. The participants were compensated US$10 per hour.

3. 2. 1. 3. Instruments

Team Diagnostic Survey. Selected items from the Team Diagnostic Survey (TDS) (Wageman, Hackman, & Lehman, 2005) were used in order to measure self-reported measures of team performance and participants' satisfaction with the teamwork and with other members. A total of fifty-eight items were selected from the original instrument, based on their applicability to the laboratory-based situations that participants would experience. Thus, items addressing organizational context were considered not relevant and excluded from this study. The questionnaire was administered individually as a paper-based test after all sessions were completed (See Appendix C for the full instrument used for this research).

Team Mental Model Questionnaire. The level of team mental models (TMM) was measured using a shortened version of the pair-wise relatedness rating scales adopted from Lim and Klein (2006)'s empirical study. The statement pairs were composed based on the original Canon-Bowers conceptualization (1993) to ensure that all four areas of team mental models (equipment, task, team interaction, and team) were covered. Lim and Klein's original scale contained a total of one hundred sixty pairs of statements. Its length was determined to be unsuitable for undergraduate students, who are expected to have shorter attention spans compared to the military personnel analyzed in the original study. Thus, a shortened version was created with the authors' permission (See Appendix D for the full instrument).

3. 2. 1. 4. Design Task and Evaluation

Design Task. To select an interdisciplinary design topic that reflects current trends, several design tasks and competition criteria were reviewed, including four existing interdisciplinary design, industrial design and engineering design competitions: the CHI 2010 Student Design Competition, the International Design Excellence Awards 2010, the Create The Future NASA Tech Brief Design Contest 2008, and the 2010 METROPOLIS Next Generation Design Competition. The competitions encompassed various design areas from sustainable technologies to interactive product experiences. After considering the domain expertise of the participants, it was decided that for the purposes of this study the teams should address an open-ended design problem with broad design specifications including the knowledge of domains of industrial design, electronic and computer engineering, and marketing. The participants were asked to design an electronic device that encourages people to exercise regularly. (This is similar to the CHI 2010 problem of designing a device that encourages people to take a walk.) Each team's solution must address one main theme that encourages people to exercise, such as health, enjoyment, or community. Each team was required to create a prototype that presents a form and some level of technical function of the product, a sketch of basic user interface, and a hand-drawn poster of a magazine advertisement for the product. The participants had two design sessions (Sessions 2 and 3) to complete the tasks. During Session 2, they explored the design problem, developed concepts, generated alternatives for the design solution, and created a list of prototype materials for Session 3. During Session 3, they used the materials provided to create a low-fidelity prototype. Also, the participants were asked to draw basic user interface sketches that show the layout of the highest level of menus. The third deliverable was the one-page magazine advertisement. The design quality of the team-produced products was reviewed based on the following criteria: 1) originality of the solution, 2) manufacturability, 3) benefit to the user, 4) appropriate aesthetics, and 5) marketability. A scoring sheet was created using an eleven-point scale (0 to 10), so that the highest score for each criterion would be 10.

Evaluation of Design Outcome. Two experienced faculty members from the Department of Electrical and Computer Engineering and the Department of Industrial Design evaluated the products that the participants created. The two evaluators have been co-instructing an interdisciplinary pervasive computing design course for the past six years, and in that context, they have evaluated this type of interdisciplinary products. The evaluators examined a total of twelve product packages (one per team) that contained the following: a participant-produced product description, photographs of the low-fidelity prototype, and sketches (e.g. magazine advertisement and UI sketches). Appendix E contains the participant instructions and Appendix F contains the evaluation sheet.

3. 2. 1. 5. Procedures

The experiment consisted of one pre-session online questionnaire (the Thomas-Kilmann Conflict Handling Mode Questionnaire) followed by three experimental sessions with at least a one-week interval between the pre-session questionnaire and the sessions. The participants were asked to review and sign informed consent forms before they completed a pre-session questionnaire. After the participants were recruited, they were randomly assigned (within the same academic discipline) to each experimental condition to create an interdisciplinary team of three, to include a member from each academic discipline. All of the sessions were video-recorded. The video-recordings were used to analyze the degree of significant participant behaviors regarding physical environment (whiteboard usage, space usage, and furniture usage).

The original procedures were written before Phase 1 was executed. To improve the design task used in Phase 2, the subject matter experts being interviewed during Phase 1 examined the procedures. Necessary changes were made based on their feedback. The final procedures are shown here.

- ***Pre-session Questionnaires (twenty minutes)***

  After the participants were recruited, they were given an online link to an informed consent form, which explains the purpose of the study and the experimental procedures involved. Once they completed the informed consent procedure the participants were given a demographic questionnaire and the Thomas-Killman Conflict Handling Mode Instrument. The questionnaires were administered as web-based tests through Virginia Tech Qualtrics (https://virginiatech.qualtrics.com) that took approximately twenty minutes to complete.

- ***Session 1: Familiarization (one hour)***

  The first session was conducted at least one week after the pre-session questionnaires were filled out. After reporting to the test site, the participants participated in a team brainstorming session (using a simple brainstorming task based on Hilliges et al. (2007)) in order to become familiar with the spatial conditions. The participants were asked to produce as many ideas as possible for taking care of an Inuit coming to a foreign country, who did not know the country's language nor had any useful equipment for the new environment. For the ISDS-present condition, a structured procedure (individual idea generation, team idea integration, and voting) was used, and the participants in the ISDS-absent condition conducted a group brainstorming without specific instructions.

- ***Session 2: Design Concept Development Procedure (2-hours)***

  In the second session, the participants were given instruction sheets describing the design task (Appendix E). The researcher read the instruction sheet to the participants. After reading the instruction sheet, ISDS-absent teams were asked to commence designing the product. For the teams in the ISDS-present condition, the researcher read further instructions to give them two facilitated brainstorming exercises. For the first exercise, adapted from the "stakeholder mapping" of MAYA Design Inc. (details in section 4.1.2.), participants were asked to generate a list of all the people who would touch the product, have any relationship with the product, or care if it worked. They wrote this down on sticky notes individually (five minutes) then posted them on the whiteboard. Once these were posted on the board, participants were asked to talk about each of the stakeholders' concerns. After this discussion, the participants were asked to map the stakeholders' relationships. Once mapping is completed, the participants were asked to decide the primary target for their product.

For the second exercise, the participants completed a facilitated brainstorming session that integrated features of "round robin" of MAYA Design Inc. (details in section 4.1.2.) to generate design concepts. The participants were asked to brainstorm individually to generate as many ideas as possible on sticky notes (ten minutes) then post the ideas on the whiteboards. Once all the notes were posted, they were asked to go through the ideas and take turns to explain: 1) what the idea was about, 2) why the idea would fail, and 3) what they could do to make the idea work. Once they finished this process, the participants were given three sticky tabs to vote for the best design ideas. After the voting, the researcher identified the upvoted ideas and asked the participants who voted for the idea to explain why she voted for the idea, and then the person who posted the upvoted idea was asked to explain the idea in further details. Once participants discussed all of the ideas with votes, they were asked to choose one design idea that they would develop for the rest of session 2 and session 3. The purpose of this process was to encourage the discussion and negotiation among team members while generating many ideas as individuals. The voting and explanation process were intended to encourage members to produce ideas with higher quality.

After teams decided the final design idea they were asked to submit a list of materials they would like to use for prototyping in the next session. After the concept generation session was completed, a team mental model questionnaire was administered.

- ***Session 3: Prototyping and Finalizing Design Procedure (2-hours)***

  In the third session, the participants were asked to prototype their product idea using the materials they had requested at the end of the previous session. The prototype was required to show the basic form and function of the product. Also, the participants were asked to sketch a series of user interface screens for a task of their choice, as well as a one page magazine advertisement for their product. The three required deliverables were selected to include domain knowledge of all three disciplinary backgrounds. After the session was completed, the Team Diagnostic Survey was administered.

3. 2. 1. 6. Data Analysis Strategies

Quantitative Data Analysis. For the quantitative measurements, the Shaprio-Wilk test was conducted to check for normality. As expected with a small sample size, the data were not normally distributed. Hence, the nonparametric tests were conducted to test for the main effect of physical space, main effect of interaction strategy design support, and the interaction effect of physical space versus ISDS. Kruskal-Wallis nonparametric one-way analysis of variance (ANOVA) was conducted to test for the main effects. To test for the two-way interaction effect, Aligned Rank Transform (ART) procedure was conducted using ARTool (Wobbrock, Findlater, Gergel & Higgins, 2011). The transformed data were tested using the parametric two-way ANOVA. For the TDS data, internal consistency of the questionnaire was tested by calculating Cronbach's alphas. The alpha values ranged from 0.91 to 0.92 for individual items with 0.91 for the entire question set. All of the statistical tests were conducted using SAS 9.3 and SAS JMP Pro 10.

<u>Qualitative Data Analysis.</u> For the qualitative data, the video-recordings of the experimental sessions and audio-recordings of interviews were transcribed verbatim by the researcher using InqScribe 2.1. A thematic analysis of verbal interactions was conducted on the transcripts of the team communications. In order to guide the analysis based on the conceptual framework of teamwork and team communications, "analyst-constructed typologies (Patton, 2002, p. 458)" were constructed before the analysis began. *A priori* codes were extracted by reviewing team literature. With the *a priori* codes, the first round of coding was conducted for samples of transcripts from all experimental conditions. During the first round of coding, "indigenous typologies (Patton, 2002, p. 458)" emerged from within the data, and the emerging codes were then added to the codebook. The final version of the codebook was used to conduct the second round of coding for all transcripts. After the codebook was finalized, the researcher trained an external coder. The external coder did not have prior knowledge of the researcher's study. After the training, each coder (the researcher and the external coder) conducted coding independently on four transcripts that were randomly

selected from each experimental condition. After one round of coding, the researcher compared the coding results, and then created a list of non-matching items. The researcher and the coder convened for a resolution meeting. During the meeting, each item on the list was reviewed. For an item that one of the coders applied a code and the other did not, the coder who assigned a code for the item explained the rationale for applying the code first. And then the coder who did not assign the code explained why he/she did not assign any code. After both turns, the coders decided to 1) remove the applied code, 2) assign the new code, or 3) not change the original status. For each item that was assigned different codes, the coders took turns for explaining their rationales. After this explanation process, the coders chose one of four resolutions: 1) follow coder A's code, 2) follow coder B's code, 3) change to a new code, or 4) remove the already assigned codes. Because the codes addressed team-related behaviors that are not mutually exclusive, Cohen's Kappa was not applicable for this study.

After the resolution process, the inter-coder reliability score was calculated based on the proportion of agreement for all coded items.

$$Proportion\ of\ agreement\ (\%) = \frac{Number\ of\ agreement}{Number\ of\ agreement + Number\ of\ disagreement} * 100$$

From the calculation, the inter-coder reliability ranged from 71% to 79%, which met the conventional level of inter-coder reliability (Table 4).

Table 4

Inter-coder Agreement for Qualitative Coding

Transcript	Proportion of Agreement (%)
Team 2 (Conf + ISDS absent)	72
Team 6 (Conf + ISDS present)	71
Team 7 (Kiva + ISDS absent)	79
Team 11 (Kiva + ISDS present)	73

After the data was coded, the researcher created concept maps of codes to create themes that describe tacit processes of team interactions. The coding procedures were completed using both Microsoft Excel and TAMS Analyzer 4.43. The codebook is shown in Table 5, and the concept map of themes is shown in Figure 8.

Table 5

Codebook for Verbal Interactions

Categories	Codes	Operational Definitions	Sources
Roles	Emergent leadership	- One member assumes a leader role by combining individual contributions, providing expectations, or clarifying member roles	Cannon-Bowers, Tannenbaum, Salas, and Volpe (1995), Salas (2005)
	Flexible leadership	- Changing leadership depending on the topic/task	Mahoney & Turkovich
	Rigid leadership	- A certain individual assumes the leadership regardless of a task/topic change	Mahoney & Turkovich

	Performance monitoring	- Following up with team members to ensure message was received, acknowledging that a message was received - Clarifying with the sender of the message that the message received is the same as the intended message - Identifying mistakes of another member - Providing feedback that leads to self-correction	Salas (2005)
	Shared understanding	- Anticipating each other's needs (e.g. providing information or tools without explicit requests, completing each other's sentences)	Salas (2005), Cannon-Bowers, Tannenbaum, Salas, and Volpe (1995); Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers (2000)
Processes	Work strategies	- Taking initiatives to create their own rules for the team regarding executing tasks, communicating ideas, making decisions, etc.	Emerged from data
	Disciplinary grounding	- Mentioning, showing, expressing the disciplinary grounded expertise (e.g. concepts, methods, background knowledge, technical terms, etc	Boix-Mansilla & Duraising (2007)
	Appreciation of expertise	- Recognizing expertise that other members bring to the team - Positive attitude towards another member's idea/remark	Boix-Mansilla & Duraising (2007)
	Interdisciplinary integration	- More than one person work together on one deliverable - Members provide feedback to each other - Term exchanges occur among members	Emerged from data
	Division of work (divide-and-conquer)	- Members assign work based on disciplines - One person works on one deliverable without asking for other members' input/feedback	Emerged from data
Outcomes	Satisfaction	- Expressing satisfaction with members, process, environment, or product (that	Emerged from data

they are designing)

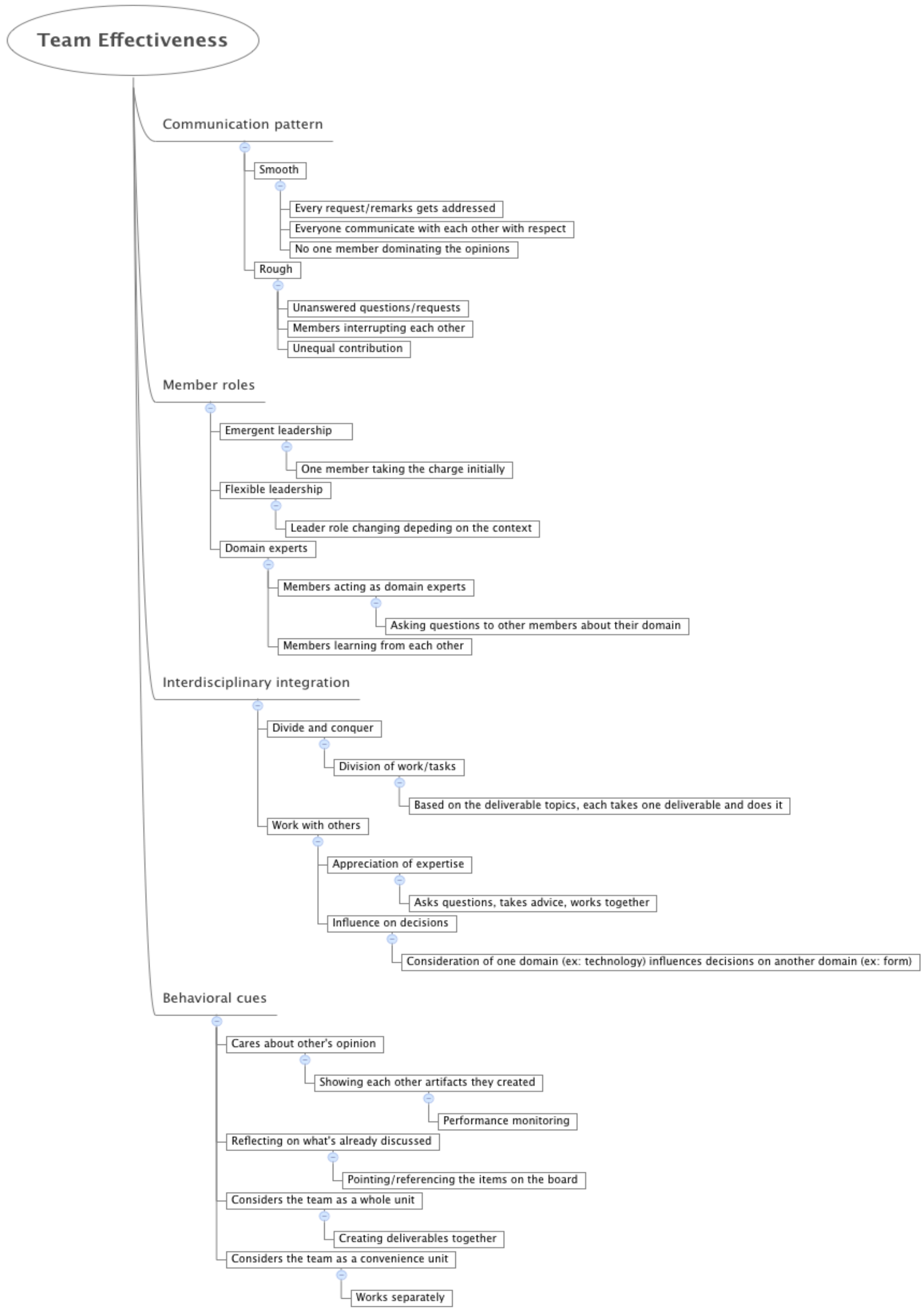

Figure 8. Concept map for thematic analysis

For the physical interactions, video-recordings from the top-down view were coded. A Sony DCR SX-45 camera was used to video-record the conference room sessions, and a fish-eye lens attachment was used to capture the sessions occurring in the Kiva. From Phase 1 data, critical physical actions (walking, drawing, annotating, pointing, acquiring, reconfiguring, and showing) were identified (details explained in section 4. 1. 4.). The video recordings were coded for present – absent status of these actions. The researcher created a codebook that included the list of codes, definition of codes, and start/stop decision rules. The events were coded as start and stop events following the decision rules using Noldus Observer XT 8.0 (shown in Figure 9). In addition, occupancy maps of the space usage were constructed based on the portion occupied by team members during the experimental sessions. The operational definitions of the codes are shown in Table 6.

Table 6

Code Definitions for Physical Interactions

Categories	Codes	Definitions	Sources
Spatial arrangement	Walking	A change in spatial occupation by a participant: moving oneself from one location to another	Emerged from phase 1 data
	Reconfiguring	Changing spatial arrangement of the space by moving furniture	Emerged from phase 1 data
Tools	Drawing	Adding a new item on the shared surface. Items can be words or figures, and the shared surface can be whiteboards or paper. The activity should involve more than one member to be coded as drawing.	Bly 1988
	Annotating -self	Adding something to an item on the board drawn/written by him/herself	Emerged from phase 1 data
	Annotating -other	Adding something to an item on the board drawn/written by another team member	Emerged from phase 1 data
	Pointing	Physically referencing a previously discussed item on the board with: a hand gesture and/or a head movement	Bly 1988

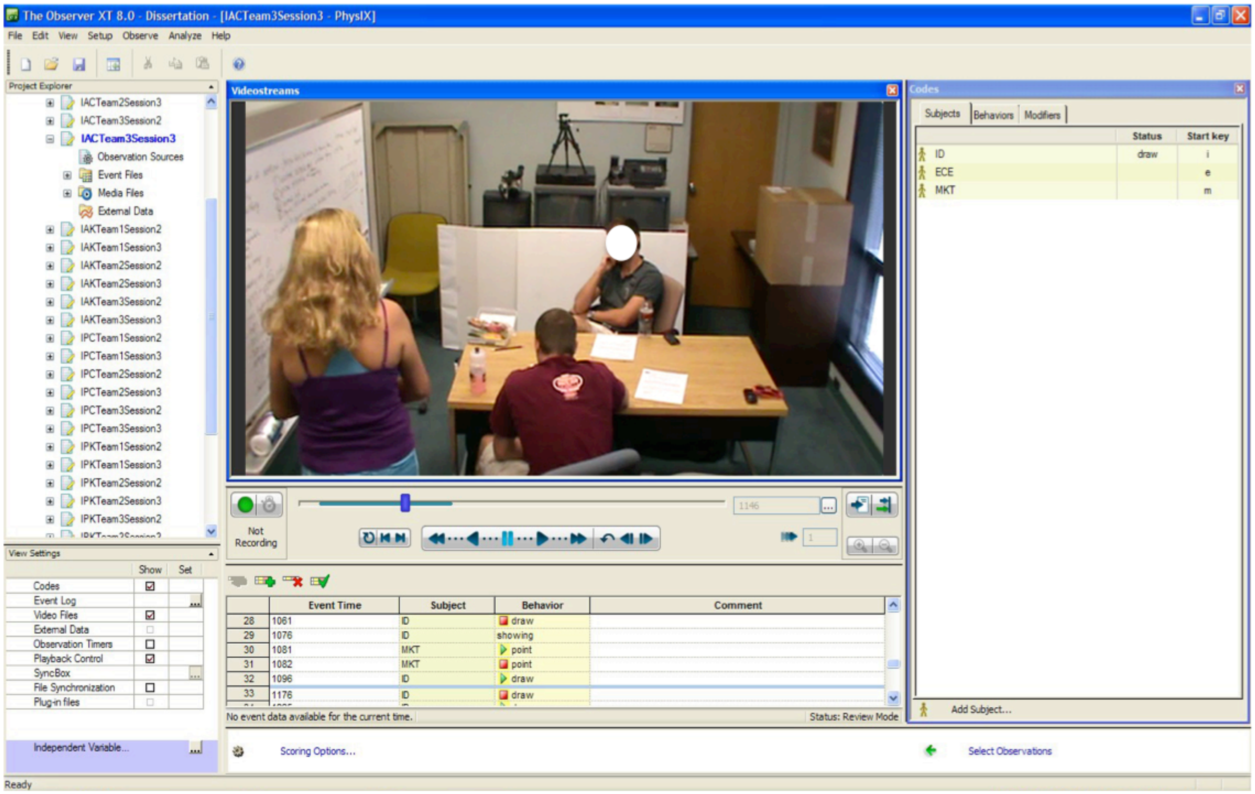

Figure 9. Sample of a Noldus Observer® XT 8.0 behavior coding screen

In summary, to allow for a holistic investigation of the factors impacting the effectiveness of interdisciplinary design teams, mixed methods of both qualitative and quantitative strategies were chosen. In particular, the independent variables of interest for this study were the types of physical environment and the presence of interaction strategy design support. The dependent variables were: verbal interactions (rate and quality), physical interactions (rate and quality), team effectiveness scores, similarity of team mental models, and quality of the team-produced products. These variables were measured using team communication transcripts (verbal interactions), video analysis (physical interactions), questionnaires (team effectiveness scores and similarity of team mental models), and expert evaluations (quality of the team-produced products).

