# COMBINING TANGIBLE AND GESTURAL INTERACTION DURING COLLABORATIVE GAMEPLAY WITH MULTIPLE DISPLAYS

by

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# DEDICATION

*I dedicate this thesis to,*

***Sophie**, my gorgeous four-year-old Maine Coon cat. She stayed awake all the nights that I have worked on my thesis, watching over. The best friend anyone can ask for.*

*My parents who made me believe in myself. Especially **my mother**, who has sacrificed so much for me to give me unconditional love and support. My parents always put me first, before their own needs. I hope that I make them proud someday.*

*To the Almighty, who has always looked over me.*

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# ABSTRACT

We explore the use of combined gestural and tangible interfaces during collaborative gameplay by youth in small groups. In our setup, gestural interaction is used to manipulate reference content projected on a wall-mounted display, to support a main task involving tangible interaction on a tabletop display. We designed two games for this setup: Block Rock involves placing tangibles (blocks) in a target configuration shown on the wall display, and Furniture Finder requires toy furniture to be placed in a target configuration, but the specific furniture to place must first be "uncovered" on the wall display. We conducted a within-subjects user study with 92 children between the ages of 8 and 15, and considered the impact of several factors on collaboration: game type (Block Rock vs. Furniture Finder), orientation control (discrete vs. continuous), group size (dyads vs. triads), and age range (concrete vs. formal operational stage of cognitive development). Using structured coding we derived five basic gameplay strategies. The most commonly used strategy was for one player to perform gestural interaction while other players place tangibles, while the frequency of other strategies varied by game type, orientation control and group size. Furniture Finder encouraged sequential role-based coordination, as one player uncovered furniture on the 3D model while others placed that furniture on the table, while Block Rock permitted players to work independently, often leading to resource contention. Gestural control occurred more often in Block Rock when discrete gestures were used to rotate the 3D model in canonical orientations than when a grab gesture was available to control rotation continuously. Continuous control also led to faster game completion time than discrete control. In general, infringement occurred more often over tangible control than gestural control, but discrete gestures led to more contention over getting the "right" view on the 3D model in Block Rock. Triads observed the work of their partners more frequently than dyads (the measure is normalized by group size), while dyads were more aware of each other but this had no impact on either game completion time or score. We discuss the implications of our findings on the design of collaborative games that employ similar multimodal interface configurations.

# LIST OF ABBREVATIONS USED

| | |
|---|---|
| TUI | Tangible User Interaction |
| CVTS | Computer Vision Through Screen |
| RDI | Rear Diffuse Infrared |
| IBEC | Integrated Backlight Emitter Camera |
| MTS | Matrix Tracking System |
| EHTE | Extensible Hybrid Tracking Engine |
| HMD | Head Mounted Display |

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# CHAPTER 1 INTRODUCTION

## 1.1 Problem Definition

Affordable devices supporting gestural interaction such as Microsoft Kinect, PlayStation Move, and Wiimote are becoming commonplace [1]. Furthermore, commercialization of multi-touch tabletops has led to their deployment in community settings such as museums and schools [1]. Tangible User Interaction (TUI) makes it possible to use physical objects as interaction tools to manipulate digital content, and is becoming a common feature on interactive tabletop displays and elsewhere. The gaming industry has begun exploring the use of tabletops and embodied interaction to provide unique, compelling gaming experiences [1]. The games typically employ unimodal interaction, using either only gesture or tangible/touch-based interactions. Magerkurth et al. [9] in their overview of pervasive gaming, cover several examples of adding computing functionality to traditional board games, often via TUI. We go further by exploring a game environment which combines tangible and gestural interaction, making use of two different screens, and creating an overlapping interaction space. Our work thereby explores the potential of using a combination of gestural and tangible interfaces in a multimodal design, to facilitate collaborative gameplay. In-air gestural interactions are performed by users to interact with supportive digital content that is projected on a wall-mounted display, while tangible interactions are performed by users on a tabletop display.

We developed two games, *Furniture Finder* and *Block Rock*, where users use hand gestures to manipulate content on the wall-mounted display and receive information, and use this information to place tangibles on the tabletop display to complete the requirements of the game. In both *Furniture Finder* and *Block Rock*, players place tangible objects to complete the layout displayed on the tabletop. In *Furniture Finder*, we use the strategy of “hiding” objects in the 3D model on the wall display and revealing them when the user selects them individually using a *grab* gesture. In *Block Rock*, the entire 3D model is visible at all times, and players either use a *swipe* gesture to rotate the model back and forth between a set of canonical orientations, or *grab* the model and freely rotate it to a suitable view. The games are described in detail later in the thesis.

## 1.2 Thesis Contribution

Our work explores the potential of combining tangible and gestural interaction for collaborative gameplay and other forms of informal collaborative interaction (e.g., museum installations). Specifically, we examine a configuration whereby in-air gestural interactions are performed by users to interact with a reference digital model on a wall display, to inform a main task involving tangible elements on an interactive tabletop display.

We developed two games, *Furniture Finder* and *Block Rock*, where users use hand gestures to manipulate content on the wall-mounted display and receive information, and use this information to place tangibles on the tabletop display to complete the requirements of the game. We studied how small groups of youths (aged between 8 and 15, with 2 or 3 members in each group) play the designed games using our configuration. Specifically, we explored the impact of designed mechanisms (e.g. tangible/gestural interactions, feedthrough) and socially negotiated mechanisms (through which members of a group gain control, lose control and strategize or assign responsibilities) on collaborative gameplay.

We also evaluated the impact of game design on collaboration using our configuration. We explored if a *tightly coupled* game (Furniture Finder) would enhance collaboration in terms of player interdependence, and if a *loosely coupled* game (Block Rock) would promote more independent play among participants. We use the definition of coupling defined by Pinelle et al. [8].

We summarize the contributions of our work as follows:

- We present a case study of gestural and tangible interactions in systems that employ vertical displays to support interactions on a tabletop display. We consider a sample of youth in the age range 8-15 years in our study.
- Five collaborative strategies are defined from detailed observation of our players' behavior: one player performs both gestural and tangible interaction alone, one player performs gestures while the other player(s) place tangibles, one player performs gestures while placing tangibles is shared by all players, both gestural and tangible interaction are shared, and gestural interaction is shared while one player places tangibles. We consider the impact of our experimental factors (game type, group size, gestural control mechanism, and age range) on the frequency of each strategy.
- We discuss the importance of personal space and territorial infringement dynamics for a system in which there is an overlap of interaction space between two interactions. We find that in-game territorial infringement was significantly higher for tangible interaction vs. gestural interaction in our grab-based games (*Furniture Finder and Block Rock - Grab*) while the reverse was true for our swipe-based game (*Block Rock - Swipe*).
- We provide a number of design recommendations for interactive environments combining tangible and gestural interaction for children, including the impact of task coupling, gesture control design, group size, and the layout of interaction zones.

## 1.3 Thesis Overview

Chapter 2 provides the discussion of prior work which involves different interaction techniques such as tangibles, touch, gestures on different platforms. In this chapter, we first discuss background work involving collaboration in collocated workspaces. Next, we discuss prior work on tangible and gestural interactions. Thirdly we discuss the studies which analyzed children behavior when interacting with technology.

Chapter 3 provides the implementation details of our system for tangible interaction on a Tabletop and gestural interaction with a wall mounted display. Firstly, we discuss the technological foundation of the components used in this system including the MultiTaction tabletop and the Kinect. Next, we discuss the libraries used in implementation of the system. Thirdly, we discuss the system setup followed by the design of the three games using this system.

In Chapter 4 we present our research questions. Then we discuss the study design and motivation including the study procedure and participant sample followed by the data analysis methodology. Lastly, we discuss our pilot study and the lessons learnt from the pilot study.

Chapter 5 provides the results of our study. We analyze the impact of our experimental factors (game type, orientation control, group size and age range) on collaboration in terms of gameplay strategies, participation equality, territorial infringement, communication and completion time. We then present the observed behaviors of participants to overcome Kinect tracking issues. Lastly, we present the results of the post-game interview.

Chapter 6 provides the discussion of our analysis and results. Firstly, we present a discussion of our experimental factors namely game type, orientation control, group size and age range. Secondly, we present our recommendation for the design of such systems. Lastly, we present limitations of our system and future work.

Chapter 7 provides the summary and conclusion of our system and evaluation study and future work.

# CHAPTER 2 BACKGROUND AND MOTIVATION

In this chapter, we first discuss work involving collaboration in collocated workspaces. Here we focus on prior work on collaboration involving factors such as system setup, orientation, group size etc. Next, we discuss prior work on tangible and gestural interactions and the design guidelines recommended when building applications to support these interactions. Thirdly we discuss studies that analyzed children's behavior when interacting with technology with a focus on collaboration.

## 2.1 Collaboration Mechanisms Around Collocated Work Spaces

Pinelle et al. [8] define collaboration in terms of coordination and communication. In a collaborative activity, coordination includes shared access and transfer while communication is composed of explicit communication and information gathering. Pinelle et al. [8] define mechanics of collaboration, which include a set of common actions that describe a mapping between physical actions and each mechanic. This framework allows collaboration to be studied in terms of individual real world actions that constitute various mechanics such as explicit communication, information gathering, coordination.

This framework was used by Scott et al [16] in their work considering the design of effective collaborative tabletop interfaces. Participants in groups of two and three constructed a furniture layout on a printed floor plan using paper cutouts of furniture. Their focus was to understand the techniques players use while interacting with each other. Specifically, they explored the different territories that the players used for coordination. They found that the players used a *personal space* for their independent actions, a shared *group space* for interaction among players, and a *storage space* that was used to organize task-related and non-related items [16]. In our work, we use this notion of spaces to facilitate perceived personal spaces. We facilitate this by allowing participants to (implicitly or explicitly) agree upon a personal space for tangible interaction, storage spaces by allowing participants to use the space on the frame of the tabletop to place tangibles, and the notion of a shared space in terms of a shared data view on a vertical display. One user can control the data on the vertical display but the access is mediated.

We considered the design of our system in relation to the territory model described by Scott and Inkpen [16]. In our system, we assume that the vertical display is a shared group territory that all group members can see. This vertical display does not have personal spaces for individual group members. We further assume that the shared interaction space on the tabletop display is logically divided into personal territories for individual group members, and that the space on the metallic frame of the tabletop display which is directly in front of each user serves as their personal storage territories.

The orientation of various elements such as the game elements, information shown on the displays, has an impact on the collaborative efforts by users, namely – "*comprehension of information, coordination of activities, and communication"* [19]. To correctly comprehend the presented data elements, users usually adjust the orientation as needed. In addition, orientation of data plays a major role in the coordination between players to create personal and shared territories [19,20]. For example, orientation of data is specific to each player, wherein the other player(s) cannot view other player(s) data creates private personal territories. Orientation can also be used as a medium of communication to indicate the intended territory and rules for data elements [19]. Rogers et.al. [41] investigated the role of orientation of large interactive displays to support collaboration. They observed collaboration of participants around vertical and horizontal displays. Participants in groups of three were asked to find information on using the displays in the form of forming an itinerary for travel. They found participants using the horizontal display exchanged more ideas, where aware of the other participant's actions and often switched roles as compared to participants using the vertical display [41].

The impact of group size and table size on the interaction mechanisms around tabletops was investigated by Ryall et al. [10], in a study that required group members to assemble a poem using interactive digital tiles containing words. Their study revealed that the tabletop size does not affect time required to complete the objective. On the other hand, group size is proportional to the time taken to complete the objective, where work and resource distribution change with the number of players. They found that user positions around the tabletop are influenced by group size and gaming layout. This prompted them to recommend developers to consider the orientation of the presented information and resources on the tabletop to accommodate larger groups. Furthermore, they recommend considering an additional vertical display to present shared data for larger groups. In our work, we present the shared content on vertical display which is used as reference to support tangible interactions on the tabletop.

Interactive collaborative systems such the ones discussed in this section have three essential characteristics as identified by Hornecker et al. [7] namely – embodied constraints, shared transaction spaces and multiple access points. *Embodied constraints* are defined as "the *physical system set-up* or *configuration of space and objects*" [7]. This helps in defining the game's rules by constraining the role of each participant, promoting collaboration and limiting solitary decisions.

*Shared transaction space* is the area that can be fully utilized by a group to perform actions and interact with surroundings within reach [7,21] Having more than one participant in the same space will create a shared transaction space that might promote collaboration, especially if the transaction rules require a coordinated input by all participants. According to Hornecker, the shared transaction space increases focus on central objects as well as peripheral awareness. The shape of the space, access to objects within the space, and rules of the space define the relationship among users. Hornecker et al. define *multiple access points* in terms of the ability of all members in a group to access and manipulate objects in the interactive system via various “access points”. Rick et. al. [40] investigated the design of interactive tabletop applications using paper prototyping for children. A key finding was that children liked to interact concurrently, working together when playing in groups rather than having wait for their turn, in which case they got easily distracted [40]. Yuill and Rogers [18] identify three mechanisms of interaction that promote collaboration among participants: *awareness* of others’ actions and intentions, *control* over the interface, and information about available resources. Awareness plays a major role in promoting collaboration, this is because it enables all participants to stay alert and ready to act as expected. They define awareness as the “*degree to which awareness of users’ ongoing actions and intentions is present or made visible moment-to-moment*” [18]. Control within the context of collaboration is referred to as the ability of users to practice total control over their cognitive decisions and related actions. Both awareness and control are dependent on the availability of timely information about the users' performance and system status. Accurate and timely information are essential to have a high level of awareness and complete control over the task. To promote collaboration mechanisms, it is important to consider three different constraints: *physical*, *social* and *digital*. Constraints are recommended to be applied at different degrees based on the task handled by users. Low levels of constraints are recommended to be applied with open-ended tasks, while higher level of constraints may be applied with less challenging situations. Moraveji et al. [11], conducted a study using a system with a shared large vertical display and multiple-mice to study the impact of group size having an impact on collaboration.