CHAPTER 4. RESULTS

4. 1. Phase 1: A Field-Based Pilot Study

4. 1. 1. Observation of In-Kiva Sessions at MAYA Design, Inc.

The purpose of the observation sessions in this phase was to observe the Kiva space usage with structured exercises run by experts. The exercises were designed to promote ideation process and impress upon users to take advantage of the features of the Kiva. Analyzing the observation data resulted in solid protocols for interaction design strategies as well as a list of critical user behaviors to be used in Phase 2.

Two in-Kiva sessions were observed and video-recorded at MAYA Design Inc. Both sessions were dedicated to service design projects. In Session 1, the goal of the meeting was to design a sustainable business model for a non-profit charity organization. In Session 2, the goal of the meeting was to design a mentor program for a local chapter of designers' association. The participants were informed about the video recording and signed the informed consent forms.

Observation Session #1. A non-profit charity organization was the client for this session. A total of fourteen participants (eight male, six female) participated in the session. Two moderators who were senior designers at MAYA Design Inc. led the session. The session lasted for approximately 8eighthours. The goal of the session was to design a new, sustainable business model for the Institute, which would include new profitable services utilizing the existing facilities. A total of four structured exercises—rose-bud-thorn analysis, trend mapping, stakeholder mapping, and monster-in-a-box—were conducted (MAYA Design Inc., 2007).

Observation Session #2. A non-profit professional association for design was the client for this session. A total of fifteen participants (twelve male, three female) participated in the session. Two moderators who were junior designers at MAYA Design led the session. The session lasted approximately 3.5 hours. The goal of the session was to design a council-based mentor program that provides a platform for members to develop trusted counsel. A total of three structured exercises—rose-bud-thorn analysis, monster-in-a-box, and round robin—were conducted.

4. 1. 2. In-Kiva Activities Used During the Sessions

Using the observation transcripts as well as documents gathered from MAYA Design, Inc., a procedure for each structured exercise was constructed. Every remark a moderator made relative to the session management was gathered from the observation transcripts and integrated with the information from the "MAYA Team Toolkit" document, and then converted into a step-by-step procedure. A total of five structured exercises (Rose-Bud-Thorn Analysis, Trend Mapping, Stakeholder Mapping, Monster-in-a-Box, and Round Robin) were identified. The detailed procedures are explained below.

Rose-Bud-Thorn Analysis. This type of brainstorming session focuses on the challenges and opportunities surrounding the design problem. The material generated from this activity feeds other activities.

1. Pick three to four different topic areas and draw corresponding circles for each topic area on the whiteboard. For example, the areas can be software, hardware, service, customer, etc.

2. Hand out pink, green, and yellow sticky notes for different idea categories. Explain what rose, bud, and thorn mean. A pink note corresponds to a 'rose,' which is a perfect design opportunity related to the topic area that is fully formed. A rose could be a newly developed technology, a socioeconomic change, etc. A green note corresponds to a 'bud', which is an opportunity that has potential of turning into a rose. A bud is an opportunity not yet fully formed but worth exploring. A yellow note corresponds to a 'thorn', which is a challenge or obstacle related to a topic area. An example of a thorn could be a regulatory restriction or cultural reluctance.
3. Ask each participant to write down at least one rose, bud, and thorn for each topic area. Give them five minutes to work individually on this.
4. After individual work, ask participants to give roses, buds, and thorns. Ask participants to elaborate on each item when they submit their notes. Group the notes in bubbles surrounding topic area. Ask participants to explain relationships between bubbles and continue making connections between items when they are pointed out. Repeat this for all of the topic areas.
5. Once the map of opportunities and challenges is completed, review the map with the participants. After the review, hand out sticky tabs. Ask each participant to identify her top two opportunities and challenges that they think need to be addressed or offer the largest potential, and vote with the sticky tabs.

6. Go over the items with the highest number of votes. Ask participants who voted for the item to give the reason why they voted for it. Ask the participant who submitted that item to elaborate further. Summarize the results with the participants by reviewing the map. (MAYA Design, Inc., 2007)

Trend Mapping. This is a brainstorming exercise focused on considering future trends to identify opportunities and restrictions along with the time dimension.

1. Draw a timeline ranging from the current year to a future date (e.g., 2020) across the top of a whiteboard. On the left side, add categories related to the design problem (e.g., software, hardware, service, user, competition, regulation, etc.).
2. Hand out sticky notes. Ask participants to come up with at least two trends for any category and write each trend on a sticky note. Ask them to do this individually.
3. Ask all the participants to come up to the board and place their sticky notes on the cell that corresponds to appropriate category and place on the timeline. As they place their notes, encourage them to group similar items together.
4. Ask participants to look at the timeline and choose a trend they did not write but find intriguing.
5. Ask for volunteers to talk about the trend of their choices. Ask each to say why she chose the particular trend and to explain her own opinion about

that trend. Find the person who wrote the trend and ask for elaboration. Lead this into a group discussion on different trends that are emerging and expected to emerge in the future regarding the design problem.

6. Capture the differences and comments on the whiteboard and annotate to make connections to build an idea map. Ask participants how the trends will affect the design decisions.
7. Hand out sticky tabs for voting. Ask everyone to vote on the top two trends that deserve to be addressed. Go over the items with the highest number of votes. Ask each participant who voted for the item to give a reason why she voted for it. Ask the participant who submitted that item to elaborate further. Summarize the results with the participants by reviewing the map. (MAYA Design, Inc., 2007)

Stakeholder Mapping. A stakeholder map is a visualization of everyone who has an interest in a certain product. This exercise is a brainstorming session that focuses on the different stakeholders of the product. Participants define the user landscape through this activity.

1. Form smaller groups with one moderator per group. Ask participants to generate a list of all the people who touch the product (or have any relationship with the product, in case of a service product) or care if it works. Write this list down on the whiteboard.
2. Ask participants what each of those stakeholders' concern is. Note their role, needs, market segment, personal goals, behaviors, frustrations, etc.

3. Map the stakeholders' relationships including reporting hierarchy, frictions, and friendliness, etc.
4. Review the map with the participants and ask them to identify the primary user group for their design.

Monster-in-a-Box. This exercise was a design activity that uses ideas generated from the previous exercises to produce a design solution that reflects various perspectives.

1. Prepare an adhesive poster sheet for each participant.
2. Ask them to spend ten minutes to review the material from previous brainstorming sessions and select a main design idea and key stakeholders.
3. Tell the participants to draw a product-packaging box that they would use if the product were sold at a supermarket. Tell them to name the product, include information about specific features.
4. On the poster sheet, ask the participants to annotate the drawing, explaining the features, user groups, and other details of the product.
5. Once everyone is done, go around the room and have everyone present their monster-in-a-box.
6. Hand out colored sticky notes in two different colors. Ask participants to use one color to vote for the top two big ideas, and use the other color to vote for the top two detailed features. They cannot vote for their own poster.

7. Once voting is done, review the items (both big ideas and details) that received the highest number of votes. Integrate the big ideas and detailed features that the group thought were the best. (MAYA Design, Inc., 2007)

Round Robin. This exercise focuses on generating a collection of ideas to discover challenges and turning those challenges into solutions.

1. Form a group of three and assign each member a number (e.g. 1, 2, and 3).
2. On a piece of paper, write a brief challenge or an issue related to the given design problem.
3. Ask member 1 to read the issue and generate a solution (“hack”) to solve it.
4. Ask member 2 to review the solution member 2 generated and explain why it will fail and write it down.
5. Ask member 3 to review the critique that member 2 wrote down, and come up with an idea to resolve the issues that were discussed in the critique.
6. Ask each group to shift to the right so each team has another group’s output.
7. Ask each group to work as a team to come up with a solution that resolves all of the issues by creatively meeting the challenge.
8. Ask each team to present their solution. Ask them to explain the issues, the hack, and the final solution. (MAYA Design, Inc., 2007)

4. 1. 3. Characteristics of MAYA's Interaction Design Strategies

Observing structured exercises that MAYA Design used during the sessions revealed two unique features that nominal group brainstorming exercises (Paulus, 2002) do not employ. First, they allotted individual idea generation in the beginning of every exercise. It enabled every participant to prepare his/her own idea to contribute to the team level discussion later. This protects the brainstorming process from being dominated by a few outspoken members and ensures that everyone's voice is heard. Second, an instant and visual voting system is built into the exercises. The participants were asked to vote for the best ideas using sticky notes. This forces everyone to walk around the perimeter and examine every item written and drawn on the board, which encouraged the use of physical space as well as discussions as members run into each other. Once the voting is completed, it was easy to identify the items with the highest votes, because the votes were visible. This was an immediate and easy way to gauge the team's preference on each item after ideation. These identified characteristics were confirmed in interviews with the subject matter experts.

4. 1. 4. Use of Physical Features in the Kiva

Another goal of the observation sessions in Phase 1 was to identify critical behaviors that participants show in relation to the space usage, so that a coding scheme can be constructed for Phase 2. The video recording of the observation sessions were transcribed verbatim and then coded for physical movements of the participants and their behaviors. The codes were generated during the first round of coding and then later-added codes were applied again during the second round of coding. During these sessions, participants moved around the Kiva, rearranged furniture, and used whiteboards for drawing, writing, and referencing. In both sessions, the degree of physical movements increased with the time they spent in the Kiva. The list of codes that were used for coding transcripts is shown below.

1. Acquiring (ACQUIRE): This code was used for an act of acquiring needed materials. This included obtaining markers, sticky notes, adhesive poster sheets, pens, etc.
2. Walking (WALK): This code was used for an act of walking within, to, and from the Kiva.
3. Pointing (P): This code was used for an act of pointing at items on the whiteboard in the Kiva. A participant explicitly reading something from the whiteboard was coded as referencing (R).
4. Referencing (R): This code was used for an act of referencing to a previously discussed item by reading it from the whiteboard. This was also shown in a previous empirical study (Bly, 1988).
5. Writing or drawing (D): This code was used for an act of writing or drawing on the whiteboard. This was also shown in a previous empirical study (Bly, 1988).
6. Moving (MOVE): This code was used for an act of moving items within the Kiva. This included moving chairs, desks, and poster sheets in the Kiva.

One observation was that certain movements were indicative of certain events. For example, when participants moved their chairs to turn around or change their sitting location, it indicated that the center of the attention has been changed. The participants turned their chairs to redirect their attention to the center of the discussion. Because the space did not have a ‘front,’ the center of the attention was distributed to different locations in the room. When there was a disagreement among members, they tended to reference specific items on the board to argue their points. Additionally, dense acquirement activity indicated the beginning of a new exercise. The list of critical behaviors is shown below.

1. Referencing the previously mentioned items from the whiteboard
2. Drawing or writing down ideas on the whiteboard
3. Adding to an existing item on the board
4. Acquiring tools such as sticky notes, markers, etc.
5. Moving furniture to rearrange the direction/setting
6. Walking/turning to another team member to discuss something further

4. 1. 5. Interviews with Experts

Two interviews were conducted with subject matter experts who are senior designers at MAYA Design Inc. to obtain their feedback on the design task for Phase 2 and gain insights into the process of interdisciplinary design and its relationship with spatial factors.

<u>Feedback for Design Task.</u> Interviewee #1 suggested being more clear on the deliverables. He suggested that the deliverable should be either one hand-drawn poster or a magazine advertisement. He also had some suggestions regarding prototyping activity planned for session 3. He mentioned that communicating the design ideas after session 2 and having teams come up with their own list of prototyping materials would

be ideal. In terms of material, using mailing tubes or plastic tubes was recommended. For structured brainstorming sessions, he listed paper prototyping, drawing an issue-value chart, monster-in-a-box and stakeholder role-playing. Interviewee #2 recommended being more specific about the “sketching the user interface” task. He suggested giving a specific scenario that a user might encounter (e.g. “User A just received this product as a gift and needs to set it up for the first time”) and asking teams to sketch the interface for that particular situation. For structured brainstorming, he recommended an activity called “alternate worlds.” For this activity, each team is asked to select a company with strong brands such as Google or Disney that the product will be made by, and then think about how that particular company would solve this design challenge.

Interdisciplinary Design and Space. Because both interviewees had more than five years of experience with the Kiva and interdisciplinary design, the questions were asked to gather their insights into the subject. When asked indications of successful interdisciplinary teams, interviewee #1 mentioned that having a member keeping records of their ideas was an indication of a successful team. Also, he recalled that successful teams made consistent progress and showed continual and equal contribution from all of the members. On the other hand, unsuccessful teams tend to lose track of their discussion and repeat the same process several times. Interviewee #2 thought the indicators lay in the communications of the teams. He said that the communication among team members needed to be examined to see if ideas are integrated across the disciplines or they are simply “sitting together” to “check off the interdisciplinary part of their project." When asked about the benefits that the Kiva provided, he expressed that he believed that drawing was "the way people of different types and perspectives carried on the most effective conversations," because people tend to use the same visual symbols even when they have different jargons. Because the Kiva provides enough space for drawing, it allows visualization and "prototyping" of the idea displayed on a public space, which can lead to a conversation. He also mentioned that he believed having a circular surface gave people equal treatment by removing "head of the table hierarchy." The interview results are summarized in Table 7.

Table 7

Subject Matter Expert Interview Results

	Interviewee 1	**Interviewee 2**
Suggestions for design task	Clearer deliverables (e.g., hand drawn magazine advertisement) Team-generated list of prototyping materials Use of mailing tubes for prototyping Paper prototyping Issue-value chart Monster-in-a-box Stakeholder roleplaying	Clearer description for user interface sketch task "Alternate Worlds" activity for brainstorming
Indicators of successful interdisciplinary teams	Presence of a record-keeper in the team Continual and equal contribution of all team members	Integration across disciplinary boundaries portrayed in communication
Indicators of unsuccessful interdisciplinary teams	Tendency of losing track of discussion Repeated processes	Divide-and-conquer approach

Benefit of the Kiva space on interdisciplinary teams	Visual communication Quick prototyping Removal of hierarchy

4. 1. 6. Revised Procedures for Phase 2

Based on the observation and interview results gathered from Phase 1, the experimental procedures for Phase 2 were revised. The sessions planned for Phase 2 differed from Phase 1 conditions regarding time constraints and team sizes. Also, the design task focused on product design rather than service design. To adjust for these differences, only two in-Kiva activities (stakeholder mapping and round robin) from Phase 1 were selected for Phase 2, Session 2. These two activities were modified and integrated into structured brainstorming in Session 2, while teams under the ISDS-present condition generate and develop design concepts. Additionally, based on the interview results, participants chose materials used for prototyping in Session 3. Revised procedures reflecting these changes are shown in the procedure section.

4. 2. Phase 2: Laboratory-based Experimental Study

4. 2. 1. Verbal Interaction Data

4. 2. 1. 1. Quantity and Quality of Verbal Communication

- Research question: To what extent does quantity and quality of team interactions affect team effectiveness?

It was hypothesized that the teams showing higher level of team interactions will present higher levels of team effectiveness. To examine the level of team interactions, the rate of verbal communication measured by number of utterances spoken by participants and the quality of team communications measured by thematic analysis of verbal transcripts were used.

Verbal Communication Rate. The verbal communication rates were calculated based on the number of utterances divided by total session length. The total number of utterances was determined from the transcripts of team communications. It was hypothesized that the teams operating under the Kiva conditions would show the higher rate of verbal communications. However, the results indicated that the verbal communication rate was higher in teams in the conference room conditions. The two-way ANOVA revealed that there was a significant main effect of the room condition ($F(1, 8) = 10.65$, $p < .01$) with the conference room condition showing higher mean communication rates ($M = 7.12$, $SD = 0.65$) than Kiva conditions ($M = 4.10$, $SD = 0.65$), as shown in Figure 10.

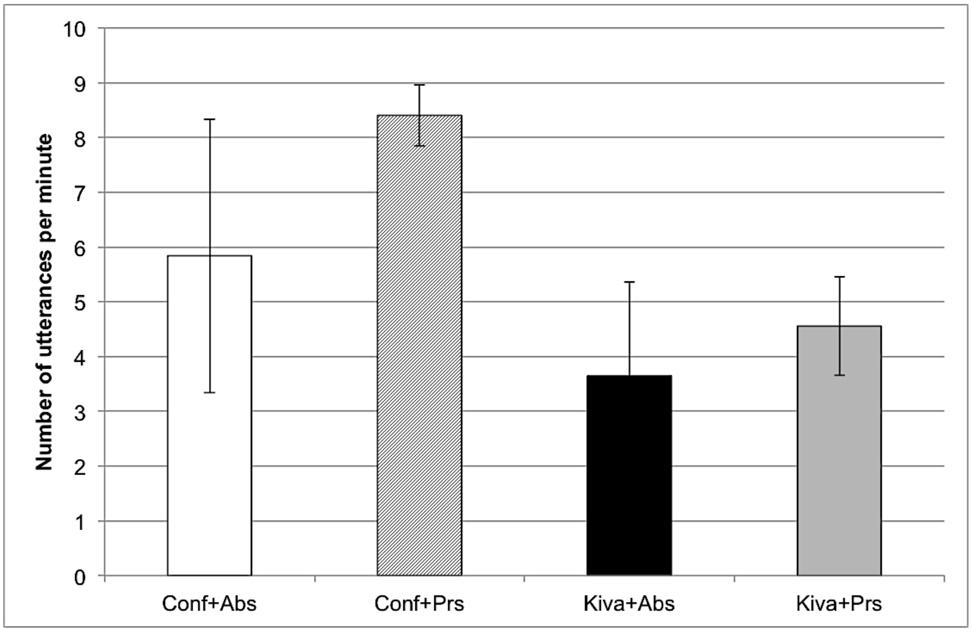

Figure 10. Descriptive statistics of verbal communication rate (utterance/min) by experimental condition

Quality of Team Communications. In addition to the rate of verbal communication, the quality of verbal communication was also examined. In particular, the analysis of verbal communication focused on how teams presented the evidence of interdisciplinary integrations. Following the methods of Rogers, Lim, Hazlewood, and Marshall (2009), the normalized frequency counts of the codes were used. The coding results for the "interdisciplinary integration" showed that the teams that operated in the Kiva with the interaction design strategy support presented the highest quality of team communications among the four experimental conditions. When other codes related to effective team communications, such as satisfaction (where team members explicitly expressing satisfaction with team produced ideas or artifacts), shared understanding (where team members can supply missing information to each other without overt requests), performance monitoring (where team members monitor each other's performance and the team’s resources and asks follow-up questions) and appreciation of expertise (where team members explicitly recognize the value of other members’ expertise), the teams that received interaction design strategy support (i. e., facilitated brainstorming sessions) showed higher quality of communications in both conference room and kiva conditions. Also, communication breakdown (where team members interrupt each other, questions are left unanswered, or requests are left unaddressed) showed the highest frequency in the ISDS-absent, conference room teams, whereas ISDS-present in-Kiva teams presented no evidence of communication breakdown. The detailed frequency counts of the team communication codes by experimental conditions are summarized in Table 8.

Table 8

Frequency of Codes by Experimental Conditions

Code	Conf. + Abs	Conf. + Prs	Kiva + Abs	Kiva + Prs
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
Disciplinary grounding	12.70 (3.41)	15.49 (0.26)	8.69 (1.89)	12.55 (6.65)
Interdisciplinary integration	3.35 (1.26)	9.57 (1.09)	4.50 (0.91)	17.42 (1.04)
Shared understanding	1.06 (1.26)	6.31 (1.08)	2.31 (0.91)	5.09 (1.04)
Performance monitoring	1.92 (0.99)	5.36 (0.95)	1.33 (1.32)	4.69 (3.16)
Flexible leadership	0.73 (0.63)	2.11 (1.80)	1.87 (1.38)	2.50 (1.03)
Work strategy	1.15 (1.10)	1.54 (0.90)	0.98 (1.01)	1.90 (2.07)
Communication breakdown	3.70 (4.06)	0.19 (0.34)	1.82 (3.15)	0 (0)
Appreciation of expertise	0.73 (1.27)	2.11 (1.44)	1.88 (0.93)	2.50 (2.45)

Note: N = 12, median is reported where SD exceeded 50% of M

The two-way ANOVA on the normalized code frequencies showed a significant main effect of ISDS support on shared understanding ($F(1, 8) = 41.31$, $p<.01$) and performance monitoring ($F(1, 8) = 10.14$, $p<.02$) with ISDS-present teams showing significantly higher levels of both. There was no main effect of room condition. A significant two-way interaction between room and support was found for interdisciplinary integration ($F(1, 8) = 6.12$, $p<.04$). It was revealed that the Kiva teams showed significantly higher level of interdisciplinary integration when the ISDS support was provided, while there were no significant differences between the different room conditions when the ISDS support was not provided (shown in Figure 11).

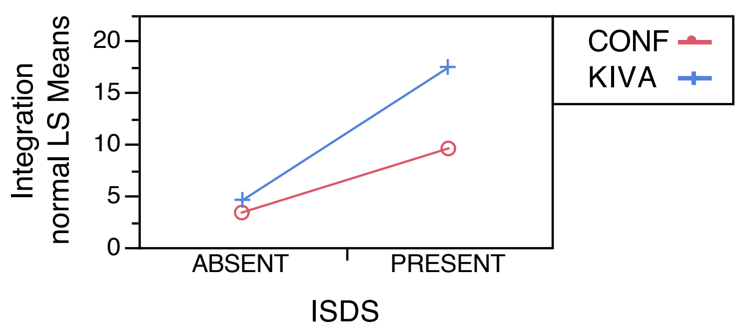

Figure 11. Two-way interaction of room x support on interdisciplinary integration

Planned pair-wise contrast analysis revealed the biggest significant differences between conference room + ISDS absent teams and Kiva + ISDS present teams ($F(1, 8) = 53.95$, $p <.01$) followed by the differences between Kiva + ISDS absent & Kiva + ISDS present conditions ($F(1, 8) = 45.50$, $p <.01$), conference room + ISDS present & Kiva + ISDS present ($F(1, 8) = 16.80$, $p <.01$), conference room + ISDS absent & conference room + ISDS present ($F(1, 8) = 10.54$, $p <.01$), and conference room + ISDS present & Kiva + ISDS absent ($F(1, 8) = 7.00$, $p <.03$), In summary, the hypothesis that teams showing higher communication rates would present higher level of communication effectiveness was not supported. The conference room teams showed higher rates of communication than the Kiva teams. While no statistically significant effects were found, the results were in the direction that the Kiva teams showing higher quality of communication in terms interdisciplinary integration. The hypothesis that ISDS-present teams will show higher quality of team communication was supported in levels of shared understanding and performance monitoring. The hypothesis that the Kiva teams will show higher quality of team communication was not supported, but the results were in the same direction with the hypothesis. The significant interaction between room and support for interdisciplinary integration was found, and it supported the original hypothesis that there would be a significant interaction of the two factors on the quality of team communication.

4. 2. 1. 2. Interdisciplinary Teaming Behaviors

- Research questions: How does physical environment and ISDS support impact interdisciplinary team behaviors? What are the indicators of the successful interdisciplinary teams?

Interdisciplinary Behaviors Shown in Communications. The participants presented various types of interdisciplinary behaviors in their verbal communications. First, the participants considered the aspects of the design project that were outside of their own background. For example, in this conversation, all team members were considering the pricing aspect and discussing appropriate price for their product.

M: Our target price, goal price?
I: 25 dollars, I don't know.
E: I think it should be under 100 dollars.
M: Yeah, it will be under 100 dollars. I think it needs to be like $80.
I: Really?
E: Yeah, for all the stuff that it has in it.
M: I could see 70 dollars.
E: Yeah.
M: I don't think we'll be able to make it at 70 dollars (laugh).
I: $69.99 (laugh)? So it looks cheaper.
M: Yeah.
I: Can we get it down to 50? I feel like for a middle schooler...I don't think I had anything over 50 bucks when I was in middle school (laugh).
E: Yeah, but kids now, they get smartphones and iPods for Christmas presents. So I think, they wouldn't buy it themselves but their parents will.
(Excerpt from IAK Team 1, Team #7)

In this conversation, the marketing student was setting the direction of the discussion by asking other team members' opinion on the target price of their product. The industrial design student suggests a price without confidence, and then the ECE student counters it with a higher target price. Following the marketing student's agreement for a higher price, the ECE student considers the features and required technology that needs to go into the product, and backs up his argument for a higher price point. The industrial design student adopts a common marketing strategy of reducing the price by one cent to make the product appear cheaper, then later reflects on his own experience and explore the option of a lower price range. To counter the industrial design student's suggestion, the ECE student raises the issue as to where actual purchasing power belongs regarding a product targeted at younger users. From this conversation, it is clear that all three members are considering the marketing aspect of their product, and the discussion of the marketing topic is driving everyone to think about the pricing decisions and adopt marketing strategies.

Second, the participants picked up domain-specific terms from another member of the team and used them in their own sentences. For example, one team was discussing different ways to motivate users to exercise regularly, and the industrial design student uses the term ‘reinforcement,’ and others pick it up. As a result, all three team members consider the concept of positive and negative reinforcement to decide the feature to increase user motivation.

I: So, playing around with that idea, can we do something that motivates- it's kind of like a negative **reinforcement**, I think?

(…)

M: It's like a wire basket that hangs around from your neck you can put things in it, @@ it's a fake commercial, obviously, but maybe you can put it up in front of you without special support. And then like you said, the money shredder, a negative **reinforcement**, would be like a shredder, and then a positive **reinforcement** like motivation, would be like a point system. I don't know. I feel like it's a whole lot of ideas.

(…)

E: Um...can we agree on the, I mean, actually no. Not yet. You are right, money shredding is one feature of **reinforcement**, but what else can you lose that makes you work hard?

(Excerpt from IPC Team 1, Team #4)

Third, the design decisions were influenced by domain knowledge of more than one discipline. In the next example, this team was in the process of deciding where to place sensors. Both design and engineering expertise influence their decision.

I: So just circle the areas we need to install sensors on. So it could be really mesh with strips of something solid to put some sensors on. I'm thinking aesthetically.

E: @@ most of the time, the sensors won't be seen.

I: Hah, I see.

(Excerpt from IPK Team 2, Team #11)

In this interaction, the industrial design student was considering the technological element (i.e., sensors) of the product and trying to decide where it should be placed and how that decision would impact the aesthetic appearance of the product. The ECE student offers a piece of information related to the technological element that the industrial design student is not familiar with, the invisibility of sensors, and the issue is resolved. This conversation shows how taking advantage of diverse expertise in the group can increase the effectiveness of team design processes.

In another instance, one team was trying to decide whether or not they wanted to use GPS for their device.

I: Do we really want to do that though? I don't know...does it have to go with GPS?

E: No, I mean- Are we marketing towards the people who workout at home or workout at the gym?

M: That's a good question.

E: We should be able to get them both.

(Excerpt from IPC Team 2, Team #5)

When the industrial design student asks the other two members whether or not their product has to have a GPS, the ECE student tries to answer the question and soon discovers that they do not know whether or not their product is targeted for indoor users or outdoor users. This leads the team to think about more specific characteristics of target users, which can influence the decision for feature sets as well as required technologies. This behavior of term exchange was found only in ISDS-present teams' communication.

Fourth, each participant acted as an expert in her own discipline. For instance, industrial design students often referred to their "studio" experiences. On finding names for their product, one participant with Industrial Design background (P7) said, "it's the worst part of any studio project, finding a name for it." Another participant, also from Industrial Design (P4) mentioned that they could "do a designer thing and just pick a foreign word" to decide the name of their product. Sometimes, they would elicit help from members with other backgrounds by identifying them with their discipline. One participant with an engineering background (P5) asked the Industrial Design participant's help with deciding the form of the product; he said, "Well, you are the designer (laugh)."

Finally, participants asked team members certain domain questions pertaining to the member's discipline. In this conversation, for example, the industrial design student was asking the ECE student about the existing technology and how it worked.

E: It just depends- it has a hard drive on it- so...
I: This thing has a hard drive on it?
E: Yeah, it's got a small drive on it. It has lots of chips and circuitry.
M: So, your phone's like a computer. Yeah.
E: It's amazing how these phones, there's just so much things stuffed in there. You wouldn't have to put too much stuff for this though, we don't need a camera, we don't need...I'll probably need a processor.

(Excerpt from IPC Team 3, Team 6)

These themes were also confirmed in the quantification of qualitative codes. From the qualitative coding, disciplinary grounding, interdisciplinary integration, and appreciation of expertise were the codes related to interdisciplinary teaming behaviors. One code showed significant interaction effect between room condition and ISDS support. The descriptive statistics are shown in Figure 12.

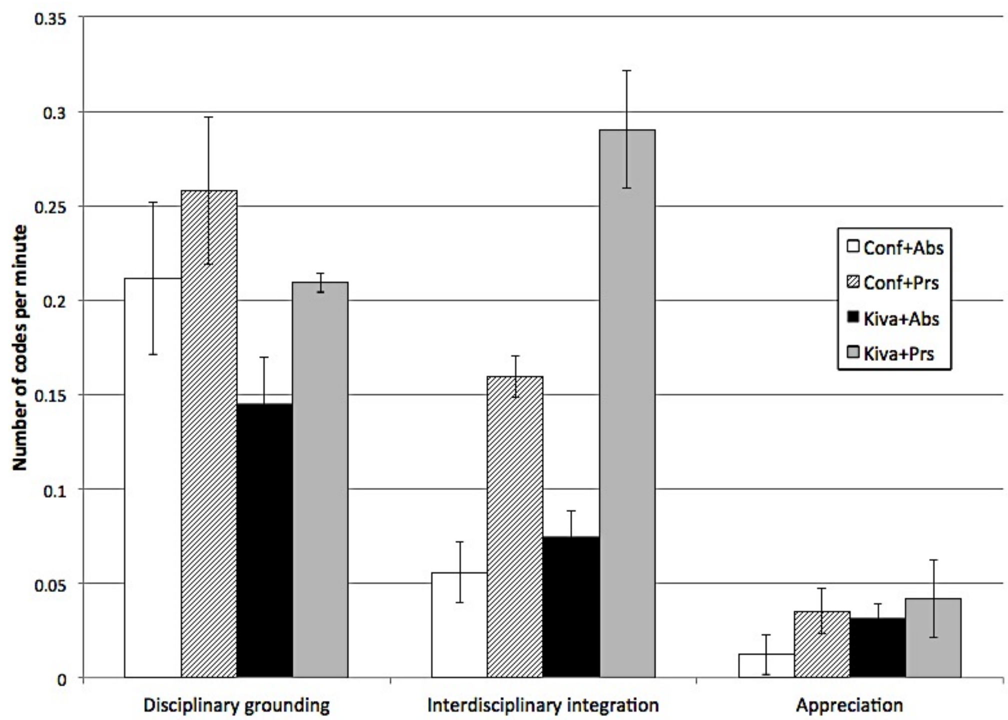

Figure 12. Mean numbers of codes per minute by condition

Communication Breakdown in Conference Room + ISDS Absent Conditions. One of the codes that emerged from the transcript data was “communication breakdown”, evident in teams that operated without interaction strategy design support. This behavior was indicated as team members cutting into each other's remarks and interrupting to express their own opinions, as well as unaddressed and unanswered questions and issues. For example, in this conversation, one member asks the other two about product naming, and it is left unaddressed.

M: Should we work on the name?
(pause)
E: Well another thing we could do is have them wear for a day and see how you do for a normal day and suggest, tomorrow, try to do 500 more. So that you have the baseline of what you normally do.
I: Yeah.
E: So that you can get extra motivation.
(Excerpt from IACT1, Team #1)

In another conversation, one team member (again, with marketing background) asks others' opinion on the product naming. One member tries to address it, and then the other member cuts in and drops the topic by declaring that they do not need to work on the advertisement. After it is agreed that they do not need to work on the magazine advertisement during the given session, one of the members moves onto a different topic (modeling), without addressing when to come back to the original issue that was brought up by the marketing student.

M: Good. What are we going to name it?
I: Let's call it...
E: (interrupting) Do we have to do the magazine thing tonight?
M: What?
E: The magazine advertisement?
M: We're doing the magazine ad tonight?

I: No.

E: Oh, okay.

I: I think we should come up with the final- really good form of what it will look like. We need to model it next time.

(Excerpt from IACT1, Team #1)

The frequency counts of codes indicated that these instances of communication breakdown occurred more often in teams without ISDS who operated in the conference rooms. On the other hand, none of the three teams that operated in the Kiva with ISDS support showed an instance of these communication breakdowns (Figure 13).

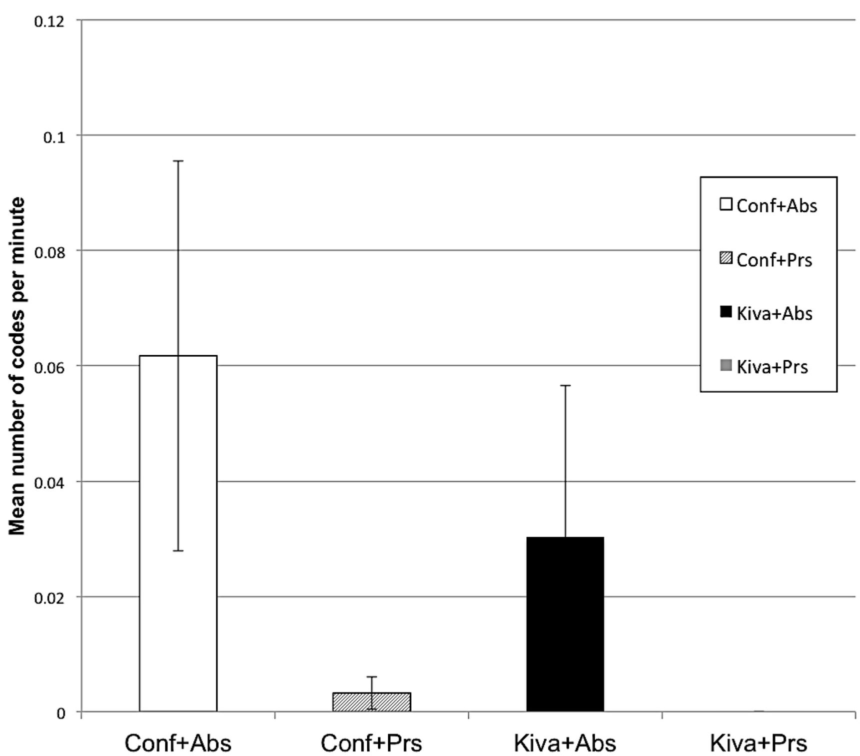

Figure 13. Mean numbers of ‘communication breakdown’ code per minute by condition

4. 2. 2. Physical Interaction Data

4. 2. 2. 1. Interaction between Physical Environment & Participants

As part of the team interactions, it was hypothesized that teams showing higher level of the non-verbal interaction of the team will present higher level of team effectiveness. The analysis of video-recordings of team sessions indicated that there was higher level of non-verbal interaction for the Kiva + ISDS-present teams. In addition, it was shown that the teams showed more balanced non-verbal interactions among all three team members. When the teams within the Kiva conditions were compared, the teams who received the ISDS support showed higher level of physical interactions than the teams who did not receive the ISDS support. The trend was more evident during the prototype session. When the physical interaction behaviors (significant actions such as walking, drawing, pointing; shown listed on Y-axis) were visualized over time (X-axis), the different trends between four experimental conditions were clearly shown (Figures 14 through 17).

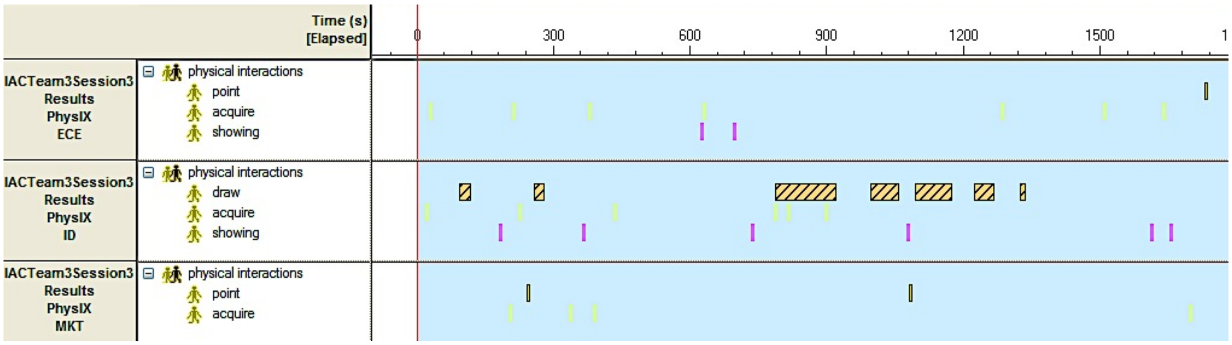

Figure 14. Physical interaction timeline of Conf. + ISDS absent team during session 3

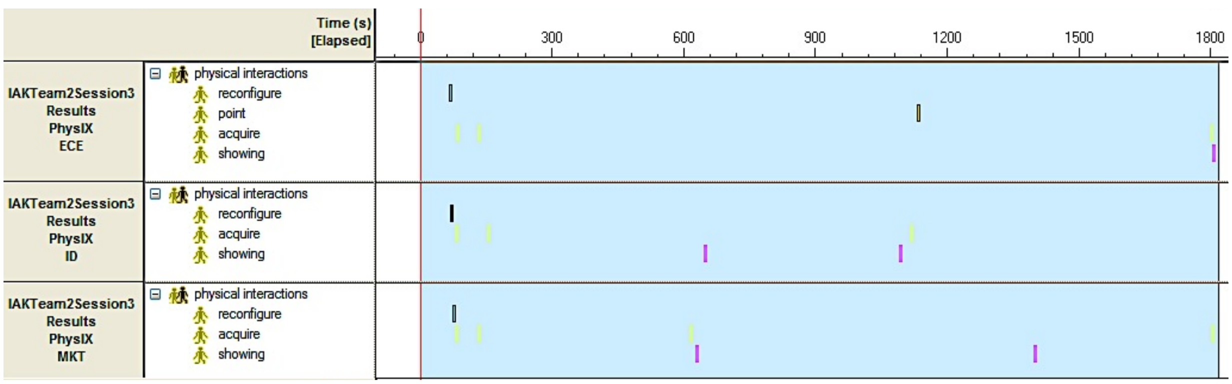

Figure 15. Physical interaction timeline of a Kiva + ISDS absent team during session 3