In our work, we set out to study interaction behaviors in collaborative environments; specifically, collaborative gameplay for children. We were motivated by Ryall et al.'s [10] suggestion about augmenting collaborative actions on a tabletop display with task related information on a vertical display [10], to enhance engagement of group members by providing multiple access points in terms of access to tangibles and mediated control for gestural interaction as it can be controlled by only one person.

### 2.2 Tangible and Gestural Interactions

In this section, we discuss prior research that focus on multi-modal interactions using tangibles and gestures and design guidelines. Rossol et al. [2] explored the use of mid-air gestural interaction to control visual displays. The study focused on the use of mid-air hand gestures, while using handheld objects to precisely control medical displays. Their study showed that workflow is more fluid and uninterrupted while using mid-air hand gestures as compared to a touchscreen interface. Furthermore, they found that performance of participants significantly improved after redoing the gestures in a short time. There was no considerable decline in performance when participants performed gestures with tools in their hand as compared to putting them down.

Studies by Seyed et al. [22] and Anthony et al. [6] emphasize the importance of considering several categories of users, including children, while designing gesture controlled systems. A study by Poor et al. [1] investigated the use of tangibles and gestures for 3D manipulation task. Participants manipulated a 3D object projected on a display using tangible and gestures. They found that there are no significant differences between using tangible interactions or gestural interactions to manipulate 3D objects. Dover et.al. [27] conducted a study to evaluate the impact of improved cursors in the use of gestural interaction in terms of performance and usability of in-air gestures. The study focused on comparison of in-air gestures for pointing small targets aided by use of *Bubble Lens Cursor* and without the *Bubble Lens cursor* [27,28]. They found that use of the cursors with augmentations improved performance in terms of selecting small targets [27]. Hilliges et. al. [30] evaluated the use of area above a tabletop as interaction space for in-air gestures, to aid the interactions on the tabletop for 3D object manipulation. They focused on designing the in-air interactions like real world actions [30]. Grandhi et. al. [33] provided guidelines for design of natural and instinctual in-air gestures. They found that designing gestures which closely resemble real world actions help improve user experience [33]. Wu et.al. [42] studied the use of multi user input and hand gestures in tabletop display to concurrently support different users [42]. Tse et. al. [43] investigated the perceptions of users, working together on a large display, about their location with respect to others in the group. They found that users refrained from intruding with other's actions mostly without the need of any verbal communication [43]. Jude et.al [47] accessed the use of in-air gestures with both the dominant and non-dominant hand of users. They evaluated the performance of in-air gestures by using mouse and touch pad as yardstick for performance evaluation. In their study, square targets appeared in a random sequence on a large display. Participants were required to linger over the target for 500 milliseconds to destroy the target and spawn a new target. Participants used three modes of interaction, mouse, touch pad and in air gesture to interact with the targets. This activity was done over two iterations. They found that in-air gesture showed better performance improvement in the two iterations as compared to mouse and touch pad. Furthermore, participants could easily switch between hands when using in-air gesture as compared to mouse and touchpad [47]. Visual indicators are widely used to help users identify persons in control during collaboration. Indicators also assist disoriented players who accidentally leave the tracking the field of view to identify if they are in the tracking field once they return [33]. The influence of visual indicators, however, also depends on the set up of the system. Ng et al. [34] designed a system with back-projection to visualize interactive games and an infrared camera to record the user's silhouette, which they then used as the visual indicator. A small percentage (33%) of total participants found the indicator to be useful in their setup.

### 2.3 Children as Technology Users

User interaction with any system depends on cognitive ability, to understand what is expected and to make decisions leading towards a goal. Since children move through different stages of cognitive development, it is challenging to design multimodal collaborative systems for children in a wide age range, such as those who might visit a science museum. Piaget identifies stages of cognitive development in children [23]. These include *sensorimotor* stage (birth to age 2), *preoperational* stage (ages 2 through 7), *concrete operational* stage (ages 7 through 11) and *formal operational* stage (ages 11 and above). Daily and varied interactions with a child's surroundings play a major role in their progress through the four stages. Our focus is on the latter two stages, because their cognitive abilities are developed to an extent that allows them to act independently as well as in a collaborative environment. rya In our system, we chose to allow only one member of the group to interact with the vertical model, to observe any interesting behaviours among group members as they would try to contend for access to the controller.

Contention is an important aspect to consider because what observant participants comprehend from interactions being performed by the person in control depends on how they perceive the visible information. What they observe on the screen could lead observant to contend for control. This ability to process visible information depends on the age group of the children and their cognitive abilities [23]. Olson et.al. [44] investigated collaboration among children using a multi-touch tabletop application. The observed jostle among participants over a toolbar which could be interacted with using touch. After this observation, they introduced a tangible which needed to be used to view the toolbar, due to disagreement among participants over the control of toolbar reduced [44]. Cho et. al. [45] studied children's involvement when using tangible blocks while playing together. They found that children use of tangibles encouraged involvement from all members in a group, decrease in attention to the activity for a passive observant when participant took turns and strategizing to resolve conflict [45]. In our system, although only one person could interact with the vertical display, all participants had simultaneous access to the shared interaction space on the tabletop display, thereby creating multiple access points [7]. The two shared group spaces also necessitate that group members always remain aware of what they see on both vertical and tabletop displays, and the interactions being performed by other group members [18]. This mix of flexibility and implied restriction in our system design also inherently assumes the presence of physical, digital and social constraints [18] as it requires group members to come to an agreement (either implicit or explicit) to manage their interactions in the shared spaces. Five factors that influence the choice of gestures among children were identified as "the influence of 2D touchscreens on children's interactions in 3D, the role of contextual cues in designing a stimulus set, individual preferences for dominant styles of interaction, different approaches children employ to simulate the same object path, and allocentric versus egocentric approaches for manipulating objects on screen" [24]. The use of tangibles has been found to be afford more fast and immersive gameplay as compared to the traditional (paper based) and digital variant of the same activity [22,46]. Xie et. al [46] investigated the design of interface in terms of its appeal to school children in terms of enjoyment and involvement. 132 participants, divided in groups of two, played three variants of a jigsaw puzzle: regular (cardboard pieces), digital and tangible. They found that while using tangibles, majority of groups adopted a parallel play approach, working independently. However, participants observed the actions of their team mate and often mimicked them. While using the graphical variant of the jigsaw puzzle, participants took more time and had difficulty in playing as they could only interact one at a time using the mouse [46]. Children's understanding and comprehension of technology is different from adults, and this requires developers to pay special attention to children's perspective on technology [12, 13, 14]. Children tend to socialize and share tasks as they grow older. A study [26] that involved 400 children showed that the group size and collaboration increase as the age increases. The study also concluded different types of playing patterns such as: *Co-operative*: children play together and distribute tasks to achieve one goal; *Unoccupied*: children do not get involved in any activity; *Onlooker*: children who only watch others playing; *Solitary*: children who play alone; *Parallel*: children who play alone but stay close to the group to share material; and, *Associative*: children associate with each other while playing the same game. The lack of knowledge about problem solving techniques that are used by children motivated Roden [25] to identify and classify children's procedural knowledge. A set of inter-related strategies emerged over the period of the longevity study as follows: personalization, practice, focus, difficulties identification, needs identification, egocentric actions, negotiating, tackling obstacles, encouragement, cooperating, pretend panic and persistence. As mentioned before, the strategies are interrelated and usually used by children in a concurrent approach. Antle [36] proposed "Children Tangible Interaction" (CTI) framework which focuses use of the affordances provided by tangible and spatial interactions to design tangible systems for children below the age of 12. The framework consists of five themes: *Space for Action* (tangible interactions used as input to interact with the system)*, Perceptual Mappings* (relationship of look of an object and its behavior)*, Behavioral Mappings* (relationship between the feed to the system and result of the feed*), Semantic Mappings (*data represented by different elements of the system*)* and *Space for Friends* (consideration of elements that promote collaboration in users*)* [36]. Do-Lenh [38] et.al. investigated the use of Tangible User Interfaces (TUI) in a classroom setting and its impact on activity performance and learning. They compared the TUI setting with paper and pens, in which participants performed the activity of designing a warehouse. They found that while learning was not affected use of tangibles, TUI offered improved activity performance as participants explored different options to arrive at the optimal design [38]. Marco et. al. [39] provide design guidelines to consider when building tabletop applications using tangibles for children. They provided a case study of iterations in design of games which used tangibles as input devices. One of the key recommendation was the need to consider the cognitive stage of the expected age range of children users to get a better understanding of the expectations and requirements of the target users [39]. Sakai et.al [31] proposed a whole-body interaction game for children aged 10-11 years to play together in small groups. They explore how children collaboration together when playing together in this environment. They found that children strategized with each to play the game by coordinating their actions, observing and communication with each other [31]. Alencar et. al. [32] explored the impact of factors such as gender, group size cooperation among children in a public goods game, wherein children had to donate candy bars. They found that group size had a significant impact on cooperation. Smaller groups collaborated significantly higher than larger groups [32]. Dillenbourg et. al. [34] recommended that "free collaboration" wherein there is no scripting from the designers is ineffective as it leads to unforeseen results [34]. McCrindle et.al. [35] designed a tabletop application which used tangible interaction to evaluate children's decision making. The application was based on groups of children using tangibles to vote on a topic of interest from a selection in a museum setting. They focus on providing "*implicit scripting*", wherein the need to provide guidelines by an adult is minimized, allowing children to manage their work among themselves [35]. Crook [37] focused on how collaboration can be fostered in small groups of children from an early age. Crook [37] emphasizes that two factors to foster collaboration: a collection of toys or tangible elements of the game which can accessed by all members of the group to achieve a common goal and secondly having "*scripted routines*" which allow the children to focus on the collaborative task [37].

Our work is aimed at observing how youth in small groups (of two and three) collaborate when using multimodal interfaces, in which gestural interaction is used to support tangible interaction. Our specific focus, however, is on using both, gestural interaction to support a main task that employed tangible interaction on a tabletop display. Our system and game design, thus, is founded on the principles and concepts established by prior researchers. We adapt some of the concepts as discussed previously in this section to help us design the system and games to support our research objectives. In the following sections, we discuss system implementation specifics and the overview of each game.

# CHAPTER 3 DESIGN AND IMPLEMENTATION

In this chapter, we discuss the implementation details of our multimodal system which incorporates tangible interaction on a tabletop and gestural interaction with a wall mounted display. First, we discuss the technological foundation of the components used in this system including the MultiTaction tabletop [57] and the Microsoft Kinect v2 sensor [63]. Secondly, we discuss the libraries used in the system implementation. Thirdly, we discuss the system setup followed by the design of the three games using our multimodal system.

## 3.1 Devices Used

### 3.1.1 MultiTaction Cell

The MultiTaction Cell is a multi-touch based interactive display which can detect finger touches and markers [57]. Figure 1 shows the different components housed in a MultiTaction Cell.

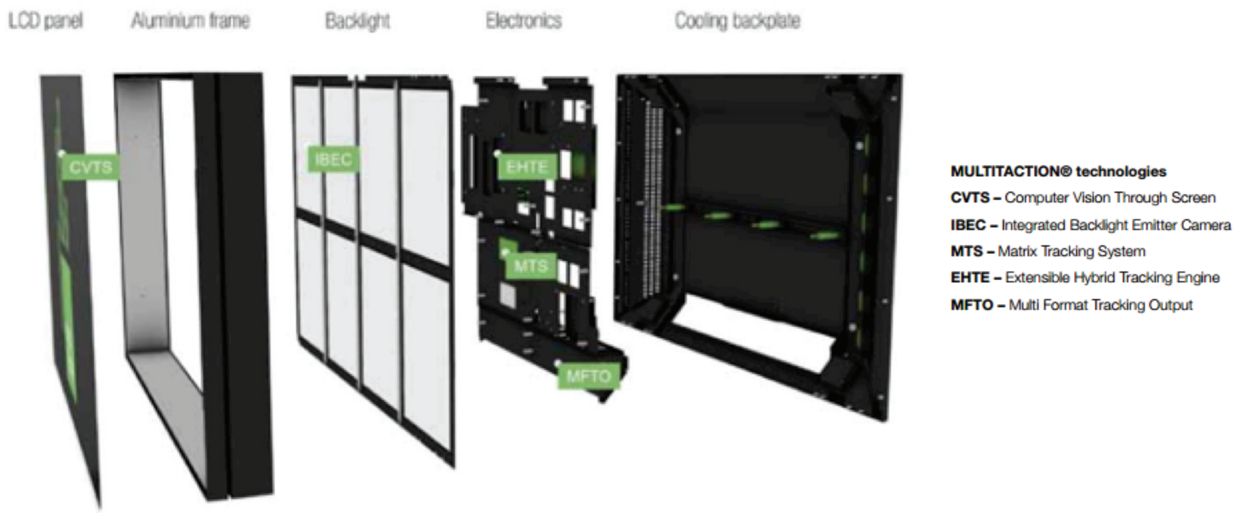


**Figure 1: Components of a MultiTaction Cell [57]. Figure from [58]**

As opposed to using a projector, a MultiTaction Cell deploys Computer Vision Through Screen (CVTS). CVTS is used to overcome the problem with rear diffuse infrared (RDI). RDI, used in rear projectors, is not suitable for LCD displays since the LCD display blocks 95-97% of the emitted light. CVTS solves this problem by enabling the camera housed in the MultiTaction Cell to see through the LCD display. Figure 2 shows the CVTS Operating Principle [58].

The display consists of an Integrated Backlight Emitter Camera (IBEC), which lets out infrared light. This infrared light is used to detect finger touches and markers after reflecting off them [59]. Feed to the cameras is combined by the Matrix Tracking System (MTS) [59] as shown in Figure 3.