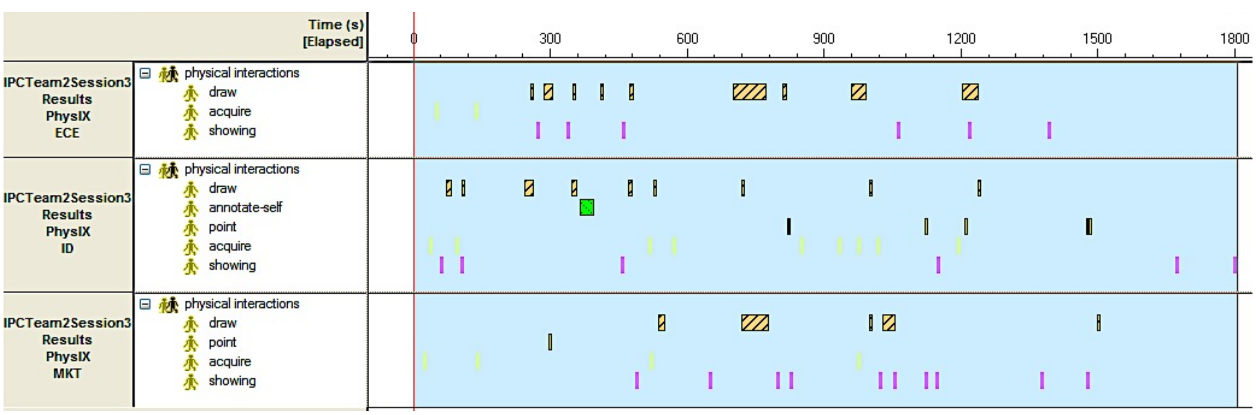

Figure 16. Physical interaction timeline of a Conf. + ISDS present team during session 3

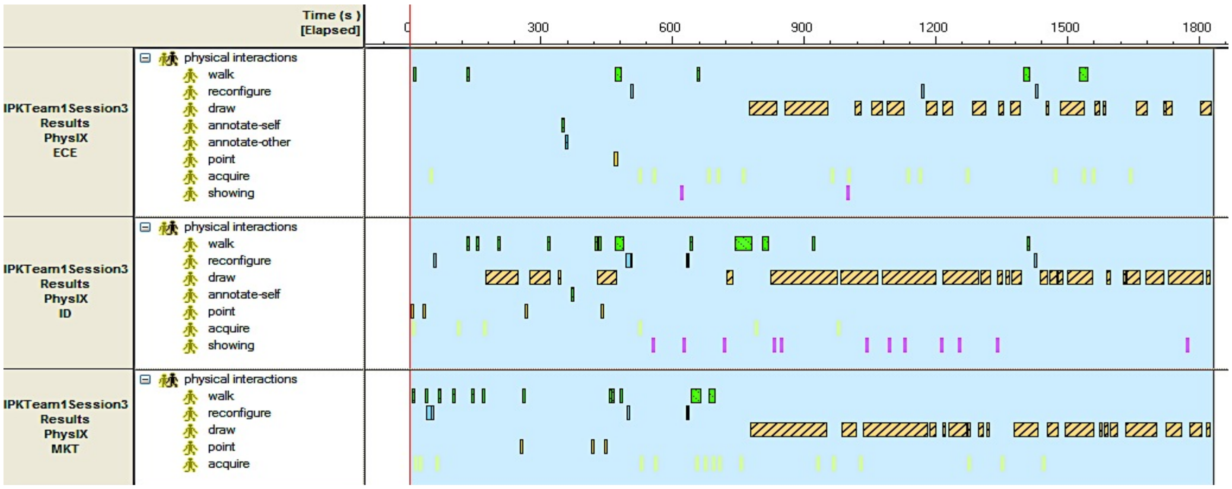

Figure 17. Physical interaction timeline of a Kiva + ISDS present team during Session 3

To delve into more accurate data, the duration of which participants spent for different physical interactions was normalized by dividing with the number of minutes that session lasted to calculate the duration (seconds) per minute to test for differences among different experimental conditions. From the descriptive statistics, the Kiva teams with ISDS-present condition indicated the highest level of physical engagement across all physical interaction behaviors for both concept generation session (Session 2) and prototyping session (Session 3). For Session 3 data, the two-way ANOVA results indicated that there was a statistically significant main effect of ISDS support on the duration of “Point” ($F(1, 8) = 16.97$, $p < .01$). That is, teams operated with the ISDS support referenced the items on the whiteboard more than the teams operated without the ISDS support. For the duration of “drawing,” “reconfiguring,” and “walking,” a significant two-way interaction between room and ISDS support was found ($F(1, 8) = 19.97$, $p < .01$, $F(1, 8) = 7.05$, $p < .01$, $F(1, 8) = 4.00$, $p < .01$, respectively). Mean and standard deviations for the duration of each physical interaction behavior during Session 2 (Figure 18) and 3 (Figure 19) are shown below.

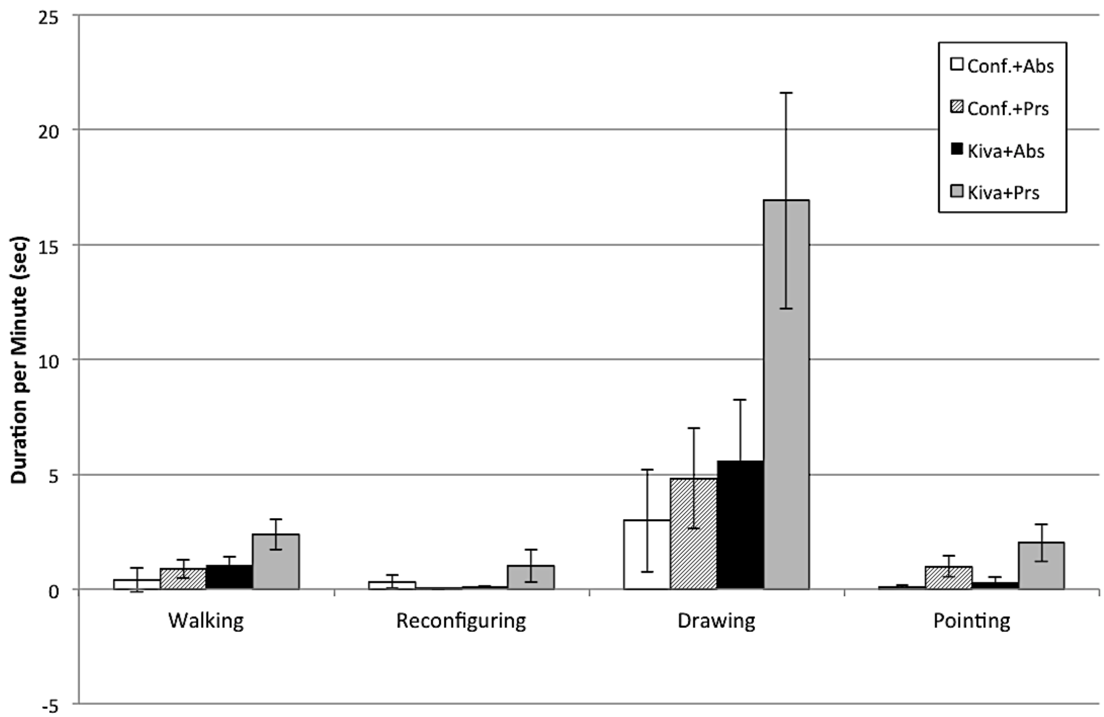

Figure 18. Descriptive statistics for duration of physical interaction behaviors during session 2

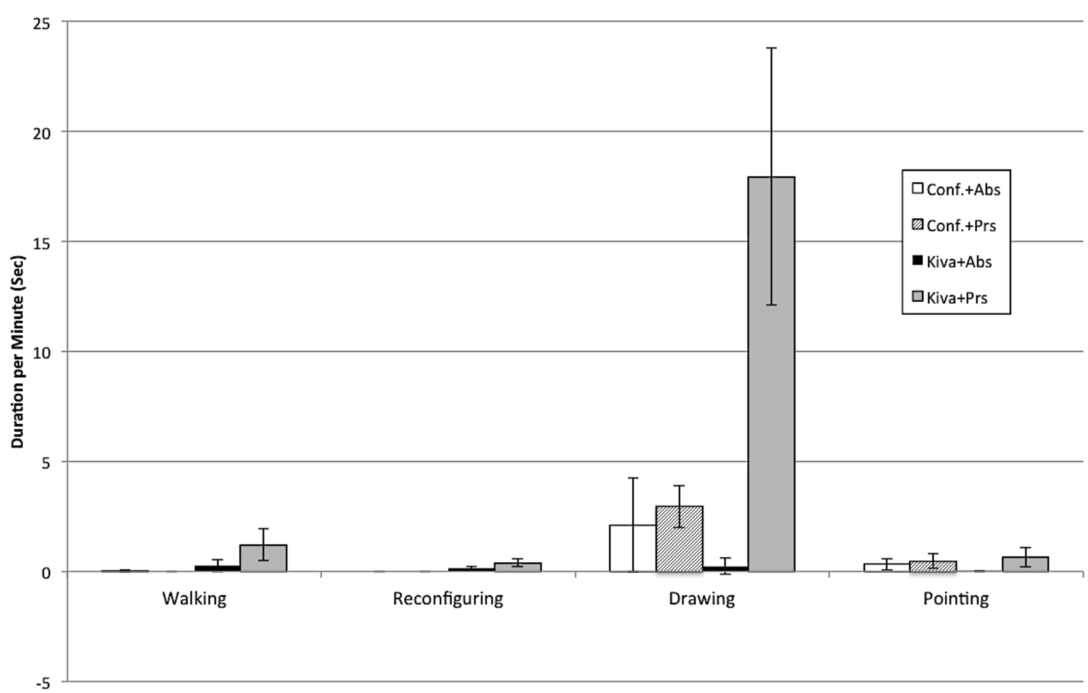

Figure 19. Descriptive statistics for duration of physical interaction behaviors during session 3

4. 2. 2. 2. Characteristics of Space Usage Pattern

In addition to the duration of physical behaviors, the extent of space usage was examined by tracking the whiteboard spaces used by each team during direct observation (See Appendix I for the observation protocol). The direct observation revealed that the participants used the whiteboard mainly during the concept generation session (Session 2). During Session 2, ten of the twelve teams used the whiteboard. The two teams that did not use the whiteboard were conference room teams without ISDS support. All of the conference room + ISDS absent condition teams showed unequal control of the shared information surface. During the prototyping session (Session 3), the conference room teams seated at the conference table in the middle of the room and used the table during the entire session. In general, the teams who received the ISDS support showed higher level of physical interactions during concept generation session (Session 2).

Table 10

Characteristics of physical interactions and team behaviors during session 2

Condition		Whiteboard use	Whiteboard usage patterns
Conf. + ISDS Abs	Team 1	Yes	One member (ID) controlled the whiteboard throughout the session.
	Team 2	No	No one used the whiteboard. One member (MKT) controlled a large piece of paper as a shared information surface throughout the session.
	Team 3	No	No one used the whiteboard. One member (ECE) controlled a large piece of paper as a shared information surface throughout the session.

Conf. + ISDS Prs	Team 4	Yes	All three used the whiteboard during the facilitation. Members took turns to control the board depending on the topic being discussed. After the facilitation, members took turns to control of legal-sized papers as shared information surfaces.
	Team 5	Yes	All three used the whiteboard during the first half of the session. After the facilitation, members took turns to control a large piece of paper as a shared information surface.
	Team 6	Yes	All three used the whiteboard during the first half of the session. After the facilitated exercises, members took turns to control a large piece of paper as a shared information surface.
Kiva + ISDS Abs	Team 7	Yes	All three used the whiteboard. One member mostly controlled the board (ID). As they filled up the whiteboard surface, they moved around the perimeter to find more whiteboard space to use.
	Team 8	Yes	All three used the whiteboard. One member mostly controlled the board (ID).
	Team 9	Yes	Sat in the middle of the Kiva and did not move around, individual work with occasional performance checking.
Kiva + ISDS Prs	Team 10	Yes	Sat on the Kiva floor. Used the floor as an extension of whiteboard. Used the board in the beginning of the session to create a reference figure. Sat in the middle of the Kiva, co-creating a big drawing.
	Team 11	Yes	Used the whiteboard in the beginning of the session to write down summary of their ideas, and create a reference figure. All three members drew reference figures.
	Team 12	Yes	Used the whiteboard in the beginning of the session to create a reference figure. Sat in the middle of the Kiva, on the floor.

As summarized in Table 9, all of the teams who received ISDS support used the whiteboards during Session 2. The difference was that the Kiva teams kept using the whiteboard after the facilitated sessions were completed, while the conference room teams stopped using the whiteboard after the sessions were completed. In addition, the teams who received the ISDS support showed more equal control of the shared information surfaces (whiteboard and paper) than the teams who did not receive the support. This result was aligned with the subject matter expert interview results from Phase 1 of the study. The interviewee B stated that the interdisciplinary teams used the Kiva to employ the "visual communication." In the same context, the Kiva teams in Phase 2 used the whiteboards to produce visual artifacts that helped them to create and retain information shared among team members.

Table 11

Characteristics of physical interactions and team behaviors during session 3

Condition		Whiteboard usage	Significant actions	Prototyping behaviors
Conf. + ISDS Abs	Team 1	Yes	One member uses the whiteboard briefly in the beginning of the session to sketch forms. Individual work throughout the session. Occasional performance check.	Divide-and-conquer approach. Prototype was assigned to ID, ad was assigned to MKT, and interface sketch was assigned to ECE.
	Team 2	No	No whiteboard use, after dividing up the workload, individual work throughout the session with occasional performance check.	Divide-and-conquer approach. Prototype was assigned to ID, ad was assigned to MKT, and interface sketch was assigned to ECE.
	Team 3	No	No whiteboard use, after dividing up the workload, individual work throughout the session with occasional performance check.	Divide-and-conquer approach. Prototype was assigned to ID, ad was assigned to MKT, and interface sketch was assigned to ECE.
Conf. + ISDS Prs	Team 4	No	Using the conference table as a work surface. Passing items between team members throughout the session.	All members worked together to create the prototype and other deliverables.

	Team 5	No	Using the conference table as a work surface. Passing items between team members throughout the session.	All members worked together to create the prototype. After a while, ID continued working on the prototype while the ad was assigned to MKT, and the interface sketch is assigned to ECE.
	Team 6	No	Using the conference table as a work surface. Passing items between team members.	All members worked together to create the prototype. After a while, ID continued working on the prototype while the ad was assigned to MKT, and the interface sketch is assigned to ECE.
Kiva + ISDS Abs	Team 7	No	Sat in the middle of the Kiva. Used chairs. They did not move around, individual work throughout the session.	Divide-and-conquer approach. Prototype was assigned to ID, ad was assigned to MKT, and interface sketch was assigned to ECE.
	Team 8	No	Sat in one side of the Kiva using chairs. They did not move around. Individual work throughout the session.	Divide-and-conquer approach. Prototype was assigned to ID, ad was assigned to MKT, and interface sketch was assigned to ECE.
	Team 9	No	Sat in one side of the Kiva on the floor. They did not move around, individual work throughout the session.	Divide-and-conquer approach. Prototype is assigned to ID, ad is assigned to MKT, and interface sketch is assigned to ECE.
Kiva + ISDS Prs	Team 10	Yes	Sat on the Kiva floor. Two members used the whiteboard in the beginning of the session to create a reference figure. Sat in the middle of the Kiva to co-create a large drawing that acted as a prototype of a wall-display.	All members worked together to create deliverables

Team 11	Yes	All three members used the whiteboard in the beginning of the session to write down summary of their ideas, and then explore different forms of wearable devices. Sat on the Kiva floor after they were done using the board.	All members worked together to create deliverables
Team 12	Yes	Used the whiteboard in the beginning of the session to create a reference figure. Sat in the middle of the Kiva, on the floor.	All members worked together to create the prototype. After a while, ID continued working on the prototype while the ad was assigned to MKT, and the interface sketch is assigned to ECE.

As shown in Table 10, the behaviors during the prototyping session show clear differences between the ISDS-supported teams and the other teams. All of the teams who operated under ISDS support condition worked on the prototype together as a team, while the other teams took a divide-and-conquer approach. The other teams divided the workload based on each member's disciplinary background. These teams assigned 1) user interface sketches to the member with Electrical & Computer Engineering background, 2) low-fidelity prototypes to the member with Industrial Design background, and 3) one-page magazine advertisement to the member with Marketing background. While they were creating the deliverables based on their own assignments, the team members showed minimal interactions, hence showing a very low level of integration across disciplinary boundaries.

On the other hand, the teams who created the deliverables together spoke with each other during the entire session, asked for other members' opinions and inputs, and made design decisions together. Also, they shared the workload for creating every deliverable together rather than each person taking one deliverable. For example, Team #10 created the interactive wall display of the prototype by pasting together drawing papers to create a large piece of paper. The industrial design student drew the guide figure on the whiteboard, and then all three members drew the display with pastel referencing the figure on the board. During this process, the industrial design student acted as a domain expert and explained the characteristics of the material (pastel) and taught others usage techniques.

4. 2. 3. Questionnaire Data

4. 2. 3. 1. Team Diagnostic Survey

Another important research question guiding this study was examining to what extent the physical room condition and the interaction strategy design support affects the effectiveness of the interdisciplinary teams. The Team Diagnostic Survey (Wageman, Hackman, & Lehman, 2005) measured the overall team effectiveness by asking participants questions regarding various aspects of team effectiveness including processes, performance, and satisfaction. The TDS was administered after all of the experimental sessions were completed. The participants were asked to rate their responses on a 5-point Likert-type scale (i. e., 1: Highly inaccurate, 2: Somewhat inaccurate, 3: Neutral, 4: Somewhat accurate, 5: Highly accurate). The main effects of the physical environment (room) and the ISDS support were examined using nonparametric one-way analysis of variance, Kruskal-Wallis test. The two-way interaction effect was tested using the aligned rank transformation (ART) procedure followed by two-way analysis of variance (Wobbrock, Findlater, Gergle, & Higgins, 2011). The tests were conducted on the individual question items, and then the same tests were conducted on the aggregate measures. The aggregate measures were constructed by computing means of individual item scores under each question category. The nine categories were: real team, compelling direction, team composition, task design, group norm, team processes, interpersonal relationship, internal motivation, and team satisfaction.

Individual TDS Items. The nonparametric one-way ANOVA, Kruskal-Wallis test showed a significant main effect of physical environment on one item (Q24: "Carrying out our team's task automatically generates trustworthy indicators of how well we are doing."), with Kiva teams showing higher score than conference room teams ($\chi^2(1) = 4.00$, $p<.05$). A significant main effect of the ISDS support was found on six individual items. As shown in , five items presented higher ratings for ISDS present conditions. One item, question 12, was an exception, showing lower median rating for ISDS present conditions. That is, the teams receiving ISDS support was less satisfied with the size of their team. The ISDS-present teams felt that more capable of assessing their own success than ISDS-absent teams (Q26). The ISDS-present teams perceived to be their workload sharing more equal (Q35), and had a clearer strategy of handling information (Q39). Also, the ISDS-present teams enjoyed getting to know each other more (Q48) and identified with the team's success (Q49) than the ISDS-absent teams. The results are summarized in Table 12.

Table 12

Significant Main Effects of ISDS supports on TDS Ratings

Source	TDS Question Item	*df*	χ^2	*p*	Median
Support	Q12(R): This team has too few members for what it has to accomplish.	1	6.08	.01	A>P
	Q26(R): The only way we can figure out how well we are performing is for other people to tell us.	1	4.28	.04	A<P
	Q35(R): Some members of our team do not carry their fair share of the overall workload.	1	5.68	.02	A<P
	Q39(R): How seriously a member's ideas are taken by others on our team often depends on more on who the person is than on how much he or she actually knows.	1	5.01	.03	A<P

	Q48: The chance to get to know my teammates is one of the best parts of working on this team.	1	8.04	.01	A<P
	Q49: I feel a real sense of personal satisfaction when our team does well.	1	7.18	.01	A<P
Room	Q24: Carrying out team's task automatically generates trustworthy indicators of how well we are doing.	1	4.00	.05	C<K

When individual items were examined for the two-way interaction of room condition x ISDS support, a total of eleven items showed significant interactions. The direction of the effects was the same as the two-way interactions found from aggregate measures. The results are shown in Table 13 below.