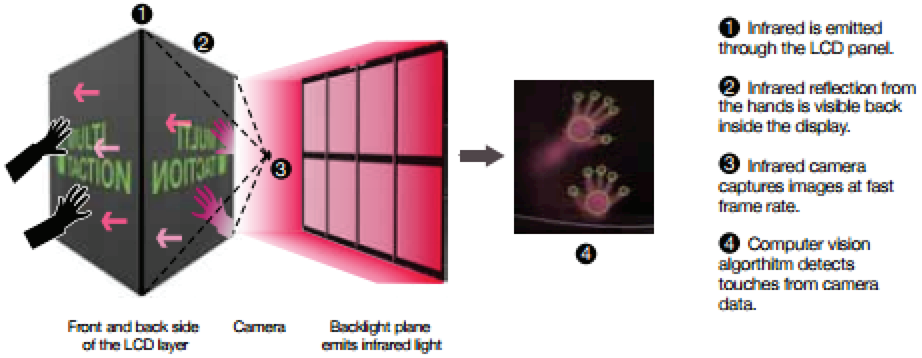


**Figure 2: Computer Vision Through Screen Operating Principle. Figure from [57]**

The next step is to track this data which is performed by an embedded computer which employs the Extensible Hybrid Tracking Engine (EHTE) [60]. EHTE has the capability to make use of the reflected infrared light and reflections of objects from the surrounding light alternating them every other frame and combining those two images as shown in Figure 3. This capability helps to enhance the quality when the surrounding environment does not have optimal lighting features (for example in sunlight, or under halogen spot lights). EHTE, as reported on the MultiTaction website [62], can track "*Finger Points, Fingers, hands, Objects (shapes), optical markers (fiducials, tags), and proximity (presence of users in front of the display)*" and further adds an SDK to build on this tracking capability [62].

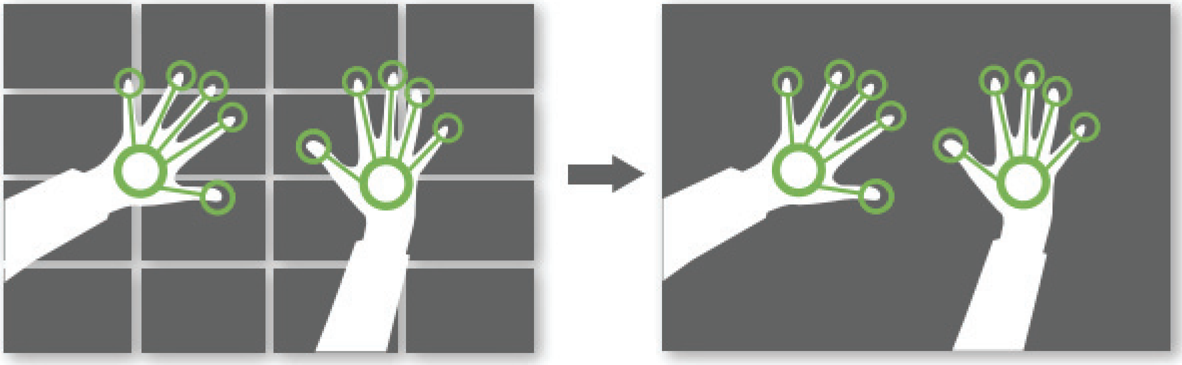


**Figure 3: Matrix Tracking System (MTS). Figure from [60]**

MultiTaction Cell supports transmitting the touch based information in multiple ways, including "*TUIO protocol, Windows 7 Native Touch and XML Stream*". The tracking data is transmitted via a cross Ethernet cable [57].

### 3.1.2. Microsoft Kinect v2

The Microsoft Kinect v2 sensor [63] is used to implement the gestural interactions in our system. The Kinect is a sensor which provides full body tracking, facial and voice recognition functionality [63]. The sensor has RGB camera, depth sensor and microphone as shown in Figure 4.

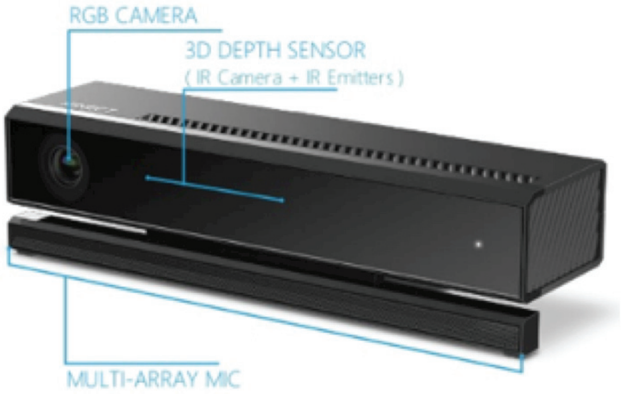


**Figure 4: Kinect v2 Sensor. Figure from [63]**

Furthermore, the Kinect can track up to 6 persons at once and 25 joints for each person. The Kinect v2 sensor has a higher depth sensing capability of 512 x 424, color camera of 1920 x 1080 at 30 frames per second (fps) and Field of View (FOV) of 70 H x 60 V . Kinect v2 sensor offers better visualization, body tracking robustness as compared to Kinect v1 due to better noise floor and greater depth fidelity. The Kinect makes use of machine learning and structured light to detect the body position of the user. Structure Light constructs the depth map based on which machine learning is used to compute the user's position [63]. The Kinect v2 sensor is designed to work with Xbox One [65]. To use the Microsoft Kinect v2 with Windows a Kinect adapter [66] needs to be used as shown in Figure 5. We used the adapter [66] to integrate Kinect with our Windows machine for developing the gestural interaction application.

**Figure 5: Microsoft Kinect Adapter. Figure from [66]**

## 3.2 Libraries and Tools

### 3.2.1 TUIO

TUIO stands for Tangible User Interface Objects. As reported on the TUIO website [51], "*TUIO is an open framework that defines a common protocol and API for tangible multi touch surfaces*". As shown in Figure 6, using the TUIO protocol the tracker application sends the touch and marker information to the TUIO Client. TUIO protocol is capable of tracking three elements: Fiducial markers (which has attributes such as ID, position and rotation), finger touches and untagged objects (wherein the distinct object shapes are tracked). TUIO relies on the Open Sound Control [67] encoding scheme to transmit information [51].

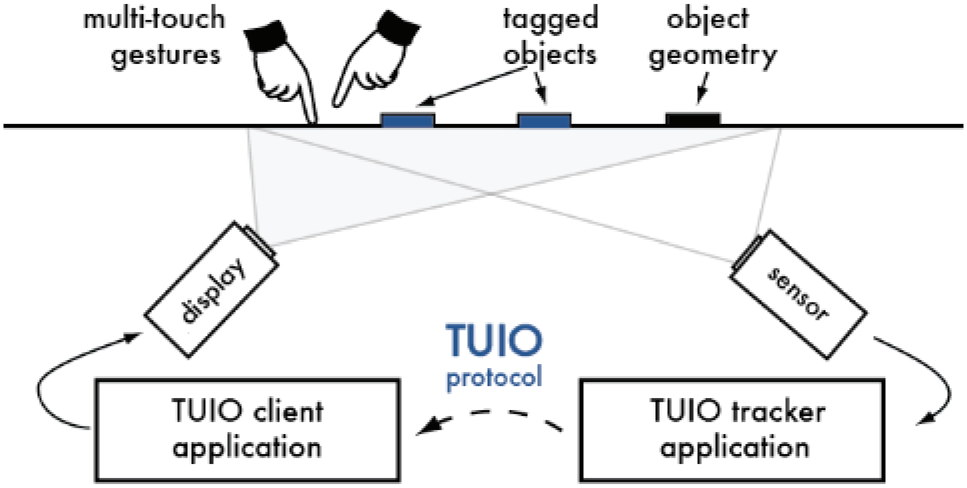


**Figure 6: TUIO Protocol. Figure from [51]**

### 3.2.2 Fiducial Markers

A Fiducial Marker is an image, like a QR code, through which a marker identity is determined and the position and rotation are computed [68]. Each Fiducial marker has a distinct pattern and thus a unique identity. When a fiducial marker is attached to underside of an object and placed on a touch table which can detect the fiducial marker, it provides a robust way to track the object and compute its position and rotation. Since the fiducial marker is detected and not the object, the object can take any form and shape. Thus, by attaching a fiducial marker to the underside of any object, it is straightforward and inexpensive to use object for tangible interaction [68]. Figure 7 shows fiducial marker created using an application called Marker Factory [69] available in the Cornerstone SDK, which is the SDK shipped with MultiTaction Cell [62].

**Figure 7: Fiducial Marker created using Marker Factory.**

### 3.2.3 Unity3D

Unity3D [70] is a game engine that is used for making 2D and 3D games. The Unity3D environment consists of an editor in which users can create "*game objects*" to create "*scenes*", which depict the levels in a game or other states such as a game main menu [70].

Each game object in Unity3D has set of attributes which can be manipulated. These attributes include the game object's position, rotation, and scale. Further it is possible to define custom behavior for these game objects. For example, enabling the rigid body attribute of a game object makes Unity treat it as a physical entity. Thus, the game object then has mass and gets acted upon by gravitational forces. Many other features can be added in a scene such as the camera view, light sources, and audio sources. Unity3D has an Unity Asset Store [52], wherein game components, scripts, sample games, textures, materials, font, audio sounds etc. are available for free or for a price depending on the product. Code in Unity3D can be written in C#, JavaScript or Boo. Unity3D provides an in-built IDE for writing code, called MonoDevelop [73]. However, code can be written in any text editor and other IDEs including Microsoft Visual Studio provide support for Unity3D , assisting users in debugging by displaying errors and breakpoints [70].

Unity3D is used in the development our system because it provides a cohesive environment that incorporates the SDK for Microsoft Kinect [63] as well as libraries which enable interaction with the MultiTaction tabletop. Using this, game objects such camera, light source, audio sources etc.

allowed us to create interactive game scenes for both the MultiTaction Tabletop and a wall display with gestural control using the Kinect v2. During development, the ability to modify values of different game objects at run time and to run the application directly in the editor helped in rapid testing and development of the application [70].

### 3.2.4 Uniducial Library

The Uniducial Library [4] is used to detect fiducial markers on multi-touch tabletops using the TUIO protocol, employing the TUIO Client Reference to get TUIO data. The Library contains code for channeling the tracking data received into Unity3D coordinates. Thus, including the Uniducial library in Unity3D allowed us to track position and rotation of fiducial markers, and in turn the tangible objects to which the marker was attached. The Uniducial library is open source and is available free for download and use in Unity3D [4]. We used Uniducial library in Unity3D to detect the fiducial markers made using the Marker Factory application. These fiducial markers were put on the underside tangibles, to track their position and orientation on the MultiTaction tabletop.

### 3.2.5 Kinect v2 Examples with MS-SDK

The Kinect v2 Examples [75] set provides a collection of examples of Kinect v2 demonstration sample applications which can be used in Unity3D. The package contains scripts, examples, and descriptions of the provided example scenes. This package serves as a good entry point for integrating Kinect v2 and Unity3D. This package is free to use for academic purposes. This package was used as a starting point to build the gestural interaction of our multimodal system.

### 3.2.6 SketchUp

SketchUp [76], (previously known as Google SketchUp) is 3D modelling software. It provides tools such as geometric shapes, colors, textures to create 3D models in an x-y-z coordinate world.

The models can be saved into common formats including .3ds and. stl. SketchUp was used to create 3D models of the furniture used in the Furniture Finder game, which is discussed later. The models created in SketchUp were imported into Unity3D in .3ds format.

### 3.2.7 Credits for other content resources used

In addition to the default geometric primitives and game objects provided in Unity 3D, the following assets were used:

The font used in all the scenes is Sans Creed [77].

The sound effects used are the classic Mario sound [78] of getting a coin, and a buzzer sound [79].

As already described, the Kinect v2 examples included with the MS-SDK [75] package were used as a starting point to integrate the Kinect SDK into Unity for gestural interaction.

## 3.3 System Implementation

We designed our system to support tangible interaction on a 55-inch MultiTaction [57] multi-touch tabletop display and gestural interaction with a 70-inch wall-mounted LCD display. Users can interact with the information displayed on the wall-mounted display using a Microsoft Kinect V2 sensor using gestures [63]. The overall system set up is illustrated in Figure 8. The tabletop display is housed in a custom-built aluminum frame with a 6-inch surface surrounding the display, which serves as a placeholder for tangibles. We use two kinds of tangibles, dollhouse furniture models and wooden building blocks. A sample set of tangibles is shown in Figure 9. The overall height of the frame was 30 inches allowing most children over six years of age to easily interact with the tabletop display.