Table 13

Significant Two-way Interaction Effects of Room x ISDS Support for TDS Items

Source	TDS Question Item	*df*	*F*	*p*
Room x Support	Q1(R): Members of this team have their own individual job to do, with little need for them to work together.	1	5.65	.02
	Q2: Generating the outcome or product of this team requires a great deal of communication and coordination among members.	1	13.95	.01
	Q11(R): This team is larger than it needs to be.	1	6.56	.02
	Q20: We do a whole, identifiable piece of work.	1	8.40	.01
	Q40: Members of our team actively share their special knowledge and expertise with one another.	1	5.23	.03
	Q44: Working together energizes and uplifts members of our team.	1	4.44	.04
	Q47: I very much enjoy talking and working with my teammates.	1	5.79	.02
	Q49: I feel a real sense of personal satisfaction when our team does well.	1	4.25	.05

Q53: I learn a great deal from my work on this team.	1	5.38	.03
Q55: Working on this team stretches my personal knowledge and skills.	1	4.42	.04
Q56: I enjoy the kind of work we do in this team.	1	7.76	.01

Note: N = 36

Planned pair-wise contrast analysis indicated that more than half of the items that presented significant two-way interactions (6 out of 11), showed statistical significant differences between conference room + ISDS present condition and Kiva + ISDS present condition.

Aggregate TDS Categories. Descriptive statistics of the TDS categories are shown in Table 14 below. The overall trend was also shown in the aggregate TDS measures with the Kiva teams who received ISDS support showing the highest mean scores for most of the question categories (8 out of 9).

Table 14

Descriptive Statistics for TDS Ratings by Category and Experimental Conditions

	Conf. + Abs.		Conf. + Prs.		Kiva + Abs.		Kiva + Prs.	
TDS Category	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Real team	4.22	0.44	3.89	0.41	3.44	0.65	**4.30**	0.59
Compelling direction	**4.07**	0.57	3.76	0.55	**4.07**	0.36	3.96	0.31
Team composition	4.49	0.30	4.20	0.39	4.30	0.68	**4.60**	0.31
Task design	4.26	0.37	3.95	0.29	3.94	0.50	**4.29**	0.23
Group norm	4.27	0.40	3.97	0.34	4.10	0.49	**4.28**	0.23
Team processes	4.26	0.37	3.95	0.30	3.97	0.49	**4.28**	0.22
Interpersonal relationship	4.26	0.37	3.95	0.30	3.97	0.49	**4.28**	0.22

Internal motivation	4.27	0.37	3.95	0.30	3.99	0.49	**4.28**	0.22
Satisfaction	4.30	0.36	3.99	0.31	4.04	0.52	**4.33**	0.21

Note: N=36, highest mean scores for each category are bolded.

No significant main effect of physical environment or ISDS support was found. When tested for two-way interactions using the ANOVA after ART procedures, all nine categories indicated the same direction of interactions. Seven categories (except for compelling direction and team composition) showed statistically significant interaction effects between physical environment (room) and interaction support design strategy (support). The results are shown in Table 15 followed by the detailed description interaction effects for each category.

Table 15

Significant Two-way Interaction Effects of Room x ISDS Support for TDS Categories

Source	TDS Category	*df*	*F*	*p*
Room x Support	Real team	1	13.65	.01
	Task design	1	8.94	.01
	Group norm	1	4.45	.04
	Team processes	1	7.93	.01
	Quality of interpersonal relationship	1	7.93	.01
	Internal motivation	1	6.63	.01
	Team satisfaction	1	6.88	.01

Real Team. The interaction effects showed that the teams in the Kiva felt their team was more bounded when ISDS support was present, while the teams operated in the conference room felt that their team boundary was more stable when the support was not present, $F(1, 32) = 13.65$, $p<.01$. It shows that the flexible space stimulates the self-reported feeling of team effectiveness only when combined with ISDS support.

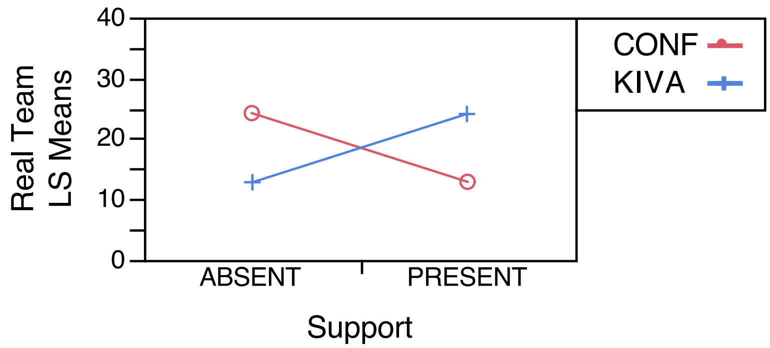

Figure 20. Two-way interaction of room x support on Real Team category of TDS

Planned pair-wise contrast analysis indicated that there are statistically significant differences between pairs of: 1) conference room + ISDS absent and conference room + ISDS present ($F(1, 32) = 6.82$, $p = .01$) , 2) conference room + ISDS absent and Kiva + ISDS absent ($F(1, 32) = 6.96$, $p = .01$), 3) conference room + ISDS present and Kiva + ISDS present ($F(1, 32) = 6.69$, $p = .01$), and 4) Kiva + ISDS absent and Kiva + ISDS present ($F(1, 32) = 6.82$, $p = .01$).

Task Design. The interaction effects showed that the teams in the Kiva perceived the task design of their teams to be more effective when ISDS support was present. On the other hand, the teams that operated in the conference room perceived the task design of their teams to be more effective when ISDS support was absent, $F(1, 32) = 8.94$, $p<.01$.

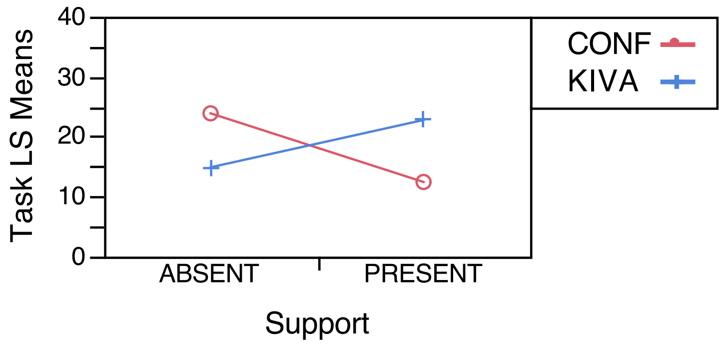

Figure 21. Two-way interaction of room x support on Task Design category of TDS

Planned pair-wise contrast analysis indicated that there are statistically significant differences between pairs of: 1) conference room + ISDS-absent and conference room + ISDS-present ($F(1, 32) = 6.26$, $p = .02$) and 2) conference room + ISDS-present and Kiva + ISDS-present ($F(1, 32) = 5.11$, $p = .03$).

<u>Group Norm.</u> The interaction effects showed that the teams in the Kiva indicated that the members of the team shared a more solid understanding with each other when ISDS support was present, whereas the teams who operated in the conference room believed their team shared a more solid understanding with each other when ISDS support was absent, $F(1, 32) = 4.45$, $p<.04$. This shows that the effectiveness of the combined condition of flexible physical space and the strategy support on the shared understanding of the team members.

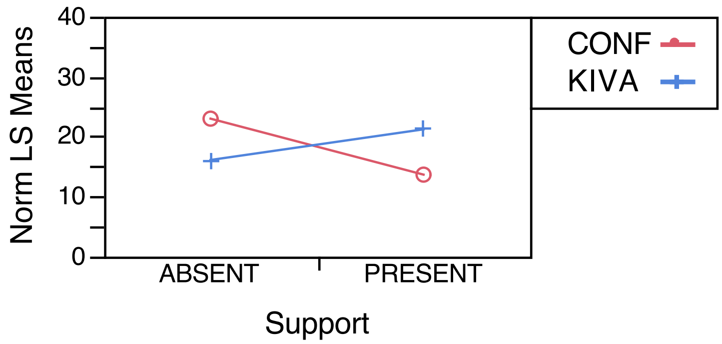

Figure 22. Two-way interaction of room x support on Group Norm category of TDS

Planned pair-wise contrast analysis indicated that there is a differences between conference room + ISDS-absent and conference room + ISDS-present ($F(1, 32) = 3.72$, $p = .06$) approaching statistical significance.

<u>Team Processes.</u> It was shown that the teams under the Kiva condition perceived their team processes to be more effective when ISDS support was present. In contrast, the teams in the conference room condition perceived their team processes less effective given the same ISDS support, $F(1, 32) = 7.93$, $p<.01$. This indicates that the effectiveness of the combined condition of flexible physical space and the strategy support on creating perception of effective team processes.

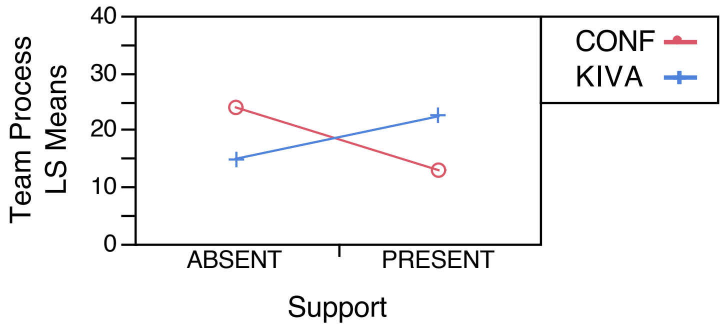

Figure 23. Two-way interaction of room x support on Team Process category of TDS

Planned pair-wise contrast analysis indicated that there are statistically significant differences between pairs of: 1) conference room + ISDS-absent and conference room + ISDS-present ($F(1, 32) = 5.64$, $p = .02$) and 2) conference room + ISDS-present and Kiva + ISDS-present ($F(1, 32) = 4.16$, $p = .05$).

Interpersonal Relationships. The interaction effects showed that the teams in the Kiva indicated that the members of the team shared a better interpersonal relationship with other members when ISDS support was present, $F(1, 32) = 7.93$, $p < .01$.

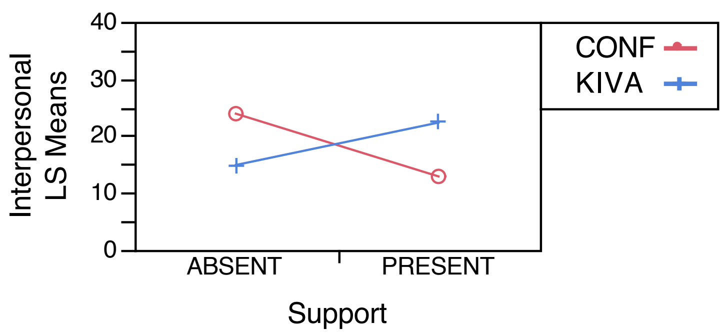

Figure 24. Two-way interaction of room x support on Interpersonal relationship category of TDS

Planned pair-wise contrast analysis indicated that there are statistically significant differences between pairs of: 1) conference room + ISDS-absent and conference room + ISDS-present ($F(1, 32) = 5.64$, $p = .02$) and 2) conference room + ISDS-present and Kiva + ISDS-present ($F(1, 32) = 4.16$, $p = .05$).

<u>Internal Motivation.</u> The Kiva teams reported higher level of internal motivation when ISDS support was present; whereas the teams who operated in the conference room showed lower level of internal motivation when given the same ISDS support, $F(1, 32) = 6.63$, $p<.01$.

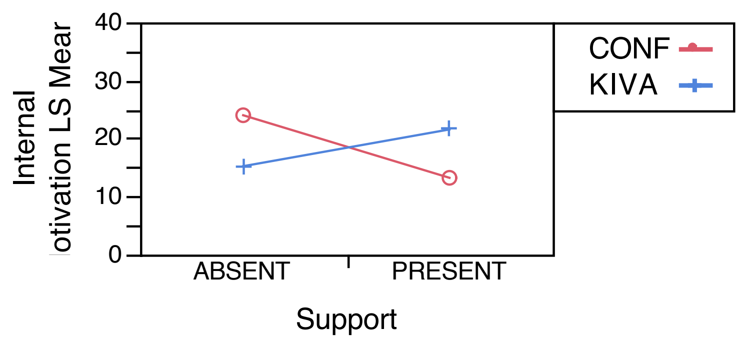

Figure 25. Two-way interaction of room x support on Internal motivation category of TDS

Planned pair-wise contrast analysis indicated that there is a statistically significant differences between conference room + ISDS-absent condition and conference room + ISDS-present condition ($F(1, 32) = 5.26$, $p = .03$).

<u>Satisfaction.</u> The Kiva teams were more satisfied with their overall performance when they received ISDS support, while conference room teams were more satisfied without the ISDS support, $F(1, 32) = 6.88$, $p<.01$.

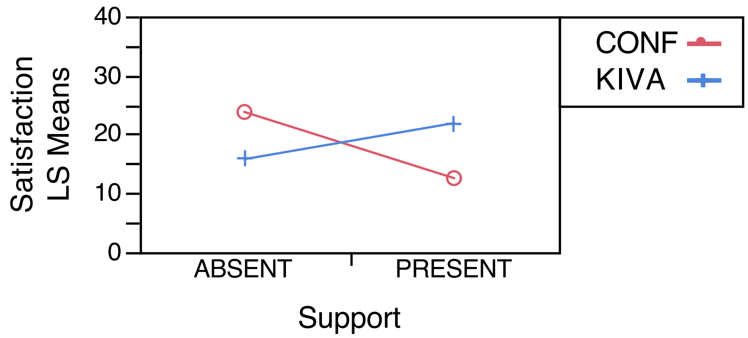

Figure 26. Two-way interaction of room x support on Satisfaction category of TDS

Planned pair-wise contrast analysis indicated that there is a statistically significant differences between conference room + ISDS absent condition and conference room + ISDS present condition ($F(1, 32) = 5.77$, $p = .02$).

It was hypothesized that there would be a significant interaction between physical environment (room) and ISDS support (support), and the Team Diagnostic Survey results confirmed that the flexible physical environment combined with appropriate team interaction supports can stimulate the level of self-reported team effectiveness.

4. 2. 3. 2. Team Mental Model Questionnaire

Table 15 presents the means, medians, and standard deviations for both task work mental model (MM) and teamwork mental model scores for each experimental condition. While these measures are correlation coefficients ranging from -1 to +1, the number is used as an index of sharedness (Mathieu et al., 2005) or index of similarity (Lim & Klein, 2006) within a team. Hence, the mean and standard deviation of the MM similarity index by experimental conditions are shown. There was no significant correlation between the task work MM and teamwork MM similarity scores. For task work MM similarity, teams who operated in the Kiva with no ISDS support showed the highest median score; and for teamwork MM similarity, teams who operated in the Kiva with ISDS support showed the highest median score.

Table 16

Descriptive Statistics of Team Mental Model Similarity Scores

Variables	Conditions	*Mean of R*	*Median of R*	*SD of R*
Taskwork MM Similarity Score	Conf.& ISDS absent	0.38	0.46	0.22
	Conf.& ISDS present	0.22	0.14	0.23
	Kiva & ISDS absent	0.43	**0.53**	0.34
	Kiva & ISDS present	0.40	0.36	0.30
Teamwork MM Similarity Score	Conf.& ISDS absent	0.33	0.30	0.30
	Conf.& ISDS present	0.21	0.31	0.35
	Kiva & ISDS absent	0.11	0.01	0.33
	Kiva & ISDS present	0.57	**0.54**	0.12

Note: N = 12

Kruskal-Wallis nonparametric one-way analysis of variance tests showed no significant main effects of room nor support on both task work and teamwork MM similarity scores. When tested for interactions, the teamwork MM similarity scores showed a significant two-way interaction of room x ISDS support, $F(1, 8) = 9.99$, $p<.01$ (shown in Figure 27). No significant interaction was found for the task work MM similarity scores.

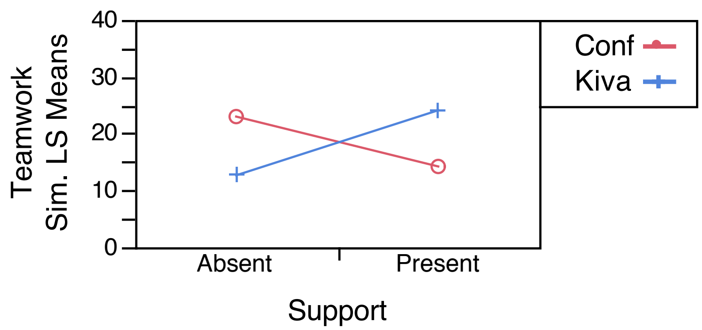

Figure 27. Two-way interaction of room x support on teamwork MM similarity

The planned contrast analysis showed the largest significant differences between the Kiva + ISDS absent teams and Kiva + ISDS present teams ($F(1, 8) = 5.22$, $p<.02$), followed by conference room + ISDS absent teams & Kiva + ISDS absent teams ($F(1, 8) = 5.22$, $p<.03$), and conference room + ISDS present teams & Kiva + ISDS present teams ($F(1, 8) = 4.78$, $p<.04$).

4. 2. 4. Participant-created Products

4. 2. 4. 1. Evaluation of Product Packages

Two expert evaluators rated the team-produced products in five areas. The Kiva teams with ISDS support received the highest scores in all five categories while conference room teams with no ISDS support received the lowest scores across all five categories. The inter-rater reliability was determined by calculating Spearman's correlation between the ratings. Evaluator A was an Industrial Design faculty member and evaluator B was an Electronic and Computer Engineering faculty member at Virginia Polytechnic Institute who had six years of experience in teaching interdisciplinary design class and assessing pervasive computing products that team. The evaluators did not have any knowledge of the participants nor the experimental conditions. The evaluation scores are summarized in Table 17.

Table 17

Product Evaluation Scores by Two Coders

		Original		Manufac.		Benefit		Aesthetic		Market	
	Team #	Coder A	Coder B	Coder A	Coder B	Coder A	Coder B	Coder A	Coder B	Coder A	Coder B
Conf.	1	5	5	10	8	5	5	7	4	5	3
+Abs	2	5	5	10	8	5	4	5	3	7	6
	3	6	5	10	8	6	6	6	3	7	6
Conf.	4	6	5	10	8	6	6	7	6	7	6
+Prs	5	7	8	10	8	6	9	7	8	7	6
	6	6	8	10	8	6	8	6	7	6	7
Kiva	7	6	8	10	8	6	7	5	8	5	8
+Abs	8	6	8	10	8	6	8	7	8	7	7
	9	6	7	10	8	6	8	5	5	5	6

Kiva	10	7	9	10	8	7	8	7	7	7	5
+Prs	11	9	9	7	3	8	8	8	9	8	5
	12	8	9	9	8	8	7	8	10	7	8

Nonparametric correlations between the scores assigned by Coder A and Coder B showed moderate to high positive correlations for originality of the solution ($\rho = .85$, $p < .01$), manufacturability ($\rho = .74$, $p < .01$), and aesthetics ($\rho = .61$, $p < .04$). The correlations for the "benefit to users" category were not statistically significant but approaching the conventional level of significance ($\rho = .52$, $p = .08$). Marketability did not show any significant correlation between the two coders.

As shown in Figure 29, descriptive statistics showed that the Kiva + ISDS support teams presented the highest level of originality ($M = 8.50$, $SD = .50$), benefits to users ($M = 7.67$, $SD = .58$), quality of aesthetics ($M = 8.17$, $SD = 1.06$), and marketability ($M = 6.67$, $SD = 1.16$). Meanwhile, their products showed the lowest manufacturability scores ($M = 7.50$, $SD = 2.20$). The conference room teams with no ISDS support showed the lowest scores for all categories except manufacturability.