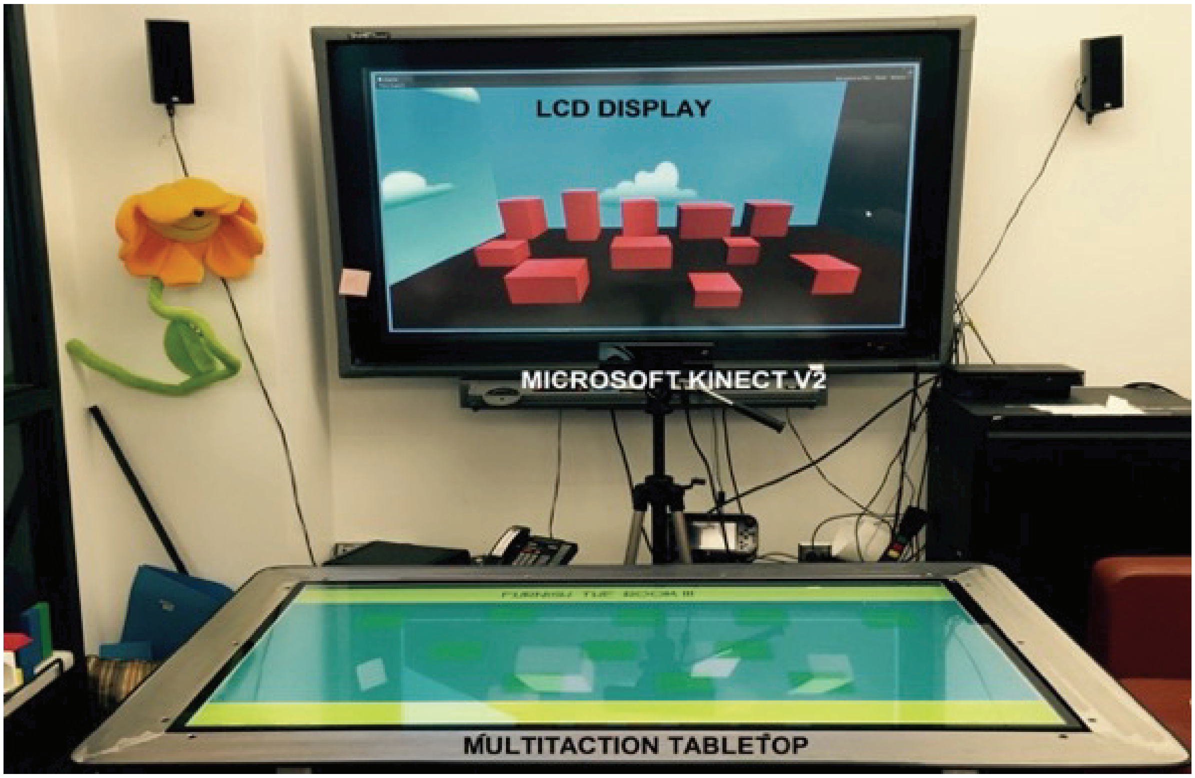


**Figure 8. System Setup**

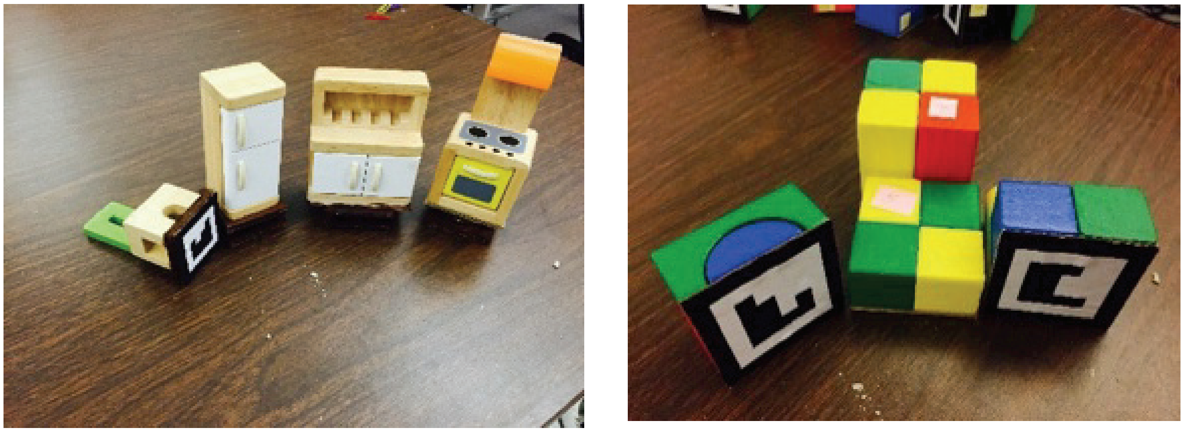


**Figure 9. Tangibles, with fiducial markers attached on the underside.**

The MultiTaction tabletop is connected to a Windows PC (Intel Core i5 2.66 GHz processor, running Microsoft Windows 7) with cross Ethernet cable. The wall mounted LCD display is connected to another Windows PC (AMD Athlon A10 2.66 processor, running Windows 8). Both PC were running applications programmed using Unity3D, which represented two different views of the same layout. While the application on the wall-mounted display presented the goal state for the current game, the tabletop display displayed only a floor layout (or a top-down view) that enabled users to place tangibles at the appropriate locations using the design on the wall-mounted display as reference.

### 3.3.1 Tangible Interaction on MultiTaction tabletop

The MultiTaction tabletop can register the identity, position and orientation of the tangibles by tracking fiducial markers attached to the underside of the tangibles. The *Uniducial* library for Unity3D [4] facilitated reception and processing of the tracking data by the tabletop application. The TUIO protocol [51] facilitated the transmission of data about the registered tangibles between the tabletop display and the PC. We used the Marker Factory [69] application to create the fiducial markers. Each marker has a unique ID. Pasting a marker on the underside of a tangible allowed each tangible to be tracked on the MultiTaction tabletop.

#### 3.3.1.1 Challenges with Fiducial Tracking

When testing the fiducial tracking on the MultiTaction Tabletop, we encountered issues with tracking precision. We noticed issues such as marker identity been lost and switching of marker ID between different markers. Tobias et al. [80] also encountered similar issues with fiducial tracking. The cause of the problem was the grid of cameras in the MultiTaction tabletop. Tracking was affected when the marker moved at the intersection of two cameras. Tobias et. al [80] provided an updated Uniducial Library when contact about the issue. Using this updated code, the session ID is maintained when the marker is moved from one camera grid to another, thereby mitigating the issue of swapped marker IDs.

Another issue was marker recognition. We observed instances of a marker not been recognized in some instances. Tobias et. al. [80] recommended to use white cutouts of markers pasted on black construction paper instead of using laser printed markers, as shown in Figure 10. We used this recommendation which helped in improving the fiducial tracking.

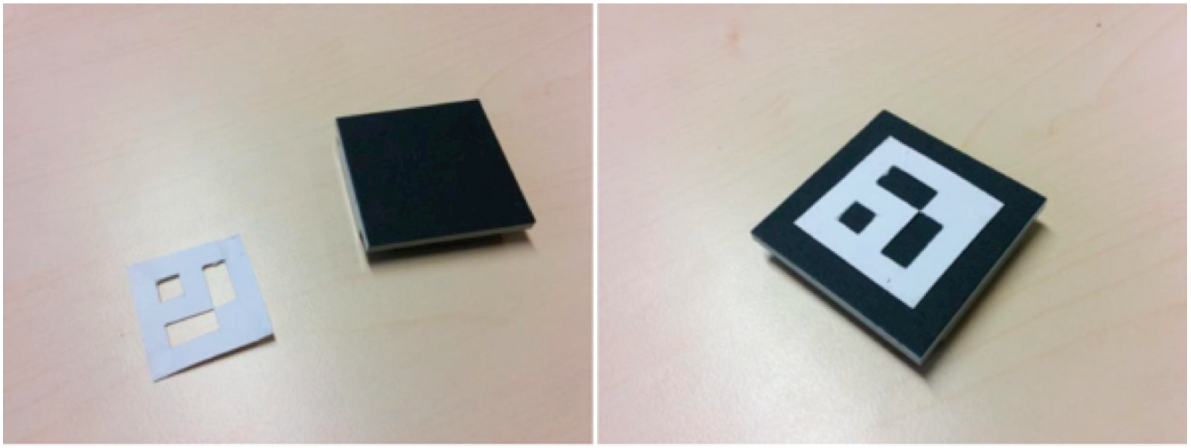
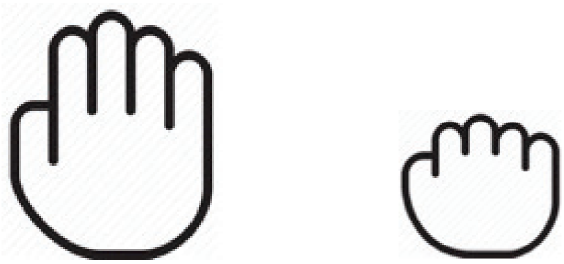


**Figure 10: Fiducial markers made from white laser print cutout pasted on black construction paper. Figure from [80].**

### 3.3.2 Gestural Interaction using Microsoft Kinect v2

The interactive application on the wall-mounted display included support for two types of gestural interactions, *grab* and *swipe*. Grab requires users to perform a hand grab or closing their hands to make a fist (illustrated in Figure 11) over a target object to select. In our case, the 3D model is projected on a 3D board which has a handle on each side. To rotate the model, user must grab a handle. Once a handle is grabbed, the user can rotate the model. The Kinect tracks user hand movements by mapping the normalized screen position to pixel position, and their grab gesture using the open and close hand events, allowing the application to infer specific actions. The position of the grabbed element, as determined by the hand position, is then used to rotate the model.



(a) (b)

**Figure 11. Open hand (b) Closed hand – grab gesture.**

The swipe gesture allowed users to perform fixed (90 degree) rotations to rotate the 3D model either clockwise or counterclockwise. The translation of hand movement actions into 3D model rotations are summarized in Table 1.

| Gesture | Action | Description |
|---|---|---|
| Rotate Left | Swipe right hand to left | Rotates the 3D model clockwise by 90 degrees |
| Rotate Right | Swipe left hand to right | Rotates the 3D model counterclockwise by 90 degrees |

**Table 1. Swipe Gestures**

In games that require the use of grab gesture, we included a virtual hand as a visual indicator that guides participants to the target object. The position of the user's hand was mapped to the virtual hand by translating world co-ordinates into Unity co-ordinates system. The games using the swipe gesture did not employ a virtual hand. However, in both the games, users can see their silhouette, in form a 3D depth map, in the both right corner of the LCD screen as shown in the Figure 12. The color of silhouette is randomly assigned by the Kinect. The purpose of the silhouette is to show the users present in the Kinect tracking area.

**Figure 12: Silhouette of the user shown on the LCD display.**

### 3.4 Game Overview

We developed two games, namely, a dollhouse game called *Furniture Finder* and a block-based game called *Block Rock*. In both games, a 3D model is projected on the wall-mounted display. Users are required to reconstruct the 3D model on the MultiTaction tabletop display using tangible objects. To provide feedback for user actions of placing or moving the tangible, a digital "shadow" of the tangible is displayed on the tabletop. The tabletop application as shown in Figure 13, displayed on the tabletop display contains triggers (green squares).

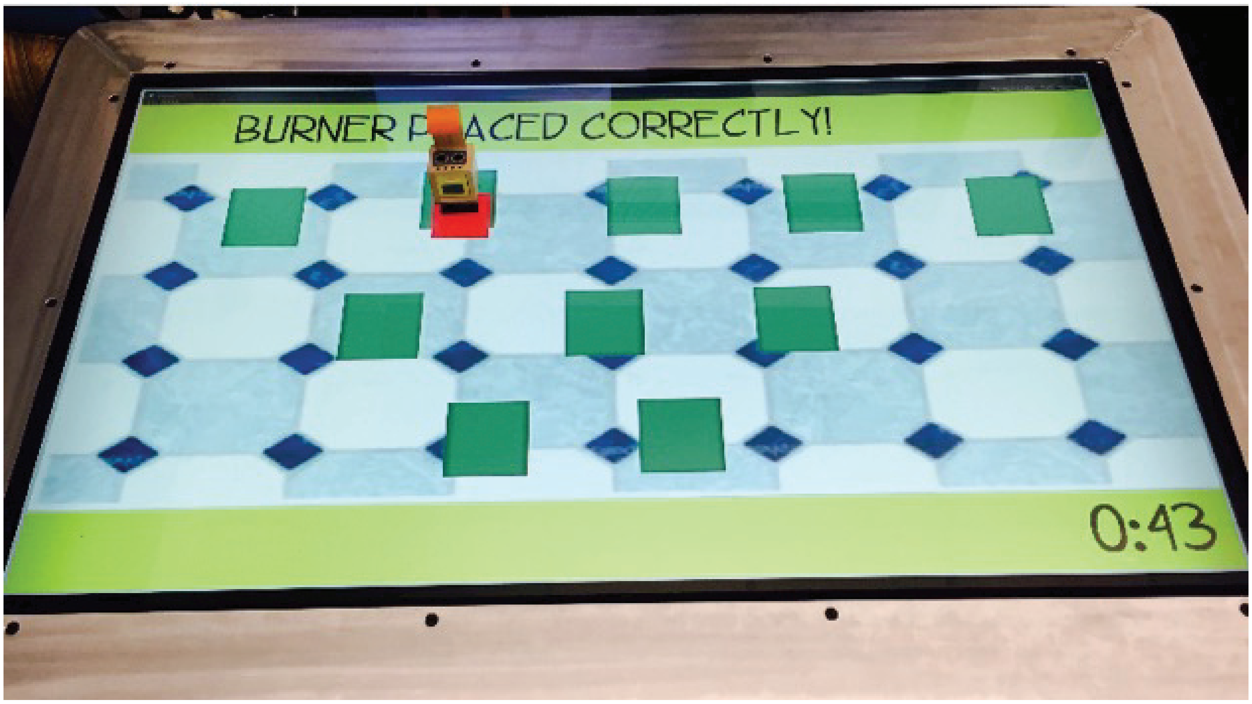


**Figure 13. Game Scene with message board on top and timer on bottom right corner.**

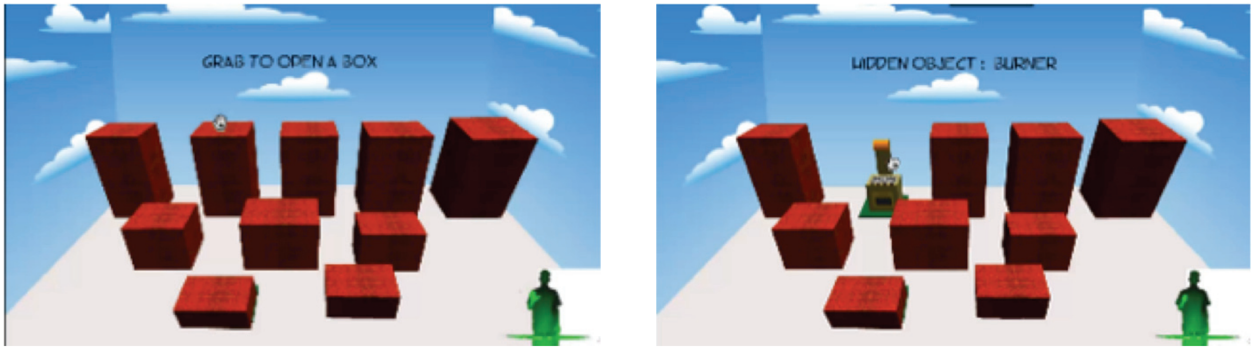
The tabletop interface consists of the “top-view” of the game scene, in addition to a message board and a timer as shown in Figure 13. When the game begins, the empty scene consists of trigger squares. If a tangible is placed correctly, the message board displays a message and the interface plays a confirmation sound. If a tangible is placed on a wrong trigger square, the message board notifies the user about the wrong placement and the interface plays a different notification sound. A countdown timer is displayed in the right corner of the tabletop, closer to the users. We set a limit of 3 minutes to complete each game.