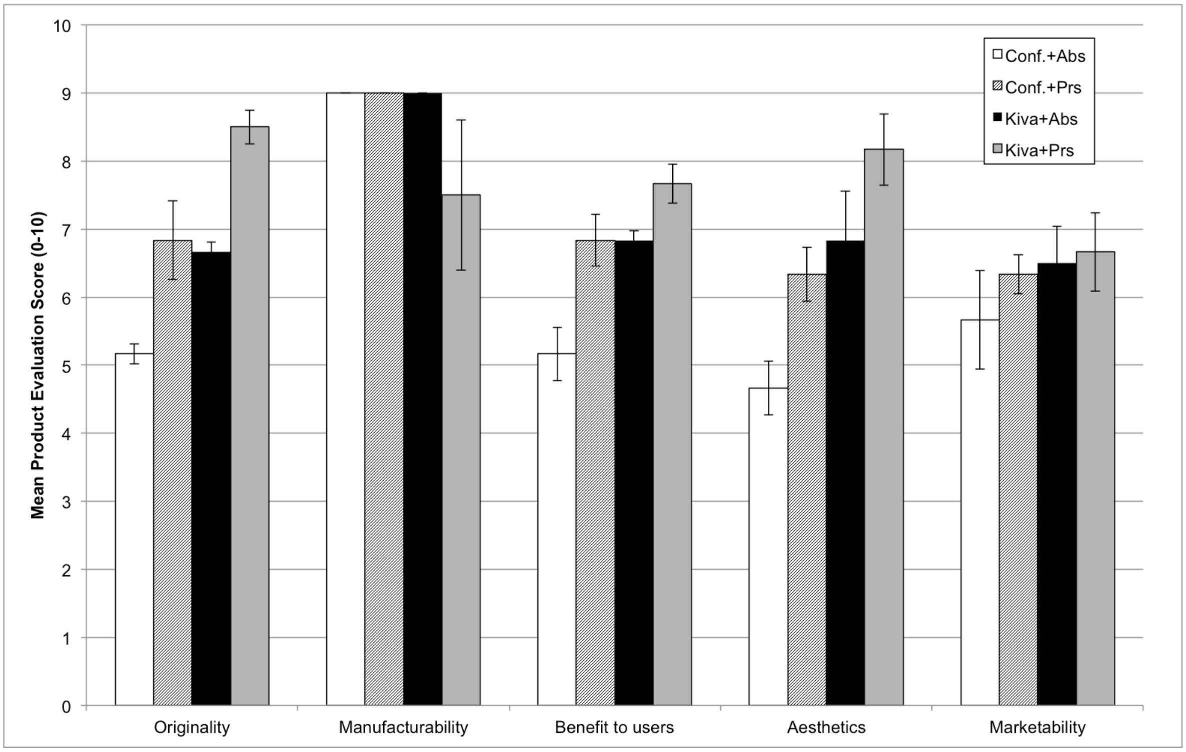

Figure 28. Mean product evaluation scores

Nonparametric one-way ANOVA showed that the teams who received the ISDS support showed significantly higher level of originality ($M = 7.58$, $SD = 1.24$), benefits to users ($M = 7.25$, $SD = .69$), and aesthetics ($M = 7.50$, $SD = 1.05$) than the teams who did not receive the ISDS support ($M = 6.00$, $SD = .95$; $M = 6.00$, $SD = 1.05$; and $M = 5.50$, $SD = 1.20$ respectively, $\chi^2(1) = 4.77$, $p = .03$; $\chi^2(1) = 4.83$, $p = .03$ and $\chi^2(1) = 4.76$, $p = .03$, respectively). In addition, there were significant main effects of the room condition on originality ($\chi^2(1) = 4.43$, $p = .04$) with Kiva teams showing higher originality ($M = 7.67$, $SD = .98$) than the conference room teams ($M = 5.92$, $SD = 1.07$). No significant two-way interaction of room x support was found.

4. 2. 4. 2. Summary of Products Generated by Participants

The teams produced three deliverables at the end of Session 3: 1) a low-fidelity prototype, 2) a one-page magazine advertisement, and 3) user interface sketches of one function of their product. There were three categories of devices that teams produced: wearable device, handheld device, and smart home device. The most common form of the device was a watch (6 out of 12), followed by headset (3 out of 12). There was one smart home device that integrates into the end user's home environment. The names and descriptions of the products are summarized in Table 18.

Table 18

Description of Products Teams Generated

Condition	Team #	Name	Form	Technology	Target Users	Description
Conference room + ISDS absent	1	Calorie Crusher	Pedometer	Pedometer, USB	Post-pregnancy women	A small clip-on device that calculates calories burnt and displays daily target calories to burn. The accompanied website lets users store the workout data and connect to other users to compete with.
	2	S. E. L. F. (Satisfaction, Enjoyment, Lifestyle, Fitness)	Headset	Bluetooth®, USB, flash storage	Anyone who listens to music when working out	A Bluetooth®-enabled music player that is connected to the around-the-neck headset. On the PC interface, the user can set up playlists based on different types of workouts. The music player selects playlists based on the pre-set workout routines.
	3	eTrainer	Watch	Heart rate monitor, Bluetooth®	Anyone who wants to stay fit	A workout watch that monitors heart rate and time during cardio. On the website, the user gets nutrition information, training schedules, and can set workout goals. Rewards points transferrable to workout items are issued based on the amount of workout completed.
Conference room + ISDS present	4	Ginko	Watch	Pedometer, Bluetooth®	Young professionals in late 20s and 30s without much free time to work out	A bracelet that track calories burned during normal activities as well as workout sessions. Based on how active he/she was, users accumulate "tink points" that can be exchanged to coupons, movie tickets, or workout sessions at local gyms. On the website, users get avatars changes appearances based on the amount of workout completed. They can get statistics, success stories, and access to local communities.
	5	My Trainer	Watch, tablet, &	Pedometer, heart rate monitor,	Working adults with	A portable fitness assistant that provides real-time fitness monitoring using smart workout technology. It

			docking station	accelerometer, Bluetooth®	busy and unhealthy lifestyle	comes with a docking station that can connect to 1 notebook screen and 2 Bluetooth®-enabled watches. The watch tracks time, heart rate, speed, distance, and calories. On the web account, the users can get nutrition tips, workout schedule, and training progress. Rewards such as a gym membership are given based on the amount of workout completed. Users can compete with friends and compare statistics. All devices sync with each other wirelessly.
	6	E. S. T.	Hand-held device	Touch screen, USB	Young adults between ages 22 and 35 with busy lifestyle	A small hand-held training device that stores user workout profiles and shows customized workout plans. It is capable of connecting to workout machines (e.g., treadmill) and downloads workout history.
Kiva + ISDS absent	7	F. I. T. (fun, interactive, trainer) Watch	Watch	Heart rate monitor, Bluetooth®	Young professionals with busy lifestyle	An interactive watch that monitors workout progress by checking heart rate and tracking running distance. The watch displays maps and connects to phones to display music information if music is playing on the phone. Users can set workout alarms.
	8	M. O. V. E. (motivate, opportunitie s, vital, encourage)	Watch & docking station	Heart rate monitor, GPS tracking	K-12 children	A watch/bracelet intended to be used during recess at elementary schools. The bracelets go on the docking station in classroom after use. Based on the heart rate, active time, and calories burnt during the use, the system ranks children and crowns the class MVP daily.
	9	Health Watch	Watch & headset	Heart rate monitor, USB	Females	This is a hybrid device of heart rate monitor watch integrated into a headset with a built-in music player. The watch tracks heart rate, workout time, and calories burned. The devices plugs into the PC via USB and syncs to a web account. The user can go to

						the website for workout statistics, recipes, and keep a blog.
Kiva + ISDS present	10	Heart	Interactive wall display & bracelet	LCD display, pedometer, heart rate monitor, Bluetooth®	Post pregnancy women and their families	An interactive wall display where its features reflect the amount of workout completed by the entire family. The more users work out the more elaborative the display design becomes. The activities are tracked through monitoring bracelets individuals wear.
	11	Burn Tracker	Wearable cuff	Non-invasive electrodes that can pick up muscle activities, waterproof casing, micro-sized processing unit, anti-viral/mesh fabric, LED lights	Workout enthusiasts who closely monitor their progress	A wearable muscle activity monitoring system. A thin elastic cuff provides instant visual feedback about muscle activation, and users can choose different products depending on the muscle groups they want to focus on.
	12	Flexatron	Bracelet	USB, Bluetooth®, accelerometer, pedometer	Obese/inactive children under 15	A bracelet with an USB/Bluetooth dongle that can plug into different workout devices and objects such as footballs or bikes. Superhero characters are adopted as a marketing tool. The children will be more inclined to use it due to the characters, and it will lead to more activities.

Targets and Features. All of the teams specified their target user groups. Some teams selected a broad group (e.g. "anyone who wants to stay fit") while others chose specific targets (e.g. "obese or inactive children under 15"). The products that had specific target user groups showed features that addressed the usage pattern of that specific target group. For example, Team 12 targeted "obese or inactive children under 15" and designed a product that integrates into different products that age group uses the most (i.e., Nerf ball, bike). They also decided to adopt superhero characters to increase the sales and engagement of target users.

Figure 29. Prototype of "Flexatron" (Team 12) (photographed by the researcher, used with permission of the participants)

Product Forms. While most of the products produced were wearable devices addressing individual users (Teams 1, 2, 3, 4, 7, 11, & 12), some products showed multiple forms or comprised a suite of products. One team produced a wearable device that integrated a watch and a headset into a single detachable form factor (Team 9, shown in Figure 30). Another team created a collection of two watches, one tablet, and a docking station so that family members could use the products simultaneously (Team 5, shown in Figure 31)

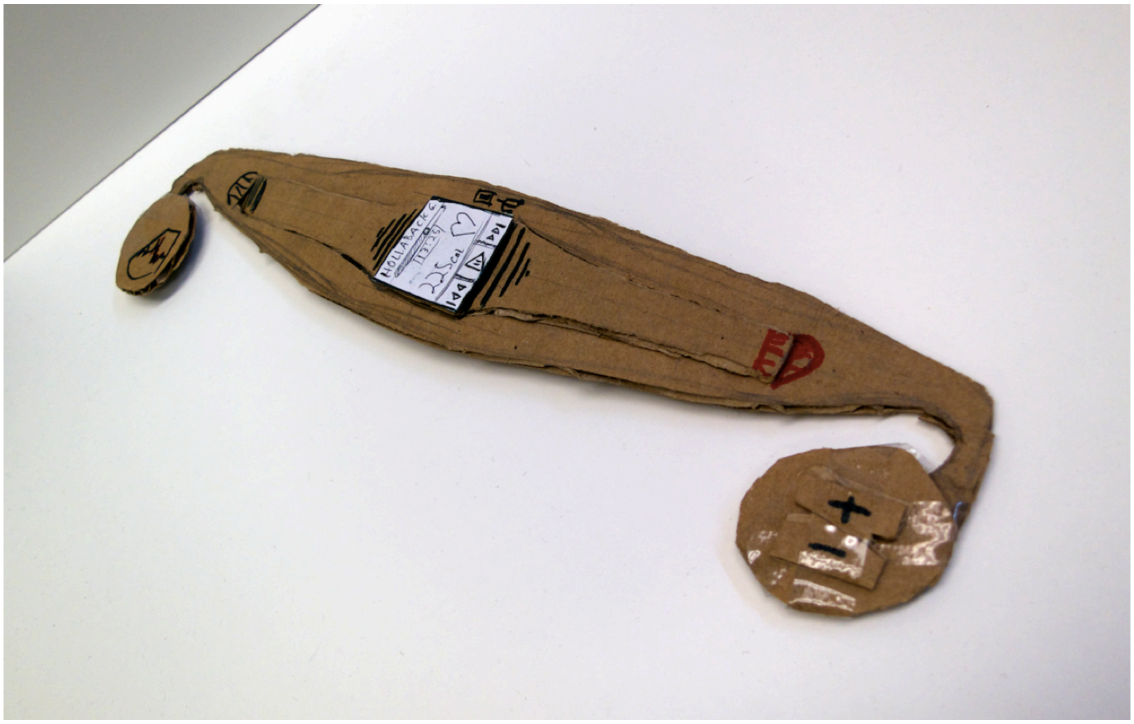

Figure 30. Prototype of a hybrid device of a watch and a headset (Team 9) (photographed by the researcher, used with permission of the participants)

Figure 31. Prototype of a workout assistant product suite (Team 5) (photographed by the researcher, used with permission of the participants)

While other teams created wearable or handhelds products, one team designed a smart home installment including a wall display that reflects activity levels of all users (Figure 32).

Figure 32. Prototype of "Heart," the interactive wall display (Team 10) (photographed by the researcher, used with permission of the participants)

4. 2. 6. Summary of Phase 2 Results

From Phase 2 of this study, the relationship between the team environment and various aspects of the multi-faceted team effectiveness was examined in a laboratory-based setting. First, the most prominent trend this study showed was that providing the combination of a physically flexible space (i.e. Kiva) and the structured facilitation for brainstorming sessions (i.e. ISDS support) to interdisciplinary engineering design teams significantly improves various team process and team output measures. In terms of team processes, a combined effect was shown from the quality of verbal interactions, quantity of physical interactions, quality of physical interactions, and teamwork mental model similarity, as well as process related measures of team diagnostic survey (e.g., group norm, team processes, and interpersonal relationship categories). In terms of team output, the significant interaction was shown from the satisfaction measure of the team diagnostic survey.

Second, this study found an effect of the physical environment on the verbal interaction rate and some of the product evaluation criteria. Unexpectedly, the conference room teams showed higher quantity of verbal communication than the Kiva teams. From the product evaluation, the products that Kiva teams created scored significantly higher in originality of the solution, benefit to users, and aesthetics.

Third, the effect of the interaction strategy design support (i.e., facilitation) was found from the originality of the solution in product evaluation with teams who received the support showing higher originality than the teams who did not received the support. Results of hypothesis testing are summarized in Table 18.

Table 9

Summary of Phase 2 Results

Dependent Variable	Measure	Main effect of room	Main effect of support	Interaction of room x support
Verbal interactions	Verbal communication rate	Yes	No	No
	Verbal communication quality	No	Yes	Yes
Physical interactions	Physical interaction rate	No	Yes	Yes
	Physical interaction quality	No	No	Yes
TDS	Real team	No	No	Yes
	Compelling direction	No	No	No

	Team composition	No	No	No
	Task design	No	No	Yes
	Group norm	No	No	Yes
	Team processes	No	No	Yes
	Interpersonal relationship	No	No	Yes
	Internal motivation	No	No	Yes
	Satisfaction	No	No	Yes
Team mental model questionnaire	Taskwork MM similarity	No	No	No
	Teamwork MM similarity	No	No	Yes
Product evaluation	Originality	Yes	Yes	No
	Manufacturability	No	No	No
	Benefit to users	No	Yes	No
	Aesthetics	No	Yes	No
	Marketability	No	No	No

4. 2. 7. Limitation of This Study

Limitations to the qualitative methods used for this study need to be documented. First, the researcher acted as a single coder for the physical interaction coding due to limited time and equipment that were available for the video analysis. In order to minimize the bias, the detailed definition of physical interaction codes were constructed, and the decision rules were continuously referenced during the coding process. Second, the experts who evaluated the products only represented two disciplines (Electrical & Computer Engineering and Industrial Design) of the participant backgrounds. The marketing expert was not available due to schedule conflict. However, it can be argued that the two evaluators have experiences in evaluating interdisciplinary design products in a holistic way from their experience with the interdisciplinary design classes.

CHAPTER 5. DISCUSSION AND CONCLUSION

The current study investigated how a physical space, an interaction strategy design support, and the interaction of the two affect the effectiveness of interdisciplinary design teams. This chapter summarizes how the results of the current study answers the initial research questions in terms of team interaction patterns, team mental models, team effectiveness (both perceived and directly measured), and characteristics of successful interdisciplinary design teams. Based on the key findings, guidelines for design and evaluation of interdisciplinary collaboration space and strategy were developed.

5. 1. Team Interaction Patterns

- Research Questions (RQ1, 7, 8): To what extent do physical conditions, interaction strategy design support, and the interaction of the two affect team interaction patterns?

5. 1. 1. Impact of Physical Environment & ISDS Support on Verbal Interactions

That a flexible space with more sharable whiteboards had a negative impact on the quantity of verbal interaction was unexpected, especially since expert interviews suggested that the Kiva space will stimulate the verbal interaction of the teams operating within. However, the previous research findings had been inconsistent regarding the impact of spatial traits on the quantity of verbal interactions. Some suggested that it would increase the level of idea exchanges in the form of verbal communication (Garzotto & Rizzo, 2007) while others found no differences among different information surface conditions (Rogers, Lim, Hazlewood, & Marshall, 2009). It can be argued that the Kiva space provided more opportunities for the participants to interact with the physical space itself, which could have led to reduced available time to interface with other team members. Because the Kiva space provided more whiteboard surface for the participants to visually communicate through sketching and writing, it could have led to increased time spent on visual communication and reduced time spent on verbal communication simultaneously. Another plausible explanation is that the number of utterances might not capture the true quantity of verbal interactions. If there were many short verbal exchanges, that would increase the captured level of verbal communication for that conversation. A more in-depth analysis of verbal communication rate might need to use discourse analysis strategies such as analyzing the directions of turn taking or the duration of each utterance, and was beyond the scope of this study. It would be interesting to further explore different ways to analyze the quantity of the verbal communication data in the future.

Additionally, the quality of the verbal communication with a focus on interdisciplinary integrations showed that there was a significant interaction of physical environment and interaction strategy design support. Previous studies suggested that the indicators of successful interdisciplinary team performances would include deep grounding within each member's discipline, integration of multiple perspectives, and appreciation of expertise of other members (Boix Mansilla, 2006; Borrego & Newswander, 2008). From examination of the transcript, it was evident that the verbal communication of more effective teams presented more evidence of these successful interdisciplinary processes.

5. 1. 2. Impact of Physical Environment & ISDS Support on Physical Interaction Patterns

First, the observed physical interaction pattern confirmed the impact of ISDS support. The significant main impact of ISDS support on the duration spent by members referencing back to previously drawn items on the shared information surface can be interpreted as the participants utilizing the physical space as a reference point to retain critical information for the team's project. This finding is consistent with the previously-documented positive impact of facilitated brainstorming sessions on a team's interaction processes (Anson, Bostrom, & Wynne, 1995; Lynch, Murthy, & Engle, 2009).

Second, the results also indicated that the flexible physical space coupled with the strategy support is effective for stimulating team's interactive processes. This process was shown in physical interaction behaviors of participants, such as drawing together or presenting artifacts created to other members and seeking feedback. The importance of idea "incubation" in the group idea generation has been reported from the examination of group-writing procedures (Paulus & Yang, 2000). The importance of team's physical spaces on innovativeness of team ideas (Kristensen, 2004) and interdisciplinary creativity (Kim & McNair, 2009) has been suggested in prior case studies. It has also been reported that the strategy of dealing with interdisciplinary team interaction has an impact on the overall effectiveness of interdisciplinary teams

(Borrego & Newswander, 2008; Huutoniemi, Klein, Bruun, & Hukkinen, 2010; Martin et al., 2012). The subject matter expert interview during Phase 1 also speculated that a visual mode of conversation could be a reason why the use of Kiva space stimulates interdisciplinary team interaction. For the context of this study, it can be argued that the ISDS support for the teams created opportunities for members to use the physical space to display their ideas, hence creating visual communication artifacts, so that they could reflect on the ideas that had been generated by the team and exchanged among the members.

5. 2. Impact of Environment & Strategy on Team Mental Models and Team Effectiveness

5. 2. 1. Team Mental Model Similarity

- Research Questions (RQ2, 5, 9): To what extent do physical conditions, interaction strategy design support, and the interaction of the two affect team mental model similarity?

It was hypothesized that there would be a significant interaction of room and ISDS support. The hypothesis was partially supported with the teamwork MM similarity scores revealing a significant two-way interaction with Kiva + ISDS present teams showing the highest level of teamwork MM similarity. The pair-wise comparison revealed that whether the teams received the strategy support made more differences in the Kiva teams than in conference room teams. Because teamwork mental models measured similarities in how members associated various aspects of teamwork, including member trust or diversity, it can be interpreted as the design support they received helped these teams to build more similar mental models and expectations; and the support was more effective in the flexible and new space than in the traditional space. It had been noted that the level of team mental model similarity among team members was correlated with the high team performance (Lim & Klein, 2006; Mathieu et al., 2000). The results of the questionnaire data were consistent with these findings.

5. 2. 2. Team Effectiveness: Team Diagnostic Survey

- Research Questions (RQ4, 6, 10): To what extent do physical conditions, interaction strategy design support, and the interaction of the two affect perceived team effectiveness?

The results of the Team Diagnostic Survey showed that the interaction strategy design support impacts the perception of team effectiveness. The participants who received the ISDS support felt that they were more capable of assessing their own success than the teams who did not receive the support. Also, teams under the ISDS support perceived their workload sharing to be more equal, and had a clearer strategy of handling information than the other teams. In addition, the ISDS present teams enjoyed getting to know each other more and more strongly identified with the team's success than did the ISDS absent teams. This indicates that the strategy-based intervention was effective for improving the effectiveness of team processes. This finding was consistent with other studies that confirmed the positive impact of strategy-based interventions such as team training (Peelle, 2006) and facilitated sessions (Kim & McNair, 2011) on the team collaboration. The questionnaire results also revealed a combined effect of a physical space and a strategy-based intervention on perceived level of team effectiveness. That is, the teams operated in the Kiva space showed higher level of perceived effectiveness only when they received the strategy-based interventions. It is worth noting that even though the impacts of the physical environment and strategy-based interventions on team effectiveness have been studied as individual factors, the researcher has no knowledge of a study that shown the interaction effect of the two in an empirical setting.