### 3.4.1 Design Motivation

We motivate the design of our games based this prior work we considered in the previous chapter. When designing games for such a system, we considered Pinelle et al.’s [8] definition of coupling in collaboration, which is defined as: “*the degree to which people can work as individuals before needing to interact with another member of the group.*” According to Pinelle et al., [8] group work with a high degree of independent actions by group members constitutes loose coupling, whereas tight coupling is characterized by frequent interactions and resulting actions, but less independent actions by group members. We designed our games to incorporate different levels of coupling. We design Furniture Finder to incorporate tight coupling, requiring group members to frequently interact as they work towards the game objectives. We do this to have a sequential gestural and tangible interaction in the game, wherein each box must be opened (gestural interaction) and then the corresponding tangible must be placed. Block Rock with Grab is designed to be less coupled than Furniture Finder, where there would be some instances of group work, but slightly more instances of independent actions. Block Rock with Swipe, however, is designed to be loosely coupled, facilitating more independent gameplay by group members. Thus, Block Rock game do not have specific number of gestural interactions, as opposed to Furniture Finder. Depending upon the orientation of the 3D model users can see positon of several 3D model of the tangibles.

### 3.4.2 Furniture Finder

In Furniture Finder, wooden models of dollhouse furniture were used as the tangibles. 3D models of these furniture models are displayed on the wall mounted LCD display. However, each furniture model is *hidden* inside a 3D box as shown in Figure 13. A corresponding "top-view" layout, like the one shown in Figure 12, is displayed on the tabletop display. This game requires user(s) to use the *grab* gesture for interaction. The purpose of the game, is for the user to "open a box", to reveal the hidden furniture item inside the box. The user sees his/her hand's virtual representation on the LCD display. The user's hand movement are mapped to the virtual hand. The user then has move their hand, so that the virtual hand is over any box that they wish to open. The user then must perform the grab gesture. This will open the box and the user can see the hidden furniture item as shown in Figure 14. The user then must place the wooden tangible of that furniture model in the correct trigger box on the tabletop as shown in Figure 13. The user can only open one box at a time. The user must place as many furniture items as possible in the given time of 3 minutes. Furniture Finder is designed to encourage sequential collaborative gameplay: when a 3D model is uncovered by one user, another user can then place the tangible in the correct place on the tabletop. Furthermore, since only one box can be opened at a time, it required users to coordinate their actions accordingly.



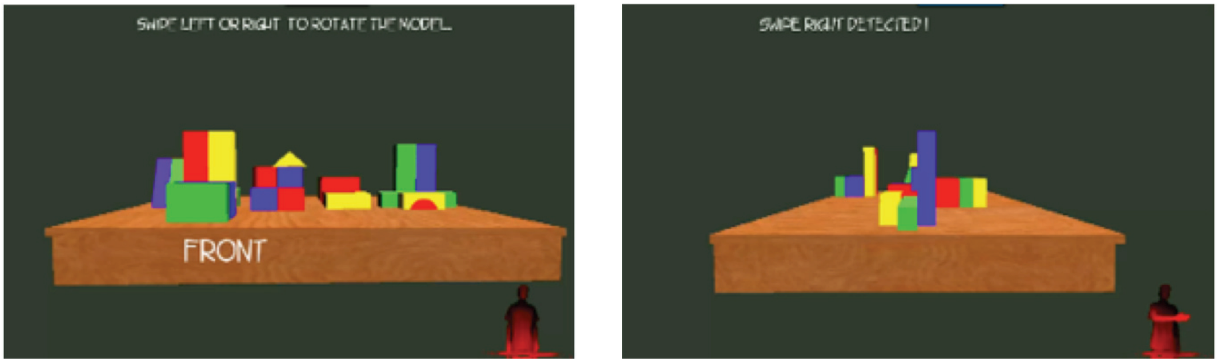
(a) (b)

**Figure 14. (a) Hidden dollhouse furniture. (b) Burner uncovered by user.**

**Figure 15: A group playing Furniture Finder**

### 3.4.3 Block Rock with Swipe

In Block Rock (Swipe), wooden blocks are used as tangibles. Users are required to interact with the 3D model using the swipe gesture. The 3D model projected on the wall mounted LCD display consists of a 3D wooden board on which the blocks are represented as shown in Figure 16 (a). As opposed to the Furniture Finder game, the 3D models of the blocks are not hidden inside a box. However, the view is projected such that users can only see the models from one orientation, due to which blocks behind one another cannot be seen at the same time. Users can rotate the 3D model using the swipe gesture, either swiping left or right. With a swipe gesture, the model rotates in the direction of the swipe by 90 degrees as shown in Figure 16 (b). Thus, swipe offers canonical orientations of the model. A corresponding empty scene "top-view" layout is displayed on the tabletop display. Users can use the 3D model for assistance as they place the tangibles to reconstruct the layout on the tabletop display. The swipe gesture provides ease of control to user(s), but limits the view to four 90 degree rotations along the x-axis. This feature is aimed at facilitating discrete gestural interaction events by any collaborator, to view the 3D model and place the tangibles correctly. Furthermore, this game does not provide user with a virtual hand indicator on the LCD display. However, users can see their silhouette in the bottom right corner.



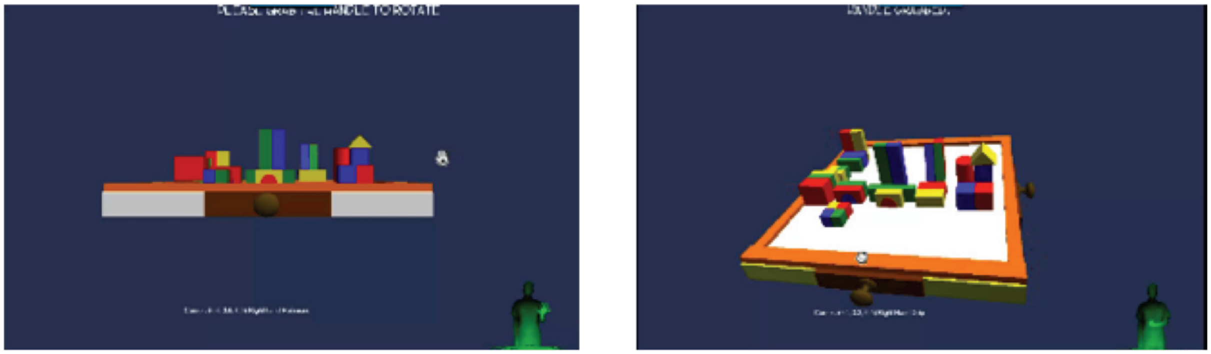
(a) (b)

**Figure 16. 3D representation of tangibles. (b) Model rotated by user through swipe gesture.**

Figure 17: A group playing Block Rock Swipe

### 3.4.4 Block Rock with Grab

Block Rock (Grab) uses the same wooden blocks as Block Rock (Swipe) as tangibles. However, Block Rock (Grab) requires users to perform a *grab* gesture to interact with the 3D model. Like the Block Rock with Swipe, the 3D model of blocks is projected on a 3D base board as shown in Figure 18 (a). However, in this game, each side of the base board consists of a 3D handle. Like Furniture Finder, this game also employs a virtual hand which is mapped to the movement of the user's hand. To interact with the 3D model, the user needs to move their hand so that virtual hand on the LCD screen comes over one of the handles on the base board. The user can then perform the grab gesture, to *grab* the model. When the user successfully does this, the base board lights up to yellow to indicate to the user that the handle is grabbed. The user can then move the handle up, down, sideways or any orientation to view that model from desired orientation. The grab gesture, thus requires precision from the user, as user must first align his/her with the handle to interact with the model. However, it allows the user to view the model from any orientation. This includes a top-down view in which the user can view the position of all the blocks at the same time as shown in Figure 18 (b).



(a) (b)

**Figure 18. (a) 3D representation of tangibles. (b) Model rotated by user through grab gesture.**

**Figure 19: A group playing Block Rock Grab**

# CHAPTER 4 METHODOLOGY

In the previous chapter, we discussed the design and implementation of the system. In this chapter, we first discuss our research questions. We then describe our study design including the study procedure, participant sample and recruitment followed by the data analysis methodology. Lastly, we describe the pilot study, lessons learnt from the pilot study which helped us refine our system and study design.

## 4.1 Research Questions

In this study, we consider the following two research questions

1) How do small groups of youths (aged 8 through 15) use a combination of tangible interaction on a tabletop display and gestural interaction with a vertical display for collaborative gameplay? Specifically, we want to explore the impact of designed mechanisms (game type, orientation control), group size and age range on gameplay and identify emergent, socially negotiated strategies of gameplay.
2) For small groups (2-3 participants) of youth (aged 8 - 15 years) playing together in a multimodal configuration (tangible and gesture), how do game design mechanisms (game type, orientation control) group size and age range promote collaboration specifically in terms of participation equality, territorial infringement, communication and completion time?

## 4.2 Study Design

### 4.2.1 Participants

We recruited participants who were part of SuperNova [81], an annual summer camp held at Dalhousie University. We contacted the organizers and counsellors (“mentors”) of SuperNova initially to get their approval to arrange for campers to participate in our study. Two mentors visited

GEM lab to get a demonstration of our system. After getting the demonstration and the overview of the system, we got their approval for the campers to participate in our study. After getting their approval, we applied to the Dalhousie Ethics Board to get approval for conducting the study. The campers age range was 8 to 15 years, thus we required signed consent from the campers' guardians to allow the campers to participate in the study. Furthermore, we also required assent from the campers. In the ethics application, we included a consent form [Appendix A] and an assent form [Appendix B]. The consent form [Appendix A] was required to be signed by the campers' guardians while the assent form [Appendix B] was required to get assent from the campers. On getting the approval for our ethics application, we sent the consent form [Appendix A] to the Supernova organizers. The consent form [Appendix A] was included by the SuperNova organizers as part of the package sent to the guardians of the campers. After this we had discussion with the SuperNova mentors to discuss the schedule of the study. It was decided that the mentors would give their schedule on a weekly basis. The schedule would include the days of the week the campers would visit the GEM lab, the number of campers in each batch and their age range. The age range of campers ranged from 8 to 16 years, ranging from grade 3 to grade 9. The SuperNova camp also had campers in Grade 1 and 2. However these campers were not included in the study after discussion with the mentors as a visit to the GEM Lab was not part of the schedule for campers in grades 1 and 2. The SuperNova organizers had the campers divided into batches. Each batch consisted of between 8 to 20 campers. Also, if the organizers had more campers in any week, it was decided to have more than two batches of campers in a week to be a part of the study. A maximum of 180 minutes (3 hours) were allocated for each batch of participants (hereafter campers are referred as participants). At the start of the week, the SuperNova coordinators provided with week schedule of the batches. This schedule consisted of the total number of batches for the week, the number of participants, age range and grade range for each batch. Over the course of 8 weeks, we recruited a total of 92 participants (58 male and 32 female). It is important to note that even though at the start of the week we knew the age and grade of the participants, we did not have any control over the age and grade range. Thus, participants came to the lab in batch consisting of 8 – 20, and stayed in the lab for a maximum time of 180 minutes (3 hours). No compensation was given to the participants for participating in the study.

## 4.3 STUDY METHODOLOGY

### 4.3.1 Study Procedure

Each batch of participants, accompanied by two SuperNova coordinators, came to the GEM lab in the Mona Campbell building, Dalhousie University. The coordinators provided the signed consent forms for the participants, signed by a parent/guardian. Children whose parents/guardians did not provide consent were placed in a group together. They were still able to play the games designed for the study, but no data was recorded for their participation. If there was only one participant who did not have a signed consent form, then they were paired with another child, and data was not recorded for this pair. After getting the consent forms, participants were divided into groups of two (dyads) and groups of three (triads). In some cases, participants wanted to be part of a group with their friends, which made forming an equal number of dyads and triads challenging; this is discussed later. After this, participants were divided into dyads and triads. Every dyad and triad was assigned a number starting from one. For each group, starting with group 1, participants were then read out the Assent form [Appendix B] by co-investigator Khalid Tearo. Groups who did not have signed consent form [Appendix A] were not read the Assent form [Appendix B]. The data for such groups was not recorded. All the participants, who were read the Assent form [Appendix B] gave their assent to participate in the study. Once the participants gave their assent, each group played the games using our multimodal system. Participants were first given an overview of the system. This included demonstrating to the participants how to use the tangibles on the MultiTaction tabletop, and to interact gesturally with the wall mounted LCD display. After this, participants were presented a simplified demonstration of the games which they completed as training task; this is discussed later. Participants then played the three games – Furniture Finder, Block Rock Swipe and Block Rock Grab. After playing the three games, co-investigator Khalid Tearo conducted the post-game interviews of the participants as a group [Appendix C]. To mitigate learning effects, we counterbalanced the order in which groups played the three games. Table 2 shows the counterbalancing of the three games across 35 groups.

| Groups | | | | | | GAMES | | |
|---|---|---|---|---|---|---|---|---|
| G1 | G7 | G13 | G19 | G25 | G31 | FF | BR-G | BR-S |
| G2 | G8 | G14 | G20 | G26 | G32 | FF | BR-S | BR-G |
| G3 | G9 | G15 | G21 | G27 | G33 | BR-G | FF | BR-S |
| G4 | G10 | G16 | G22 | G28 | G34 | BR-G | BR-S | FF |
| G5 | G11 | G17 | G23 | G29 | G35 | BR-S | FF | BR-G |
| G6 | G12 | G18 | G24 | G30 | | BR-S | BR-G | FF |

**Table 2: Order of playing the games counterbalanced across 35 groups. Every group played all the three games. Orderings are in the format {FF|BR-G|BR-S}, where in FF: Furniture Finder, BR-G: Block Rock - Grab, BR-S: Block Rock – Swipe**}

### 4.3.2 Training Task

To help participants get familiar with the different elements of our multimodal system, were asked to complete a simplified demonstration of a game. The simplified demonstration was made for each game variant. The time limit for the training task was 90 seconds for each game variant. It consisted of 3D model of a single tangible projected on the LCD display and one green trigger block to place the tangible. The participant had to find the tangible and place it on the tabletop on the green trigger block, as shown previously in Figure 13. Participants were first shown the different elements in the system. This included the MultiTaction tabletop, LCD display, Kinect and the tangibles. After this, the researcher gave a high-level overview of the games. Here the researcher explained to them that they must place tangibles on the tabletop in their correct positions using the 3D model which they see on the LCD screen which they can interact with using gestures. After this, based on the game which the group was to play first, a simplified demonstration of that game was started. Participants were told how to use the gesture to interact with the 3D model. Then asked to look for tangible like the 3D model shown on the LCD screen and place it on the green trigger block. After the participants placed the tangible, the researcher showed them the different UI elements on the tabletop which included a message board to show if the tangible placed was correct and the countdown timer. Participants were then asked if they had any questions. Participants were then told that they play the actual game which involves more tangibles which they should place correctly within 3 minutes. Participants performed the training task before each of the three games. After getting the overall description before start of first game, participants did not need description for the next two games for the training task. The only description they needed was how to use the gesture in that game variant.

### 4.3.3 Side Activities

While participants waited for their turn to play games using our multimodal system, we set up some other activities that the participants engaged in. This served three purposes. First, participants did not have to wait around doing nothing while waiting for their turn. Second, this diverted attention away from the study activity, to mitigate learning effects and reduce the potential for mimicry of the behavior of groups playing before them. Third, the area behind the group playing the games with our system needed to be kept clear of people, to avoid issues with the Kinect's tracking. Importantly, no data was recorded while participants engaged in these activities: they are not considered part of the study; we describe them here for completeness.

We had a total of four side activities, which are listed as follows:

1. Whole body interaction using the Kinect [75]

   In this demonstration, a Microsoft Kinect v2 [63] was used to show a demonstration of whole body interaction. A short throw projector [82], projected the content on a wall. The demonstration consisted of 3D model of a human. The Kinect was placed beside the short throw projector. Participants were asked to stand in front of the Kinect. The 3D humanoid model projected on the wall moved as per the movements of the participant.

2. Leap Motion sensor games [49]

   A Leap Motion sensor [27] is a small device which is used to track precise finger movements of both hands. The Leap Motion was connected to a Windows machine. The Windows machine was connected to a large wall-mounted display. Participants played a range of games designed for the Leap Motion: Sculpting [83], Q [84], Kyoto [85], Caterpillar Count [86] and Chuck Out [87].

3. Oculus Rift Demonstration [50]

   Oculus Rift [50] is a Head Mounted Display (HMD) for experiencing Virtual Reality. In this demonstration, a roller coaster experience, available with the Oculus SDK, was used. Mohamad Salimian, a PhD student at GEM lab, coordinated this activity. Each participant was told before about the possibility of having dizziness from the headset. One of the SuperNova coordinators was also present when conducting this activity. The participant was asked to put on the headset and then asked to sit on a chair. Then the experience was played. If the participant felt sick at any point, he/she was asked to take off the headset.

4. Google Maps on Touch Table [88]

   In this demo, Google Maps [88] was presented on a large touchscreen table using the Google Chrome web browser. Participants were asked to use Google Maps to explore any place that they wished to see.

## 4.4 DATA PROCESSING

### 4.4.1 Data Collection

We collected data during and after the tasks performed by participants.

Table 3 outlines our data collection methodology.

| **Phase** | **Method** | **Details** |
|---|---|---|
| **Gameplay Activity** | Video | Video recording of the participants performing the tasks. |
| | Tabletop Screen Capture | Screen recording of all the tangible interactions performed by the participants on the MultiTaction Tabletop using Snagit screen recording software. |
| | Wall Display Screen Capture | Screen recording of the wall mounted LCD display recording the gestural interactions performed by the participants using Snagit screen recording software |
| | Hand written Notes | Hand written notes, noting down the participant behavior by researcher |
| | | Feedback of the participants about the system, their experience of collaborating to complete |

| | | |
|---|---|---|
| **Post Study** | Semi Structured Interview | tasks and their recommendations to help improve the system |

**Table 3: Data Collection Methodology**

### 4.4.2 Data Coding

#### 4.4.2.1 Video Coding

The video capture of gameplay activity and the screen capture from the MultiTaction tabletop and wall mounted LCD display were synchronized together using Adobe Premiere. The screen was divided into three sections. One section occupied approximately 70% of the screen. This section showed the video recording of the gameplay activity. The other two sections approximately occupied the other 30% of the screen. One half showed the MultiTaction screen recording while the other half showed the wall mounted LCD display screen capture as shown in Figure 19. Video coding went through multiple iterations. We present details of each iteration in the following sections. Video coding was done using Vcode VData software.

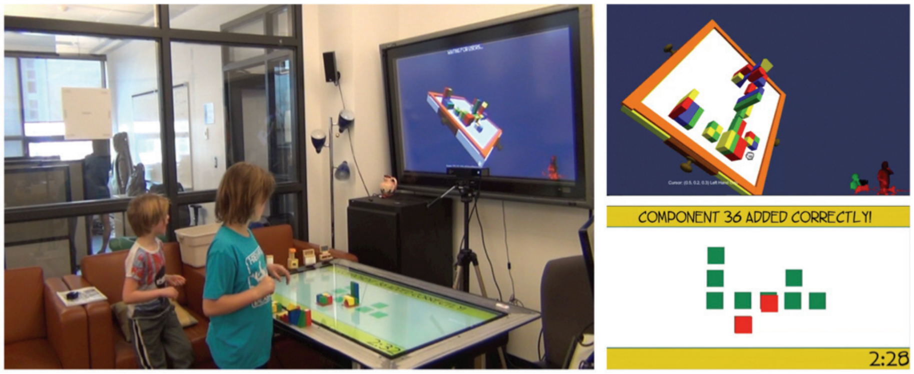


**Figure 20: Layout of video capture of gameplay activity and screen capture of LCD display and tabletop used while video coding.**

#### 4.4.2.1.1 Open Video Coding

In this iteration of video coding for collaborative behavior observed in participants, we observed the actions of the participants during gameplay activity. While actions such as placing tangibles, performing gestures were inherent to the game, we noted behavior such as talk among participants before the start of the game, movement around the tabletop, talking with each other, distraction, issues with Kinect tracking etc. In this iteration, we tried to record and annotate details about participant behavior. Apart from such as tangible placement and gesture, which were coded, all our observations were in form of annotation notes. This iteration yielded a total of 177 annotation notes.

#### 4.4.2.1.2 Affinity Diagramming

After the first iteration of open coding, we conducted an affinity diagramming exercise. The purpose of this exercise was to classify the observations we recorded in open coding. For this exercise, the observations from open coding were written on post it notes. Four researchers participated in this exercise. The post it notes, 177 in total, were distributed among the four researchers. Each researcher then placed these notes in according to their own, with related notes placed together to form clusters. After all the notes were placed, the researchers revisited the clusters to see if all the notes in each cluster were related. After this activity, each of the cluster was labelled. Figure 21 shows result of the affinity diagramming exercise. We derived a total of 22 categories. The categories and the number of notes under each category are detailed in Table 4.

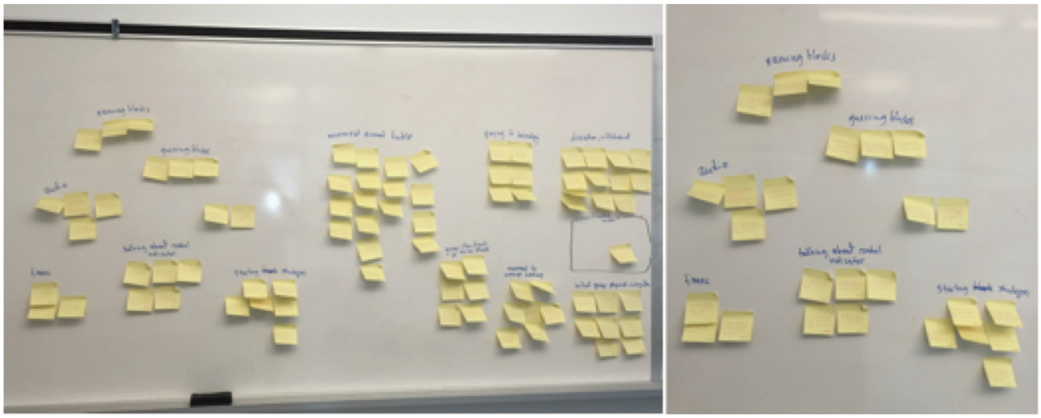


**Figure 21. Affinity Diagramming exercise**

| No. | Category | Count |
|---|---|---|
| 1 | Naming Blocks | 3 |
| 2 | Guessing Blocks | 5 |
| 3 | Audio | 4 |
| 4 | Timer | 3 |
| 5 | Talking about control | 5 |
| 6 | Starting strategies | 6 |
| 7 | Movement around tabletop | 17 |
| 8 | Group slow down and take stock | 6 |
| 9 | Movement to manage tracking | 7 |
| 10 | Playing with technology | 6 |
| 11 | Distraction withdrawal | 12 |
| 12 | Initial group physical configuration | 8 |
| 13 | Avoiding gesture recognition | 6 |
| 14 | Grabbing/gesture style | 13 |
| 15 | Gesture and tangible interaction | 7 |
| 16 | Grabbing each other’s hand | 10 |
| 17 | Direction/roles | 6 |
| 18 | Controlling actions | 20 |
| 19 | frustration | 6 |
| 20 | Kinect adjustment | 5 |

|  |  |  |
|---|---|---|
| 21 | Object recognition issues | 10 |
| 22 | Interaction difficulties | 12 |
|  | **Total Observation Notes** | **177** |

**Table 4: Cluster from Affinity Diagramming exercise**

#### 4.4.2.1.3 Structured Video Coding

From our observations from the open coding and the affinity diagramming exercise, we observed behavior patterns among patterns during gameplay activity. Specifically, in terms of role of each participant in a group. Based on these observation, we identified the most commonly observed strategies adopted by participants across all groups. We identified a total of 5 strategies which we refer to as *gameplay strategies* listed in Table 5. In our system only one person could be control gesture. Thus, it is important to note that, strategy 5 (shared gesture control and one person on tangible) is included for the sake of completeness.

| Strategy | Description |
|---|---|
| **1** | One person performs both gesture and tangible interactions. |
| **2** | One person performs gesture, one or two person(s) place tangible |
| **3** | One person performs gesture, placing tangibles is shared |
| **4** | Gesture control shared, placing tangible shared |
| **5** | Gesture control shared, one person placing tangible |

**Table 5: Gameplay Strategies.**

We conducted structured coding to code the gameplay strategies. In this iteration of coding we followed an approach in which for every tangible placed by a group we coded the adopted *gameplay strategy*. This approach allowed us to code gameplay strategies across the entire duration of the game.

### 4.4.2.1.4 Closed Video Coding

Open coding and structural coding allowed us video code for the observed collaborative behavior by annotating participant behavior and then categorizing them. In addition to these observations, we wanted to quantify collaboration into discrete events to compare the differences across our experimental factors. In our literature review, we observed that Pinelle et. al. [8] proposed mechanics of collaboration framework. According to this framework, collaboration is defined in terms of in terms of coordination and communication. The framework allows to study collaboration at a fine-grained level by providing discrete events or actions in form of mechanics. Each mechanic can be defined by a real-world action [8]. The mechanics and the actions we observed when coding, are detailed in Table 6. This framework allowed us to code for distinct actions at a very low level. We ended up with a total of 14 codes. To test interrater reliability of coding between researchers, two researchers coded the 4 same groups individually. The inter-rater reliability score was 56.95% for the four groups. The two researchers then went compared their coding results to access the reason for the low score on the interrater reliability. From observation and discussion, it became clear the low score was caused due to coding of the durational events specifically communication. It was observed that researcher 1 was more accurate as compared to researcher 2. Due to this reason, researcher 1 coded all the videos.

| | | **Mechanic** | **Action** |
|---|---|---|---|
| **Communication** | **Explicit Communication** | Spoken Message | Conversational, verbal shadowing |
| | | Gestural Message | Indicating, pointing, drawing |
| | | Deictic References | Pointing to an aspect in game and talking about it |

| | | | |
|---|---|---|---|
| | **Information Gathering** | Basic Awareness | Observing other participants in group |
| | | Feedthrough | Attention to feedback from system |
| | | Visual Evidence | Observing results of participant’s actions in shared access space |
| **Coordination** | **Tangible Co-ordination** | Obtain Tangible | Pick up a tangible |
| | | Reserve Tangible | Keep tangible to oneself |
| | | Protect Tabletop Work | Blocking access for other |
| | | Handoff Tangible | Give or take tangible |
| | | Place Tangible | Place Tangible on tabletop |
| | **Gestural Co-ordination** | Gesture Interaction | Grab, Swipe Left, Swipe Right |
| | | Protect Gesture Control | Notify others of intention |
| | | Handoff Gesture Control | Give or take gesture control |

**Table 6. Elements of the Mechanics of Collaboration framework proposed by Pinelle et al. [8]**

#### 4.4.2.2 Post-Game Interview Transpiration

Participants responses from the post-game interview were fully transcribed using O-transcribe. The responses of the participants were formulated in a table using Microsoft Excel. In this process, each response was categorized.

### 4.4.3 Limitations

Our sample consisted of children attending the SuperNova summer camp, which meant that we did not have complete control over the characteristics of the sample. We could not control the age ranges and of the sample and were not aware of numbers from one week to the next. Thus, we were unable to ensure the same numbers of dyads and triads for our two age categories, ending up with a small set of dyads in the age range of 7-11 years. Thus, we counter balanced groups while comparing across group size and age range. This is discussed in the next chapter.