5. 2. 3. Team Effectiveness: Team Produced Outcomes

- Research Questions (RQ4, 6, 10): To what extent do physical conditions, interaction strategy design support, and the interaction of the two affect team effectiveness measured from the quality of team-produced products?

Unlike the perceived level of team effectiveness shown in the TDS scores, evaluation of team-produced outcomes (product design) did not show significant interactions between the physical environment and the ISDS support. Instead, the most prominent trend found from this data was the main effect of physical environment with teams who operated in the Kiva showing higher originality and more benefits for the intended users in their design solutions. The only other measurement that showed the significant effect of the physical space was verbal interaction rates, with Kiva teams showing lower communication rates than the conference room teams. The lower number of utterances per minute that Kiva teams could have been attributed to the longer remarks per each utterance. In this measurement, one utterance could range from a short, one-word sentence to a several minute long remarks. Hence, the Kiva team members possibly spent longer time on each topic of conversation, allowing them to explore topics more deeply, leading to greater originality of solution and more benefits considered for their product.

5. 3. Success Indicators of Interdisciplinary Design Teams

- Research Question (RQ11): What are the success indicators of interdisciplinary design teams?

5. 3. 1. Equal Participation and Interdisciplinary Team Effectiveness

One of the success indicators confirmed from the current study was balanced participation of all members into the team processes. The verbal communication pattern and collaboration strategies that participants presented suggested that active engagement balanced across all team members is one of the precursors of successful interdisciplinary teamwork. This is consistent with prior empirical evidence that showed equal participation leading to more effective interdisciplinary communications (Kim & McNair, 2011). While the previous study presented evidence from a comparative case study setting that tracked the communication pattern of student product design teams operating in a semester-long class, the current study showed that when testing for the impact of interventions on the effectiveness of interdisciplinary teams in a laboratory setting, investigating the equity of participation and the level of active engagement across team members can be used as an indicator of successful interdisciplinary teamwork.

5. 3. 2. Interdisciplinary Collaboration Patterns and Team Effectiveness

The current study discovered several collaboration patterns that were associated with successful interdisciplinary design teamwork. There were clear differences in collaboration behaviors between the ISDS supported teams and the other teams. Interestingly, all of the ISDS-support teams showed more collective behaviors while the other teams took a divide-and-conquer approach. These teams assigned the team tasks based on their disciplinary background and showed minimal collaboration while working individually. The ISDS support procedures led the participants to 1) take turns in communicating, 2) make use of the shared information surfaces, and 3) make collective decisions. It can be argued that following these exercises gave the participants more opportunities to appreciate the expertise of other team members and to develop a sense of collective work unit as a team.

The interdisciplinary team research literature suggests that the indication of successful interdisciplinary team outcome shows expertise grounded in participating disciplines, integration crossing boundaries, and awareness and appreciation of other expertise (Boix Mansilla & Duraising, 2007). The success indicators that the communication and collaboration pattern revealed in the current study were consistent with these categories shown in previous studies. The indicators were: 1) presentation of domain-specific knowledge, methods, and strategies, 2) exchange of domain-specific terms among members, 3) design decisions influenced by more than one discipline, 4) active requests to solicit expertise of another domain, 5) addressing of questions to the domain expert, 6) overtly addressing teammates disciplinary background rather than personal indicators, 7) teaching other members how to use domain-specific tools or devices, and 8) co-working to create deliverables even when there is a clear dominance of required domain knowledge. This list of indicators can be used for the research that studies successful interdisciplinary integrations. Furthermore, design guidelines can be constructed that support these behavioral and communicational patterns.

5. 4. Contribution of the Current Study for Collaboration Space Design for Interdisciplinary Design Teams

While some studies posit that physical workspaces affect the team performances (Moultrie et al., 2007; Kristensen, 2004), the perception of flexibility influences job satisfaction (Lee & Brand, 2005), and supporting strategies impact team performances (Paulus, 2000), no experimental studies to the researcher's knowledge have examined the efficacy of team design space and support strategy and its interactive effect on team processes. By examining the effect of a novel, flexible design space compared to a conventional conference room space with rigid features, the current study revealed that the affordance of space alone does not effectively make a difference in interdisciplinary team collaborations. In other words, when designing a collaboration space for interdisciplinary design teams, appropriate strategies that allow users to fully utilize the spatial features should also be developed.

Although systematic research is still lacking in the area of interdisciplinary team collaboration spaces, the research focusing on collaborative learning space has received the attention of several communities, including architects, educators, and university administrators. In particular, the National Science Foundation has identified the future design of learning spaces as one of the important areas of research to ensure successful education of future students (Learning Spaces Collaboratory, 2010). Despite the call for action, few empirical studies have been conducted that use systematic methods to provide insights into this critical area (Peng, 2013). Hence, the results of this study provide robust research-based findings for designers of learning spaces who are looking to foster collaborative learning across disciplinary boundaries.

5. 4. 1. Evaluation Guideline

Creating an intervention that fosters interdisciplinary collaboration calls for effective testing of features. This process requires careful selection of variables, research methods, and measurements. In this study, the behavioral evidence of successful interdisciplinary teams was identified, and a number of ways to measure the effectiveness of interdisciplinary teams were verified. Based on the findings of this study, an evaluation guideline for interdisciplinary collaboration spaces was created in order to guide designers and architects who prototype and evaluate the spatial interventions such as project rooms intended to support interdisciplinary teams. As industry focuses more and more on fostering innovation by providing interdisciplinary industry teams with appropriate collaboration spaces, this evaluation guideline will be useful for the creators of such new spaces.

Evaluation Guideline of Interdisciplinary Collaboration Spaces
• **List of Potential Independent Variables** o <u>Spatial conditions</u> ▪ Shape of the space (Used as a factor in Phase 2 of the current study) ▪ Size of the space ▪ Area of shared information surface (Rogers et al., 2009) ▪ Technological enhancement features

        - Visibility of the space (Kristensen, 2004)
            - Is the space visible to passers-by?
        - Conservability of contents (Suggested in Phase 1 of the current study)
            - Can users save the changes they make such as drawing, additional materials, or furniture configurations?
        - Environmental factors: lighting, noise, windows, etc (Maier et al., 2009)
    - <u>Strategy conditions</u>
        - Training (Salas, Cooke, & Rosen, 2008) facilitation (Paulus et al., 2002; also used as a factor in Phase 2 of the current study)
- **List of Dependent Measures**
    - Verbal communication rate (Rogers et al., 2009)
        - Number and duration of utterances
    - Turn-taking behaviors (Suggested in Phase 1 of the current study)
        - Direction of the communication (Lee & Lee, 2009)
        - Equity of participation (Rogers et al., 2009)
    - Verbal communication quality check points
        - Is there evidence of presentation of domain-specific

knowledge, methods, and strategies? (Boix Mansilla & Duraising, 2007, Phase 2 of the current study)

- Is there evidence of exchange of domain-specific terms among members? (Phase 2 of the current study)
- Is there evidence of providing information for others before another member asks for it? (Salas et al., 2008)
- Are design decisions being influenced by more than one discipline? (Phase 2 of the current study)
- Is anyone actively requesting help from other members to solicit expertise of another domain? (Kim & McNair, 2011, Phase 2 of the current study)
- Are participants addressing questions to the domain expert in the area? (Kim & McNair, 2011, Phase 2 of the current study)
- Are participants overtly addressing another team member by his or her disciplinary background rather than personal indicators such as first name? (Kim & McNair, 2011)
- Is there evidence of participants teaching other members how to use tools or devices that his / her own disciplinary background is required? (Boix Mansilla & Duraising, 2007)

        - Are participants co-working to create deliverables even when there is a clear dominance of required domain knowledge? (Phase 2 of the current study)
    - Usage of shared surface
        - Area of used surface over time (From the observation during the Phase 2 of the current study)
        - Surface usage quality checkpoint: check the frequencies of following significant action codes.
            - Acquiring: An act of acquiring needed materials. This includes obtaining markers, sticky notes, adhesive poster sheets, pens, etc. (Phase 1 & 2 of the current study)
            - Walking: An act of walking within, to, and from the given space. (Phase 1 & 2 of the current study)
            - Pointing: An act of pointing at items on the shared information surface. (Bly, 1988)
            - Referencing: An act of referencing to a previously discussed item by reading it from the whiteboard. (Bly, 1988)
            - Writing or drawing: An act of writing or drawing on the shared information surface. (Bly, 1988; Rogers et al., 2009)

            - Reconfiguring: An act of moving items within the Kiva. This included moving chairs, desks, partitions, etc. (Phase 1& 2 of the current study)
    - Control of shared surface: record who is controlling the shared information surface (From the observation during Phase 2 of the current study)
- Recording Checklist
    - When video recording is used, consider using a wide-angle lens or fish-eye lens attachment to capture the entire perimeter.
    - Consider using a secondary video camera to capture details of the items being added to the shared information surface.
    - Make sure there is a back-up audio recording for verbal communication analysis.
    - When testing in an open-air environment, consider using directional or high-definition clip-on microphones.
- Suggested Open-Source Analysis Software
    - ImageJ from National Institute of Health for analyzing surface area used. This free software allows researchers to take measurements from digital recordings to a scale.
    - TAMSAnalyzer from University of Washington for analyzing verbal communication transcripts. This open-source, free software allows researchers to transcribe and code qualitative

data.

- Noldus Observer XT © from Noldus Information Technology for analyzing physical movements of the participants. This commercial software allows researchers to code and tag observed behaviors on a video recording.

5. 4. 2. Design Guidelines for Interdisciplinary Collaboration Space

Based on the findings of the current study, a list of design insights for the collaboration space that support interdisciplinary teams was created. This guideline is intended for designers and architects working in the industry who create the collaboration spaces that are used by interdisciplinary teams. Additionally, the educators who teach interdisciplinary classes that bring students with diverse disciplines are encouraged to reference this list when designing physical classroom environments for such classes.

- Gather information about participating disciplines of the intended users, including common collaboration patterns
    - To trigger balanced participation, analyze the specific strategies that each participating disciplines use and integrate features that suit those disciplines (more details about strategies in the next section).
- Make sure there is a shared information surface which allows simultaneous inputs so that collaboration can be seamless

    - Install designated display areas to allow users to easily share artifacts such as paper-based sketches or other materials
- Integrate features that let teams record and reference the previous discussed items
    - E.g. Whiteboards with a built-in camera for record-keeping
- Integrate features such as wheeled partitions to allow spatial flexibility in terms of size and shape of the space
    - Wheeled furniture adds flexibility. Consider adding nets on the bottom of the wheeled furniture to ensure close proximity of necessary tools to the users at all times.
- Make sure there is a shared horizontal work surface that allows visibility from other members

5. 4. 3. Design Guidelines for Interdisciplinary Collaboration Strategy

In addition to the guidelines for the physical space design, a list of design insights for the strategy-based interventions that support interdisciplinary teams was created. This guideline is intended for the interdisciplinary design teams who use the collaboration spaces, so that they can design strategy-based supports to be used when using the collaboration space to increase the effectiveness. Also, the designers of the collaboration spaces are encouraged to develop sample strategy supports that suit the intended users and the space they designed, to be paired with the collaboration space as a packaged product. Additionally, the educators who teach interdisciplinary classes that bring students with diverse disciplines are encouraged to reference this list when designing strategy-based interventions for such classes.

- Gather information about participating disciplines of the intended users, including common collaboration patterns
- For idea generation support, make sure there is an allotted time for individual idea generation in the beginning of the exercise.
- Consider integration of a visual voting system for idea generation exercise.
- For team discussions, consider time-boxing each person's response to ensure equal participation.
- Allow for reference of past discussions

5. 5. Conclusion and Future Direction

This study examined the impact of physical room condition and interaction strategy design support on the effectiveness of interdisciplinary design teams. The overall findings indicated that the benefits of having a novel, flexible team design space are only effective when they are combined with a strategy that allows users to fully utilize the features of the space.

In this study, the physical environment was examined at a holistic environment level rather than at a per-feature level. The study provided insights for different features that might have contributed to the effectiveness of interdisciplinary teams. However, it was not able to pinpoint which aspect of the environment in particular drove the differences in performance measures. Therefore, future efforts to discern different features of the physical environments such as the shape of the room, the area of the shared information surfaces, and the noise level would be highly useful in improving the intervention design for interdisciplinary design teams.

Although it is not explored in the current study, the transition between verbal and visual modes of conversation can be researched using the same data. This study found that the physical space had a significant impact on the verbal communication rate of interdisciplinary design teams. Aligning the transitions between verbal and visual modes of conversations with the usage of shared information surfaces can provide insights into how spatial features impact the team interaction processes.

Additionally, the development of a questionnaire that measures the perception of interdisciplinary team success in particular is desired. The questionnaires used for this study were originally developed for general teams. As a special case of a heterogeneous team, an interdisciplinary team has more particular success indicators as well as different integrative processes. In order to diagnose the effectiveness of these teams more accurately, the development of a new instrument that addresses the particular processes and outcomes of interdisciplinary teams will be necessary. Development of this instrument should involve industry experts with extensive experience in managing interdisciplinary design teams as well as academic experts with intensive knowledge in interdisciplinary outcome assessment. Such coordination will be desirable to ensure that the common success indicators found in both expert and novice teams are covered in the instrument.

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Appendices

Appendix A: Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants in Research Projects Involving Human Subjects

Title of Project:

Enhancing the Effectiveness of Interdisciplinary Engineering Design Teams by Using Flexible Facility and Interaction Strategy Design Support

Investigators:

Kahyun Kim, Dr. Lisa D. McNair, and Dr. Brian M. Kleiner

I. Purpose of this Research/Project

The purpose of this study is to examine the impact of physical environment and interaction strategy support on team effectiveness of interdisciplinary engineering design teams. This study will use observation, questionnaires, and interviews. You will participate in three experimental sessions and the activities will include brainstorming, team discussions, and prototyping.

The results will be presented in the form of an academic paper, and will include an interpretation of statements by participants. These findings may help inform administrators and instructors of ways to improve the learning community.

All participants must be fourth-year student, 18 years or older, speaking English as primary language, and have no previous collaboration history with each other.

II. Procedures

1) Pre-session questionnaire (20-minutes)

After the participants are recruited, they are given an online link to an informed consent form, which explains the purpose of the study and the experimental procedures involved. Once they complete the informed consent procedure the participants are given a demographic questionnaire and the Thomas-Killman Conflict Handling Mode Instrument.

2) Session 1: Familiarization (1-hour)

In the first session, the participants will be familiarized with each other as well as the experimental conditions. To familiarize the participants with the spatial conditions, a team brainstorming session using a simple brainstorming task based on Hilliges et al. (2007) will be conducted. The participants will be asked to produce as many ideas as possible to take care of an Inuit coming to a foreign country neither speaking the country's language nor having any useful equipment for the new environment.

3) Session 2: Design Concept Development (2-hours)

For the second session, the participants will be given instruction sheets describing the design task. After reading the instruction sheet, the teams will be asked to brainstorm to identify design problems and generate concepts of design solutions. By the end of the design session, the participants will be required to decide on design ideas for prototyping in the next session. This session will take approximately an hour. After the brainstorming is completed pair-wise Relatedness Rating Scales will be administered.

4) Session 3: Prototyping and Finalizing Design (2.5-hours)

In the third session, the participants will be asked to prototype their product idea using materials provided. Cardboards, colored markers, clear tapes, Styrofoam, and necessary tools (e.g. scissors) will be provided. The prototype is required to show basic form and function of the product. Also, the participants will be asked to produce a sketch of display of the basic user interface draw showing the highest level menus and a 1-page magazine advertisement for their product. The three required products are selected to include end products that require domain knowledge of all three disciplinary backgrounds. After the session, Team Diagnostic Survey will be administered.

III. Risks

There are no more than minimal risks for participating in this study.

IV. Benefits

Your participation on this study will provide valuable insights to identifying environment that fosters interdisciplinary team effectiveness. Also, you will benefit from experiencing a short interdisciplinary engineering design session, which is valuable for fourth-year students but not widely available.

V. Extent of Anonymity and Confidentiality

Your information will be kept strictly confidential, and no one other than the researchers will know your identity. Upon completion of the study, you will be assigned a code number and pseudonym as an identifier. Individuals will be referred to by this code number for data analyses and for any publication of the results.

All recordings, transcripts, and consent forms will be kept confidentially in a locked cabinet at Kahyun Kim's office, 519J Whittemore. Any data in digital form will be stored on an external hard drive in the same office with password protection. Only the researchers of this study will have an access to the data.

It is possible that the Virginia Tech Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of, and the protection of human subjects involved in research.

VI. Compensation

You will be compensated $10 per hour (maximum of $50)..

VII. Freedom to Withdraw

If you agree to participate in this study, you are free to withdraw from the study at any time without penalty.

VIII. Subject's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities for the one interview session:

1. Arrive at the designated place at the scheduled times.

2. Participate in the experimental activities.

3. Respond truthfully to the questionnaires and interview questions.

IX. Permission Statement

I have read the preceding Consent Form and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

____ Date______________

Participant signature

Participant information:

Printed name: ____

Phone number: ________________________________

E-mail address: ________________________________

Male or Female: _______________________________

Major: _______________________________________

Ethnicity (optional): _____________________________________

Age: ________________

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Kahyun Kim, Graduate Research Assistant, Investigator, kahyunk@vt.edu

David M. Moore, 540-231-4991, moored@vt.edu

Chair, Virginia Tech Institutional Review

Board for the Protection of Human Subjects

Office of Research Compliance

1880 Pratt Drive, Suite 2006 (0497)

Blacksburg, VA 24061

IRB #

Virginia Tech Institutional Review Board: Project No. xxxx, Approved xxxx, 2009 to xxxx, 20010

Appendix B: Phase 1 Interview Questions

Interventions and Kiva

1. What was the rationale behind the design of Kiva?
2. The kiva space provides the ability for everyone to share visual representation of their ideas (e.g., with diagrams on the whiteboard, artifacts, etc.), what does this do to the interaction between members with different professional/technical/disciplinary backgrounds?
3. What is the most pronounced difference in design interactions that you observe? (Comparison between interactions in Kiva vs. conventional conference rooms)

Design Process/ Indication of Success & Conflict

4. What are the representative signs of successful interdisciplinary design teams?
    a. Examples
5. What are the representative signs of unsuccessful interdisciplinary design teams?
    a. Examples
6. As a designer, what do you value most when designing a product?
7. Do you think designers and engineers think differently?
8. Does this (differences in how they think) contribute to the interdisciplinary design process?
9. Have you seen a gridlock in the middle of the design process?
10. How does gridlock usually occur and what is the typical process of resolving those issues?
11. How can Kiva help conflict resolution?

Suitable Design Activities for Kiva

12. What types of design challenges are suitable for interdisciplinary design?
13. Do you think having Kiva is particularly beneficial for certain types of design tasks? What would they be?
14. Based on your experience with various design teams, which do you think was the most effective design activity for stimulating team interactions?

Appendix C: Thomas-Kilmann Conflict Handling Mode Instrument

Thomas-Kilmann Conflict Mode Instrument

By: Kenneth W. Thomas and Ralph H. Kilmann

Instructions

Consider situations in which you find your wishes differing from those of another person. How do you usually respond to such situation?

On the following pages are several pairs of statements describing possible behavioral responses. For each pair, please circle the "A" or "B" statement, which is most characteristic of your own behavior.

In many case, neither the "A" nor the "B" statement may be very typical of your behavior; but please select the response which you would be more likely to use.

1.	A	There are times when I let others take responsibility for solving the problem.
	B	Rather than negotiate the things on which we disagree, I try to stress those things upon which we both agree.
2.	A	I try to find a compromise solution.
	B	I attempt to deal with all of his/her and my concerns.
3.	A	I am usually firm in pursuing my goals.
	B	I might try to soothe the other's feelings and preserve our relationship.
4.	A	I try to find a compromise solution.
	B	I Sometimes sacrifice my own wishes for the wishes of the other person.
5.	A	I consistently seek the other's help in working out a solution.
	B	I try to do what is necessary to avoid useless tensions.
6.	A	I try to avoid creating unpleasantness for myself.
	B	I try to win my position.
7.	A	I try to postpone the issue until I have had some time to think it over.
	B	I give up some points in exchange for others.
8.	A	I am usually firm in pursuing my goals.