## 4.5 Pilot Study

During the early phases of SuperNova campers interacting with our multimodal system, we iterated over the design of design of game elements and study design. We did this based on our observations of the participants. This helped us refine our game setup, game elements and study design from which we arrived at a stable configuration. This configuration was used for the remainder of the groups. The data for these groups was not considered for our analysis. This initial iteration of different game design and study design is referred to as pilot study. In the following section, we discuss the iterations made in the games and study design. In this pilot study, a total of 42 participants were considered (24 male and 18 female). These 42 participants in the pilot are separate from the 92 participants we considered for our study.

### 4.5.1 Updates in Game Design

We made the following updates to the games and the setup of our multimodal configuration based on our observations.

#### 4.5.1.1 Virtual Handles in Block Rock with Grab Game

In the early version of Block Rock with Grab game, participants there were no virtual handles. Participants could grab anywhere on the 3D model to rotate it. We observed that participants had difficulty in rotating the model to their view. Since the 3D model could be rotated by grabbing it any point the rotation of the model became was affected by position of the grab gesture performed on the 3D model. For example, grabbing the model at the edges would rotate the model around edge, thus making rotating the model to a desired became challenging for participants. To overcome this problem, we introduced virtual handles on each sides of the 3D model. The model could be rotated only by grabbing one of the handles. Also, we also made the 3D model base light up, by changing its color from white to yellow, when one of the handles was grabbed. The introduction of virtual handles allowed the participants to easily rotate the model to their desired view.

#### 4.5.1.2 Placing Kinect on Tripod

In the pilot study, the Kinect was placed on a small table. During the pilot, the height of the Kinect was required to be adjusted to track the participants. This is because we had participants from age 8 to 15 years. Thus, the height of the participants varied. In the pilot, height was adjusted by adjusting the height of the table. However, the table offered very little scope for adjustment of height and took time to get the required height. In our study, we replaced this table with a tripod. This allowed us to easily adjust the height of the Kinect as required.

### 4.5.2 Updates in Study Design

#### 4.5.2.1 Additional Time to complete the game

Each game had a time limit of 3 minutes. A countdown timer on the tabletop allowed the participant the time they had left to complete the game. During the pilot, one group could not complete the Furniture Finder and Block Rock with Swipe game in the allocated time. During the post-game interview, the participants of this group were very upset about not been able to complete the game. In the interview, the participants immediately asked if this information would be shared with the other groups and they prefer not to. Based on this experience, during the study, if a group could not complete any game in the allocated time, we gave them extra time to complete the game. However, participants were not told about this at the start of the game.

#### 4.5.2.2 Group Size

In the pilot, we had a group of four. In this group, we observed that the fourth participant stood the side of the tabletop as the participant could not find space to interact either with the 3D model or the tangibles. In the next game the group played, one of the participant stood on the side while this participant played the game. Thus, to allow all the participants to be able interact with the system, for the study we decided to have dyads and triads.

# CHAPTER 5 RESULTS

In this chapter, we present the results of our study. We analyze the impact of our experimental factors (game type, orientation control, group size and age range) on collaboration in terms of gameplay strategies, participation equality, territorial infringement, communication and completion time. Lastly, we present the results of the post-game interview.

### Interaction effects

We tested to see if there are any interaction effects of our experimental factors on our dependent variables. We conducted a MANOVA to test for the interaction effects of our experimental factors (group size, age range, game type) on gameplay strategy adoption, participation equality, territorial infringement, communication and completion time. There was a statistically significant difference in collaboration based on the game type, F= 11.330, p<0.005; Wilk's Lambda = 0.206. Furthermore, we conducted a MANOVA to test for the interaction effects of our experimental factors (group size, age range, orientation control) on gameplay strategy adoption, participation equality, territorial infringement, communication and completion time. There was a statistically significant difference in collaboration based on orientation control, F=0.687, p<0.005; Wilk's Lambda = 0.313.

## 5.1 Game Type

In this section, we compare the two game types: Furniture Finder (FF) and Block Rock (BR). We test the impact of game type on gameplay strategy adoption, participation equality, territorial infringement, communication and game completion time. For this comparison, in BR we consider the both of Block Rock with Grab (BR-G) and Block Rock with Swipe (BR-S).

### 5.1.1 Impact of Game Type on Gameplay Strategy Adoption

Strategy 2 was predominantly adopted in both Furniture Finder and Block games. We observed that players divided responsibilities, with one player performing gestural interaction and other player(s) placing tangibles on the tabletop.

In Furniture Finder, most groups divided responsibilities, wherein one player uncovered furniture using the gestural interface, and the other(s) placed furniture on the tabletop (28/35). A small number of groups took turns, splitting the furniture tangibles in half and then placing them (3/35). Strategy 2 was the most commonly adopted strategy across all groups, followed by Strategy 1.We observed instances of gesture controller not placing tangibles even when the tangible was within their reach. Instead they chose to handoff the tangible to their partner(s), who were responsible for placing tangibles. Also, the gesture controller said aloud the tangible's name which was uncovered on opening a box, pointing to the tangible to help their partner. Another example, is group 5 who took a turn taking approach to play the game. Each participant did both tangible and gestural interactions for half the game while the other participant stood on the side of the table, away from the tracking area and then they switched their roles. Furthermore, we observed participants directing each other to perform certain actions. For example, a participant placing tangibles asking another to open a certain box, a participant performing a gesture while directing another to place a tangible in a specific location.

We conducted a paired-samples t-test to test the impact of game type on gameplay strategy adoption. There was a statistically significant difference between in adoption of gameplay strategy 1, 3 and 4 across the two games. Strategy 1 was adopted significantly more in Furniture Finder while Strategy 3 and Strategy 4 were adopted significantly more in Block Rock. Table 7 summarizes the mean and standard deviations of gameplay strategies adoption across FF and BR.

| **Strategy** | **FF**<br>**Mean(SD)** | **BR**<br>**Mean(SD)** | **P value** |
|---|---|---|---|
| 1 | 27.42(31.56) | 12.53(2.20) | **0.012** |
| 2 | 54.85(28.63) | 47.77(19.94) | 0.205 |
| 3 | 8.85(14.09) | 18.25(16.08) | **0.022** |
| 4 | 2.00(4.72) | 21.42(15.89) | **0.000** |

**Table 7: Mean and standard deviations of gameplay strategies adoption in for FF and BR games (FF: Furniture Finder, BR: Block Rock).**

### 5.1.2 Impact of Game Type on Participation Equality

The interactions performed by participant to interact with the system consisted of gestural control and tangible placements. We consider the amount of interactions performed by each participant in a group to measure participation equality. Based on our review of prior work, we follow the approach taken by Ryall et. al. [10] to normalize data and to measure participation equality. Ryall et al. [10] consider a hypothetical group where one member performed all the expected touch interactions, and use the standard deviation from this group to normalize standard deviations of other groups. However, we had two types of interactions (tangible and gestural) that contributed to the overall work done by a group. We quantified tangible actions in terms of discrete pick-up and placement actions performed by a group member. Furthermore, gestural actions in our games were of two types – swipe and grab. We quantified swipe actions (block swipe) like tangible actions, i.e. using discrete swipe (left/right) actions, and grab actions (furniture finder, block grab) in terms of the total duration for which a grab action was performed by a member of the group.

To assess work distribution, we considered a hypothetical group where one member performed all tangible and gestural interactions. Standard deviations from that group were then calculated, and normalized. We consider a normalized standard deviation (NSD) from the hypothetical group that is between 0.0 and 1.0 to indicate the range of equality of work distribution among group members, with a score of 0.0 indicating perfectly equal distribution of the specific aspect of work and 1.00 indicating that one group member performed all interactions.

Table 8 summarizes the means and the standard deviations from the normalized standard deviation dataset for FF and BR. In Furniture Finder, there is moderate work distribution for tangible interaction, and more equal distribution of gestural interaction. In Block Rock, there is almost equal work distribution for both tangible and gestural interactions.

| Game | Interaction | Mean(SD) |
|---|---|---|
| **FF** | Tangible | 0.456(0.276) |
|  | Gestural | 0.259(0.200) |
| **BR** | Tangible | 0.346(0.242) |
|  | Gestural | 0.333(0.219) |

**Table 8: Means and the standard deviations from the normalized standard deviation dataset for FF and BR. (FF: Furniture Finder, BR: Block Rock)**

### 5.1.3 Impact of Game Type on Territorial Infringement

In our system, the tangibles required for each game were placed around the tabletop, which was housed in an aluminum frame. This frame provided a storage space for the tangibles as shown in Figure 22. For our system, territorial infringement is when participant in a group takes a tangible, which is closer to another participant. Ryall et al [10] studied the impact of group size and tabletop size on collaboration around tabletop. One of the key findings reported was the reluctance of participants to take a resource, which is closer to another participant in the group. In another study, Scott et al [16] studied territoriality in collaborative tabletop workspace. To better understand participant's interactions around tabletop, the tabletop area was divided into zones. Drawing inspiration from [10,16], we investigate territorial infringement in our multimodal setup. It helps us to investigate how does the addition of a vertical wall display affects territorial infringement behavior in participants playing together in multimodal configuration (gestural and tangible).

The tabletop was housed in a custom built aluminium frame. The frame provide space around the edges of the tabletop, which was used to as storage space for tangibles. We divided the storage space on the tabletop into four zones: – North, East, West and South as shown in Figure 22. We placed the Kinect in the North zone of the setup. South Zone been directly in front of the Kinect, had an overlap of both tangible interaction and gestural interaction. We observed that more than one participant occupied the South zone in most groups. Hence, we sub divide the South Zone into three sub zones: South East (SE), South Center (SC) and South West (SW) as shown in Figure 22.

**(a)** **(b)**

**Figure 22. (a) Storage Space Zones and (b) All participants in a group occupying the South zone while playing Furniture Finder**

As per our system setup, the gesture controller was always required to stand in the tracking zone of the Kinect, which was the South Zone. The designated gesture controller stood in front of the Kinect. The other participant(s) responsible for placing tangibles stood on either side(s) of the gesture controller or in the adjacent East and West zones. We recorded the instances wherein participants infringed into another's participants space to get a tangible (i.e. when a participant grabbed a tangible, which was closer to another participant). Each instance of infringement recorded was marked as either been performed by gesture controller or by tangible placer. Now, during gameplay, participants interchangeably took the role of gesture controller and tangible placer. An infringement marked as been performed by gesture controller indicates the participant performing both tangible and gestural interaction at that moment. To compensate for the additional participant in triads, we normalized the infringements made by tangible placer(s) by dividing them by two.

We conducted a paired-samples t-test to test the impact of game type on infringement made by tangible placer and gesture controller. There was a statistically significant difference between in infringements made by tangible placer and gesture controller in both FF ($p<0.005$) and BR ($p=0.030$). Table 9 shows the mean and standard deviation by tangible placer and gesture controller in Furniture Finder and Block Rock games.

| Game | Role | Mean (SD) | p-value |
|---|---|---|---|
| **FF** | Tangible Placer | 2.69(0.932) | **0.000** |
| | Gesture Controller | 0.80(0.759) | |
| **BR** | Tangible Placer | 4.09(1.067) | **0.030** |
| | Gesture Controller | 3.60(1.193) | |

**Table 9. Means and the standard deviations for the normalized territorial infringement occurrences for FF and BR made by Tangible Placer and Gesture Controller (FF: Furniture Finder, BR: Block Rock).**

### 5.1.4 Impact of Game Type on Communication

We used Pinelle et al [8], mechanics of Collaboration framework, to classify the different types of communication as listed in Table 3. Verbal communication included explicit forms of communication such as conversation communication, verbal shadowing, deictic references and gestural messages. Explicit communication mostly consisted of participants talking among themselves about the game, directing others, requesting to perform certain actions. Verbal shadowing was done by participants by announcing the actions they were about to perform. For example, participants would say, P32: "*I think this block goes here*", P89: "*I will now rotate it*" etc. Non-verbal communication served as an implicit form of communication. Non-verbal communication consisted of basic awareness, visual evidence and attention to feedback. According to Dourish et al. [17] awareness is, *"an understanding of the activities of others, which provides a context of your own activity"*. Basic awareness was when participants observed each other actions, position and movement around the tabletop. Visual evidence is participants observing the results of other participant's actions during gameplay. For example, in Furniture Finder game, participant controlling the gesture would keep the 3D box open until the tangible was placed by the other participant(s) and then moved along to open another box. The feedback provided on the tabletop made displayed the results of participants' actions. While the system provided audio feedback to participants, we observed participants checking message board, which displayed if a tangible was placed correctly or not.

In terms of explicit communication, participants relied on conversational communication for both FF (42.37%), while in BR conversational communication (39.33%) and verbal shadowing (36.07%) were mostly used. In terms of non-verbal communication (quantified under Information gathering in Pinelle et.al [8] framework) visual evidence was mostly used in both FF (43.84%) and BR (37.16%). Furthermore, in terms of basic awareness, participants exhibited almost same level of awareness in both FF (30.25%) and BR (30.03%).

### 5.1.5 Impact of Game Type on Completion time

We conducted a paired-samples t-test to test the impact of game completion time. There was a statistically significant difference between game completion time for FF(M=167.74) and BR (M=104.71) ($p<0.005$). While both games involved approximately the same number of tangibles, this difference was not unexpected, as FF required sequential coordinated game play (i.e., the uncovering and placement of one piece of furniture at a time), whereas BR permitted parallel independent play and *ad hoc* coordination.

## 5.2 Orientation Control

We compare the Block Rock Swipe (BR-S) and Block Rock Grab (BR-G) games. The BR-S afforded discrete canonical orientation of the 3D model while BR-G afforded continuous rotation of the 3D model. In the following section, we consider the impact of orientation control on gameplay strategy adoption, participation equality, territorial infringement and completion time.