	B	I attempt to get all concerns and issues immediately out in the open.
9.	A	I feel that differences are not always worth worrying about.
	B	I make some effort to get my way.
10.	A	I am firm in pursuing my goals.
	B	I try to find a compromise solution.
11.	A	I attempt to get all concerns and issues immediately out in the open.
	B	I might try to soothe the other's feelings and preserve our relationship.
12.	A	I sometimes avoid taking positions, which would create controversy.
	B	I will let the other person have some of his/her positions if s/he lets me have some of mine.
13.	A	I propose a middle ground.
	B	I press to get my points made.
14.	A	I tell the other person my ideas and ask for his/hers.
	B	I try to show the other person the logic and benefits of my position.
15.	A	I might try to soothe the other's feelings and preserve our relationship.
	B	I try to do what is necessary to avoid tensions.
16.	A	I try not to hurt the other's feelings.
	B	I try to convince the other person of the merits of my position.
17.	A	I am usually firm in pursuing my goals.
	B	I try to do what is necessary to avoid useless tensions.
18.	A	If it makes other people happy, I might let them maintain their views.
	B	I will let other people have some of their positions if they let me have some of mine.
19.	A	I attempt to get all concerns and issues immediately out in the open.
	B	I try to postpone the issue until I have had some time to think it over.
20.	A	I attempt to immediately work through our differences.
	B	I try to find a fair combination of gains and losses for both of us.
21.	A	In approaching negotiations, I try to be considerate of the other person's wishes.
	B	I always lean toward a direct discussion of the problem.

22.	A	I try to find a position that is intermediate between his/hers and mine.
	B	I assert my wishes.
23.	A	I am very often concerned with satisfying all our wishes.
	B	There are times when I let others take responsibility for solving the problem.
24.	A	If the other's position seems very important to him/her, I would try to meet his/her wishes.
	B	I try to get the other person to settle for a compromise.
25.	A	I try to show the other person the logic and benefits of my position.
	B	In approaching negotiations, I try to be considerate of the other person's wishes.
26.	A	I propose a middle ground.
	B	I am nearly always concerned with satisfying all our wishes.
27.	A	I sometimes avoid taking positions that would create controversy.
	B	If it makes other people happy, I might let them maintain their views.
28.	A	I am usually firm in pursuing my goals.
	B	I usually seek the other's help in working out a solution.
29.	A	I propose a middle ground.
	B	I feel that differences are not always worth worrying about.
30.	A	I try not to hurt the other's feelings.
	B	I always share the problem with the other person so that we can work it out.

Appendix D: Team Diagnostic Survey

Team Diagnostic Survey

Name: ___________________________

Read the given statement and rate how accurate the statement describes your team experience from this study.

1. Members of this team have their own individual jobs to do, with little need for them to work together.
   1: Highly inaccurate   2: Somewhat inaccurate   3: Neutral   4: Somewhat accurate   5: Highly accurate

2. Generating the outcome or product of this team requires a great deal of communication and coordination among members.
   1: Highly inaccurate   2: Somewhat inaccurate   3: Neutral   4: Somewhat accurate   5: Highly accurate

3. Members of this team have to depend heavily on one another to get the team's work done.
   1: Highly inaccurate   2: Somewhat inaccurate   3: Neutral   4: Somewhat accurate   5: Highly accurate

4. There is great uncertainty and ambiguity about what this team is supposed to accomplish.
   1: Highly inaccurate   2: Somewhat inaccurate   3: Neutral   4: Somewhat accurate   5: Highly accurate

5. This team's purposes are specified so clearly that all members should know exactly what the team exists to accomplish.
   1: Highly inaccurate   2: Somewhat inaccurate   3: Neutral   4: Somewhat accurate   5: Highly accurate

6. This team's purposes are so challenging that members have to stretch to accomplish them.
   1: Highly inaccurate   2: Somewhat inaccurate   3: Neutral   4: Somewhat accurate   5: Highly accurate

7. This team's purposes are not especially challenging--achieving them is well within reach.
   1: Highly inaccurate   2: Somewhat inaccurate   3: Neutral   4: Somewhat accurate   5: Highly accurate

8. The purposes of this team don't make much of a difference to anybody else.
   1: Highly inaccurate   2: Somewhat inaccurate   3: Neutral   4: Somewhat accurate   5: Highly accurate

9. This team's purposes are of great consequence for those we serve.
   1: Highly inaccurate   2: Somewhat inaccurate   3: Neutral   4: Somewhat accurate   5: Highly accurate

10. Choose one of the following.
    1: The purposes of our team are specified by others, but the means and procedures we use to accomplish them are left to us.

2: The means or procedures we are supposed to use in our work are specified in detail by others, but the purposes of our team are left unstated.
3: Both the purposes of our team and the means or procedures we are supposed to use in our work are specified in detail by others.
4: Neither the purposes nor the means are specified by others for our team.

11. This team is larger than it needs to be.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

12. This team has too few members for what it has to accomplish.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

13. This team is just the right size to accomplish its purposes.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

14. Members of this team are too dissimilar to work together well.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

15. This team does not have a broad enough range of experiences and perspectives to accomplish its purposes.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

16. This team has a nearly ideal "mix" of members--a diverse set of people who bring different perspectives and experiences to the work.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

17. Members of this work team have more than enough talent and experience for the kind of work that we do.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

18. Everyone in this team has the special skills that are needed for teamwork.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

19. Some members of this team lack the knowledge and skills that they need to do their parts of the team's work.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

20. We do a whole, identifiable piece of work.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

21. This team's work is inherently meaningful.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

22. The work of this team leaves little room for the exercise of judgment or initiative.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

23. The work we do requires the team to make many "judgment calls" as we carry it out.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

24. Carrying out our team's task automatically generates trustworthy indicators of how well we are doing.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

25. The work itself provides almost no trustworthy feedback about our team's performance.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

26. The only way we can figure out how well we are performing is for other people to tell us.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

27. Standards for member behavior in this team are vague and unclear.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

28. It is clear what is--and what is not--acceptable member behavior in this team.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

29. Members of this team agree about how members are expected to behave.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

30. Regular team members...
A. take initiatives to promote high shared motivation and commitment.
1 Never 2 3 4 Often
B. take initiatives to make sure the team develops and uses the best possible approach to its work.
1 Never 2 3 4 Often
C. take initiatives to help the team build and use well members' knowledge and skills.
1 Never 2 3 4 Often

31. Regular team members...
A. take initiatives to constructively resolve any problems or conflicts that develop among members.
1 Never 2 3 4 Often

32. Regular team members...
A. tell other members what to do and how they should do it.
1 Never 2 3 4 Often

33. Members demonstrate their commitment to our team by putting in extra time and effort to help it succeed.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

34. Everyone on this team is motivated to have the team succeed.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

35. Some members of our team do not carry their fair share of the overall workload.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

36. Our team often comes up with innovative ways of proceeding with the work that turn out to be just what is needed.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

37. Our team often falls into mindless routines, without noticing any changes that may have occurred in our situation.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

38. Our team has a great deal of difficulty actually carrying out the plans we make for how we will proceed with the task.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

39. How seriously a member's ideas are taken by others on our team often depends more on who the person is than on how much he or she actually knows.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

40. Members of our team actively share their special knowledge and expertise with one another.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

41. Our team is quite skilled at capturing the lessons that can be learned from our work experiences.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

42. There is a lot of unpleasantness among members of this team.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

43. The longer we work together as a team, the less well we do.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

44. Working together energizes and uplifts members of our team.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

45. Every time someone attempts to correct a team member whose behavior is not acceptable, things seem to get worse, rather than better.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

46. My relations with other team members are strained.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

47. I very much enjoy talking and working with my teammates.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

48. The chance to get to know my teammates is one of the best parts of working on this team.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

49. I feel a real sense of personal satisfaction when our team does well.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

50. I feel bad and unhappy when our team has performed poorly.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

51. My own feelings are not affected one way or the other by how well our team performs.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

52. When our team has done well, I have done well.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

53. I learn a great deal from my work on this team.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

54. My own creativity and initiative are suppressed by this team.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

55. Working on this team stretches my personal knowledge and skills.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

56. I enjoy the kind of work we do in this team.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

57. Working on this team is an exercise in frustration.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

58. Generally speaking, I am very satisfied with this team.
1: Highly inaccurate 2: Somewhat inaccurate 3: Neutral 4: Somewhat accurate 5: Highly accurate

Appendix E. Relatedness Rating Scales for Team Mental Models

Please judge the relatedness of pairs of statements below. Specifically, you need to rate how related are these statements (statement on the left column to the statement on the right column) to each other. Circle on the number of a 7-point response scale (1: unrelated and 7: highly related).

Taskwork Mental Model Items

Team members are proficient with the tools. (Drawing tools, laptops, software packages, etc.)	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members have a good understanding of the characteristics of the equipment they are designing.
Team members are proficient with the tools.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members understand the team's task.
Team members are proficient with the tools.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Tasks in the team are assigned according to individual member's ability.
Team members are proficient with the tools.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members are cross-trained to carry out other members' tasks.
Team members are proficient with the tools.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.
Team members have a good understanding of the characteristics of the equipment they are designing.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members understand the team's task.
Team members have a good understanding of the characteristics of the equipment they are designing.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Tasks in the team are assigned according to individual member's ability.
Team members have a good understanding of the characteristics of the equipment they are designing.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members are cross-trained to carry out other members' tasks.
Team members have a good understanding of the characteristics of the equipment they are designing.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.
Team members understand the team's task.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Tasks in the team are assigned according to individual member's ability.

Team members understand the team’s task.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members are cross-trained to carry out other members’ tasks.
Team members understand the team’s task.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.
Tasks in the team are assigned according to individual member’s ability.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members are cross-trained to carry out other members’ tasks.
Tasks in the team are assigned according to individual member’s ability.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.
Team members are cross-trained to carry out other members’ tasks.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.

<u>Teamwork Mental Model Items</u>

Team members trust each other and work well together.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members are aware of other team members’ abilities.
Team members trust each other and work well together.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members communicate openly with each other.
Team members trust each other and work well together.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members interact with one another outside the session.
Team members trust each other and work well together.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members are similar to each other (e.g., personality, temperament, and abilities).
Team members trust each other and work well together.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.
Team members are aware of other team members’ abilities.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members communicate openly with each other.
Team members are aware of other team members’ abilities.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members interact with one another outside the class.
Team members are aware of other team members’ abilities.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members are similar to each other (e.g., personality, temperament, and abilities).

Team members are aware of other team members’ abilities.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.
Team members communicate openly with each other.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members interact with one another outside the class.
Team members communicate openly with each other.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members are similar to each other (e.g., personality, temperament, and abilities).
Team members communicate openly with each other.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.
Team members interact with one another outside the class.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	Team members are similar to each other (e.g., personality, temperament, and abilities).
Team members interact with one another outside the class.	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.
Team members are similar to each other (e.g., personality, temperament, and abilities).	Highly Unrelated 1 2 3 4 5 6 7 Highly Related	The team is highly effective.

Appendix F. Instruction Sheet for the Design Task

The Design Problem

Your challenge is to design an electronic device intended to encourage people to exercise regularly. Your solution must address one main theme that encourages people to exercise such as health, enjoyment, or community.

You are required to produce:

1. A prototype that presents the form, function, and user interface of the device,
2. A series of basic user interface display for a task of your choice, and
3. A hand-drawn magazine advertisement for the product.

You have two design sessions (Sessions 2 and 3) to complete the tasks. During session 2, you will explore the design problem, develop concepts, and generate alternatives for the design solution. After session 2, you will generate a list of additional materials you would like to use to prototype in session 3. Foam core, sandpaper, markers, colored paper, glue, and scissors will be provided. You will notify the researcher the additional materials you want, and they will be prepared for session 3.

Session 2

- Brainstorm with your team for design concepts.
- Generate a list of additional prototyping materials.

During session 3, you will use materials provided to create a low-fidelity prototype. Also, you will sketch a series of user interface screens for a task of your choice, which show the layout of menus. A one-page magazine advertisement will need to contain the name of your device and should capture the attention of the intended users.

Session 3

- Create a low-fidelity prototype
- Sketch a series of user interface screens for one task of your choice.
- Create a one-page magazine advertisement.

The products will be reviewed based on the following criteria:

1. Originality of the solution
2. Manufacturability
3. Benefit to the user
4. Appropriate aesthetics
5. Marketability

Appendix G. Design Evaluation Sheet

Please rate your assessment on a scale of 0-10 quantitatively, and enter evaluation notes regarding each criterion.

Review Criteria	Scale	Notes
1. Originality of the solution	0 2 4 6 8 10	
2. Manufacturability	0 2 4 6 8 10	
3. Benefit to the user	0 2 4 6 8 10	
4. Appropriate aesthetics	0 2 4 6 8 10	
5. Marketability	0 2 4 6 8 10	

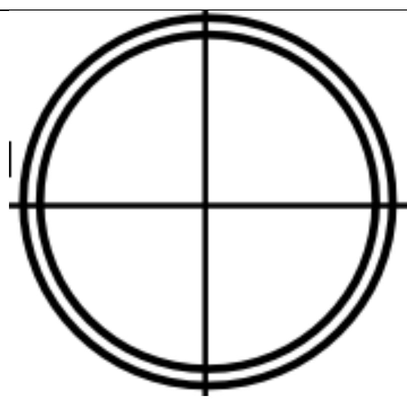
Appendix H: Observation Protocol for Phase 2

Date:

Experimental Condition:

IAK	IPK

Observation Checklist

Category	**Item**	**Yes/No**	**Observation notes**
Tool	Whiteboard usage		
Seat/walk	Reconfiguring		
	Seating arrangement		
Space usage			
Other significant actions			

Additional Notes:

Date:

Experimental Condition:

IAC	IPC

Observation Checklist

Category	**Item**	**Yes/No**	**Observation notes**
Tool	Whiteboard usage		
Seat/walk	Reconfiguring		
	Seating arrangement		
Space usage			
Other significant actions			

Additional Notes:

Appendix I: Contrast Analysis of TDS two-way Interactions

Q1		*F*	*p*
C-A	C-P	3.2351	0.0815
C-A	K-A	2.235	0.1447
C-A	K-P	0.0049	0.9446
C-P	K-A	0.0922	0.7633
C-P	K-P	3.4921	0.0708
K-A	K-P	2.4494	0.1274
Q2		F	p
C-A	C-P	14.35	0.0006
C-A	K-A	6.56	0.0154*
C-A	K-P	1.1384	0.294
C-P	K-A	1.5056	0.2288
C-P	K-P	7.4027	0.0104*
K-A	K-P	2.2313	0.145
Q11		F	p
C-A	C-P	9.8914	0.0036*
C-A	K-A	1.3395	0.2557
C-A	K-P	0.4615	0.5018
C-P	K-A	3.9509	0.0555
C-P	K-P	6.0798	0.0192*
K-A	K-P	0.2285	0.6359
Q20		F	p
C-A	C-P	3.5056	0.0703
C-A	K-A	11.1543	0.0021*
C-A	K-P	1.2394	0.2739

C-P	K-A	2.1535	0.152
C-P	K-P	0.5761	0.4534
K-A	K-P	4.9574	0.0331*
Q40		F	p
C-A	C-P	6.1272	0.0188*
C-A	K-A	0.2403	0.6274
C-A	K-P	0.0727	0.7892
C-P	K-A	3.9408	0.0558
C-P	K-P	7.5345	0.0098*
K-A	K-P	0.5772	0.453
Q44		F	p
C-A	C-P	3.4718	0.0716
C-A	K-A	4.106	0.0511
C-A	K-P	0.8251	0.3705
C-P	K-A	0.0266	0.8715
C-P	K-P	0.9119	0.3468
K-A	K-P	1.2499	0.2719
Q47		F	p
C-A	C-P	6.5811	0.0152*
C-A	K-A	2.2814	0.1407
C-A	K-P	0.4507	0.5068
C-P	K-A	1.1128	0.2994
C-P	K-P	3.5874	0.0673
K-A	K-P	0.7041	0.4076
Q49		F	p
C-A	C-P	1.9911	0.1679

C-A	K-A	0.4032	0.53
C-A	K-P	0.7572	0.3907
C-P	K-A	0.6023	0.4434
C-P	K-P	5.2039	0.0293*
K-A	K-P	2.2654	0.1421
Q53		F	p
C-A	C-P	5.5422	0.0249*
C-A	K-A	1.0456	0.3142
C-A	K-P	0.009	0.9248
C-P	K-A	1.7733	0.1924
C-P	K-P	5.1034	0.0308*
K-A	K-P	0.8601	0.3607
Q55		F	p
C-A	C-P	3.9891	0.0544
C-A	K-A	1.295	0.2636
C-A	K-P	0.0264	0.8719
C-P	K-A	0.7384	0.0144*
C-P	K-P	3.3661	0.0759
K-A	K-P	0.9514	0.3367
Q56		F	p
C-A	C-P	5.8829	0.021*
C-A	K-A	19.6226	0.0027*
C-A	K-P	3.0391	0.0909
C-P	K-A	0.6951	0.4106

C-P	K-P	0.4654	0.5
K-A	K-P	2.298	0.1394

[TDS Aggregate Categories]

Real Team		F	P
C-A	C-P	6.8241	0.0136*
C-A	K-A	6.9586	0.0128*
C-A	K-P	0.0007	0.9797
C-P	K-A	0.0007	0.9797
C-P	K-P	6.691	0.0144*
K-A	K-P	6.8241	0.0136*

Task Design		F	P
C-A	C-P	6.2637	0.0176*
C-A	K-A	3.8737	0.0578
C-A	K-P	0.059	0.8096
C-P	K-A	0.2858	0.5966
C-P	K-P	5.1065	0.0308*
K-A	K-P	2.9763	0.0941

Norm		F	P
C-A	C-P	3.7179	0.0627
C-A	K-A	2.0255	0.1644
C-A	K-P	0.1349	0.7158
C-P	K-A	0.255	0.617
C-P	K-P	2.4364	0.1284
K-A	K-P	1.1149	0.1284

Team process		F	P
C-A	C-P	5.6385	0.0237*
C-A	K-A	3.7746	0.0609
C-A	K-P	0.1128	0.7392
C-P	K-A	0.1864	0.6688
C-P	K-P	4.1566	0.0498*
K-A	K-P	2.5825	0.1179
Interpersonal		F	P
C-A	C-P	5.6385	0.0237*
C-A	K-A	3.7746	0.0609
C-A	K-P	0.1128	0.7392
C-P	K-A	0.1864	0.6688
C-P	K-P	4.1566	0.0498*
K-A	K-P	2.5825	0.1179
Motivation		F	P
C-A	C-P	5.2587	0.0286*
C-A	K-A	3.4881	0.071
C-A	K-P	0.2075	0.6066
C-P	K-A	0.1811	0.6733
C-P	K-P	3.1438	0.0857
K-A	K-P	1.8159	0.1873
Satisfaction		F	P
C-A	C-P	5.765	0.0223*
C-A	K-A	2.9297	0.0966
C-A	K-P	0.1633	0.6888
C-P	K-A	0.4753	0.4955
C-P	K-P	3.9876	0.0544

K-A	K-P	1.7096	0.2004

Appendix J: Annotated List of Figures

Figure 32. Prototype of "Heart," the interactive wall display (Team 10) (photographed by the researcher, used with consents of the participants)

Appendix K: IRB Approval Letter

VirginiaTech

Office of Research Compliance
Institutional Review Board
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, Virginia 24060
540/231-4606 Fax 540/231-0959
e-mail irb@vt.edu
Website: www.irb.vt.edu

MEMORANDUM

DATE: June 13, 2011

TO: Elizabeth McNair, Brian M. Kleiner, Sophie Kim

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires May 31, 2014)

PROTOCOL TITLE: Impact of Meeting Space and Strategy on Effectiveness of Interdisciplinary Engineering Design Teams

IRB NUMBER: 10-531

Effective June 28, 2011, the Virginia Tech IRB Chair, Dr. David M. Moore, approved the continuation request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at http://www.irb.vt.edu/pages/responsibilities.htm (please review before the commencement of your research).

PROTOCOL INFORMATION:
Approved as: **Expedited, under 45 CFR 46.110 category(ies) 6, 7**
Protocol Approval Date: **6/28/2011 (protocol's initial approval date: 6/28/2010)**
Protocol Expiration Date: **6/27/2012**
Continuing Review Due Date*: **6/13/2012**
*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:
Per federally regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals / work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

An equal opportunity, affirmative action institution

Date*	OSP Number	Sponsor	Grant Comparison Conducted?
6/28/2010	09207903	NSF	yes on 6/28/2010

*Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

cc: File