### 5.2.1 Impact of Orientation Control on Gameplay Strategy Adoption

We observed more parallel play in BR-S as compared to BR-G, wherein each using participant used gestures to manipulate the model on the wall display and placed tangibles. We observed that Strategy 2 was mostly adopted in both BR-S (44.48%) and BR-G (53%), with one gesture controller and other participant(s) placing tangibles. Strategy 4 was more prevalent in BR-S, while Strategy 3 was more prevalent in BR-G.

We conducted a paired-samples t-test to test the impact of orientation control on gameplay strategy adoption. There was a statistically significant difference between in adoption of gameplay strategies 3 and 4 across the two games. Strategy 3 was adopted significantly more in Block Rock with Grab while Strategy 4 was adopted significantly more in Block Rock with Swipe. Table 10 summarizes the mean and standard deviations of gameplay strategies adoption across BR-S and BR-G.

| **Strategy** | **BR-S Mean (SD)** | **BR - G Mean (SD)** | **p value** |
|---|---|---|---|
| **1** | 14.28(19.35) | 10.79(21.64) | 0.520 |
| **2** | 43.49(52.06) | 52.06(30.93) | 0.266 |
| **3** | 6.98(17.89) | 29.52(27.34) | **0.000** |
| **4** | 35.23(31.36) | 7.61(14.20) | **0.000** |

**Table 10. Means and the standard deviations of gameplay strategies adopted for BR-S and BR-G (BR-S: Block Rock with Swipe, BR- G: Block Rock with Grab).**

In Block Rock Swipe, most groups (18/35) adopted a "parallel play" approach with each player rotating the model using the swipe gesture and placing tangibles. Other groups divided responsibilities, having a player designated to perform gestural control (12/35), or took turns, with one player at a time rotating the model and placing tangibles (5/35). Strategy 2 was mostly adopted by groups, followed by Strategy 3. The "parallel play strategy" adopted in most of the groups, had two variations. First variation was when participants would work in parallel without much communication between them. They worked independently of each other. The other variation observed was that participants though working in parallel, made each other aware of their own actions. They did this by saying out loud the actions they were performing such as, P31: "*I think this goes here*", P54: "*This block goes here*" etc. Also, participants would observe each other of what they were doing. A common behaviour observed across all groups was when participants swiped to get to the front view after they initially had rotated it. It is important to note that the in our system the Kinect detected gestures only made by one participant. This game had no visual indicator such as the virtual hand which is available in grab based games. Thus, we observed instances of more than one participant performing the swipe gesture. However, when participants still had issues with tracking, we observed they took stopped and took stock of the situation. For example, in group 33, participants had decided p86 would be the gesture controller. However, at start of the game, they did not know who was in control of gesture, so all of them swiped. P85 stopped swiping and asked p87 to stop swiping as well saying, "*He is supposed to be the swiper*" and held p87's hand put it down to stop her from swiping. Then only p86 tried, while p85 and p87 moved to the sides of the table, and got control of the gestures. After that only p87 swiped as directed by p85 and p87.

In Block Rock Grab, we observed two variations of adoption of Strategy 4 in Block Rock with Grab game. In one variation, the designated gesture controller, rotated the 3D model to get a bird's eye view. Then he/she would start placing tangibles along with the other participant. Thus, the gesture controller held the 3D model with one hand (by performing the grab gesture) while placing tangibles with the other hand. It is important to note that the gesture controller held on the 3D handle for the entire duration of the game and kept it in the required view. A variation to this strategy was that the gesture controller would rotate the 3D model to a desired view. Then would let go of the 3D handle and start placing the tangibles along with the other participant(s). If the model accidentally moved, the participant(s) placing tangibles would ask the gesture controller to focus on it saying, for example, P33: "*You are moving it*", P8: "*That's your job*" etc. For example, in group 14, P31 rotated the 3D model to get a bird's eye view. P31 then let go of the model and started placing tangibles. However, in the process she flipped the model upside over by accidentally rotating the model. Her partner, P32 asked P31 to focus only on gesture. P32 again rotated the model to get a bird's eye view. After this P31 asked P32 to keep both of her hands in the same position and did not move while P31 placed the tangibles. So, for the rest of the game

P31 kept her both hands open, palms facing out near her chest, to avoid accidentally moving the model again.

### 5.2.2 Impact of Orientation Control on Participation Equality

In BR-S, we observed that both tangible and gestural interactions were more equally distributed. In BR-G, tangible interactions were more moderately distributed as compared to gestural interactions. Table 11 summarizes the means and the standard deviations from the normalized standard deviation dataset for BR-S and BR-G.

| Game | Interaction | Mean(SD) |
|---|---|---|
| **BR-S** | Tangible | 0.289(0.227) |
| | Gestural | 0.372(0.232) |
| **BR-G** | Tangible | 0.374(0.237) |
| | Gestural | 0.532(0.345) |

**Table 11. Means and the standard deviations from the normalized standard deviation dataset for BR-S and BR-G. (BR-S: Block Rock Swipe and BR-G: Block Rock Grab)**

### 5.2.3 Impact of Orientation Control on Territorial Infringement

We conducted a paired-samples t-test to test the impact of game on infringement made by tangible placer and gesture controller. There was a statistically significant difference in infringements made by tangible placer and gesture controller in both BR-S ($p<0.005$) and BR-G ($p<0.005$). Table 12 shows the mean and standard deviations of territorial infringement by tangible placer and gesture controller in the BR-S and BR-G.

| Game | Role | Mean (SD) | p-value |
|---|---|---|---|
| **BR-S** | Tangible Placer | 1.74(0.701) | **0.000** |
| | Gesture Controller | 2.46(0.980) | |

|  |  |  |  |
|---|---|---|---|
| **BR-G** | Tangible Placer | 2.34(0.725) | **0.000** |
|  | Gesture Controller | 1.14(0.692) |  |

**Table 12. Means and the standard deviations for the normalized territorial infringement occurrences for BR-S and BR-G made by TP and GC. (BR-S: Block Rock Swipe and BR-G: Block Rock Grab, TP: Tangible Placer, GC: Gesture Controller)**

### 5.2.4 Impact of Game Type on Communication

In both BR-S and BR-G, conversational communication and verbal shadowing were most commonly used. In BR-S, conversational communication (38.27%) and verbal shadowing (38.19%) were almost equally used. In BR-G, conversational communication (40.38 %) was used more as compared to verbal shadowing (33.95%). We observed was that participants when working in parallel, made each other aware of their own actions. They did this by saying out loud the actions they were performing such as, P31: "*I think this goes here*", P54: "*This block goes here*" etc.

### 5.2.5 Impact of Orientation Control on Completion Time

We conducted a paired-samples t-test to test the impact of game completion time. There was a statistically significant difference between game completion time for BR-S (M=117.85 sec) and BR-G (M=91.57 sec) (p=0.028).

## 5.3 Group Size

For this analysis, we consider only Formal Operational age group. This is because we have a balanced number of groups for comparison in Formal Operational age group (9 dyads vs 6 triads) as compared to Concrete Operational age group (4 dyads vs 16 triads).

### 5.3.1 Impact of Group Size on Gameplay Strategy Adoption

In FF, most of dyads and triads divided responsibilities, one player uncovering furniture using the gestural interface, and the other(s) placing furniture on the tabletop. We saw evidence of more defined division of roles in triads than in dyads in the BR games, with 4/6 in BR-G and 3/6 in BR-S strictly dividing between model rotation and tangible placement roles (vs. 3/9 and 1/9 for dyads, respectively). Finally, we see some turn taking in dyads (2 cases in FF, 2 cases in BR-S), but none in triads. In Furniture Finder Strategy 2 is more prevalent in dyads as compared to triads. In Block rock with Grab, Strategy 1 is more adopted in dyads as compared to triads. In Block Rock with Swipe, Strategy 4 is more prevalent in dyads. The normalized distribution of gameplay strategies adopted across the three games by dyads and triads is summarized in Table 13.

| **Strategy** | **FF** | | **BR-S** | | **BR-G** | |
|---|---|---|---|---|---|---|
| | **Dyad** | **Triad** | **Dyad** | **Triad** | **Dyad** | **Triad** |
| **1** | 3.33 | 5.00 | 1.22 | 1.17 | 0.11 | 1.50 |
| **2** | 6.00 | 4.50 | 2.11 | 3.17 | 4.78 | 4.33 |
| **3** | 0.67 | 0.50 | 0.22 | 0.67 | 3.78 | 0.50 |
| **4** | 0.11 | 0.67 | 4.78 | 3.17 | 0.33 | 0.33 |
| **5** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table 13: Normalized distribution of gameplay strategies for dyads and triads for the three games (FF: Furniture Finder, BR-S: Block Rock Swipe and BR-G: Block Rock Grab)**

We compared the percentage of gameplay strategies adopted by dyads and triads across the three games: FF, BR-S and BR-G, using one – way ANOVA. We found that there was a statistically significant difference in dyads and triads in BR-G for strategy 1. Triads adopted strategy 1 significantly higher as compared to dyads. Furthermore, in FF, strategy 4 was more prevalent in triads as compared to dyads, but the difference is not significant (p=0.070), while in BR- S, strategy 3 was adopted more in triads as compared to dyads, but again the difference is not significant (p=0.071). Table summarizes the mean and SD for gameplay strategies adoption across dyads and triads.

| **Game** | **Strategy** | **Dyads Mean(SD)** | **Triads Mean (SD)** | **Comparison** |
|---|---|---|---|---|
| **Furniture Finder** | 1 | 25.55 (43.33) | 46.66(33.26) | F (1,13) = 1.015, p = 0.332 |
| | 2 | 60.00(35.70) | 33.33(26.58) | F (1,13) = 0.2423, p =0.144 |
| | 3 | 6.66(8.66) | 11.66(11.69) | F (1,13) = 0.912, p= 0.357 |
| | 4 | 0.00(0.00) | 3.33(5.16) | *F (1,13) = 3.900, p= 0.070* |
| **Block Rock Swipe** | 1 | 13.58(22.75) | 12.96(12.98) | F (1,13) = 0.004, p=0.953 |
| | 2 | 23.45(18.79) | 24.07(34.00) | F (1,13) = 0.002, p=0.964 |
| | 3 | 0.00(0.00) | 20.37(31.75) | *F (1,13) = 3.852, p=0.071* |
| | 4 | 62.96(16.66) | 42.59(45.76) | F (1,13) = 1.530, p=0.238 |
| **Block Rock Grab** | 1 | 1.23(3.70) | 18.51(21.84) | **F (1,13) = 5.600, p=0.034** |
| | 2 | 50.61(29.97) | 61.11(23.04) | F (1,13) = 0.524, p =0.482 |
| | 3 | 45.67(28.02) | 20.37(24.76) | F (1,13) = 3.207, p =0.97 |
| | 4 | 2.46(4.89) | 0.00(0.00) | F (1,13) = 1.486, p=0.245 |

**Table 14. Means and the standard deviations of gameplay strategies adopted for FF, BR-S and BR-G by dyads and triads across the three games.**

### 5.3.2 Impact of Group Size on Participation Equality

We compared the means between the two group sizes using a one-way ANOVA. The ANOVA indicates that there was a statistically significant difference between tangible work distribution in Furniture Finder (p=0.020). In triads, there are more equal participation for tangible placements while in dyads there was unequal participation. Table 15 summarizes the mean and standard deviation of work distribution for dyads and triads across the three games.

| **Game** | **Work** | **Dyads Mean(SD)** | **Triads Mean (SD)** | **Comparison** |
|---|---|---|---|---|
| **FF** | Tangible | 0.6801(0.3359) | 0.3001(0.1207) | **F (1,13) =6.956; p =0.020** |
| | Gestural | 0.3851(0.2794) | 0.2017(0.1123) | F (1,13) = 2.289; p=0.154 |
| **BR-S** | Tangible | 0.3835(0.2709) | 0.3513(0.3436) | F (1,13) = 0.41; p=0.842 |
| | Gestural | 0.4055(0.3232) | 0.3205(0.2498) | F (1,13) = 0.294; p=0.597 |
| **BR-G** | Tangible | 0.2011(0.1381) | 0.1968(0.1221) | F (1,13) =0.004; p=0.952 |
| | Gestural | 0.3739(0.3369) | 0.2694(0.1117) | F (1,13) =0.527; p=0.481 |

**Table 15. Means and the standard deviations from the normalized standard deviation dataset, for dyads and triads (FF: Furniture Finder, BR-S: Block Rock Swipe, BR-G: Block Rock Grab).**

### 5.3.3 Impact of Group Size on Territorial Infringement

We conducted a paired-samples t-test to test the impact of group size on infringement made by tangible placer and gesture controller and each role (i.e. tangible placer and gesture controller). There was a statistically significant difference between in infringements made by tangible placer and gesture controller in FF and BR-G. In BR-S there was marginally significant difference in the infringement done by tangible placer and gesture controller in triads as summarized in Table 16. Furthermore, there was statistically significant difference in infringement done by tangible placer in FF. There was statistical difference in BR-S and marginally significant difference in BR-G for infringement by gesture controller. Table 17 summarizes the mean and standard deviations of territorial infringement across dyads and triads for the three games.

| Game | Group Size | Role | Mean (SD) | p-value |
|---|---|---|---|---|
| **FF** | Dyads | Tangible Placer | 3.33(0.500) | **0.000** |
| | | Gesture Controller | 0.56(0.726) | |
| | Triads | Tangible Placer | 6.17(0.753) | **0.001** |
| | | Gesture Controller | 2.50(0.837) | |
| **BR-S** | Dyads | Tangible Placer | 1.78(0.441) | 0.426 |
| | | Gesture Controller | 1.89(0.601) | |
| | Triads | Tangible Placer | 4.00(1.09) | **0.059** |
| | | Gesture Controller | 6.50(1.76) | |
| **BR-G** | Dyads | Tangible Placer | 3.00(0.500) | **0.000** |
| | | Gesture Controller | 0.78(0.667) | |
| | Triads | Tangible Placer | 5.17(1.329) | 0.12 |
| | | Gesture Controller | 3.17(1.417) | |

**Table 16. Means and the standard deviations for the normalized territorial infringement occurrences for dyads and triads (FF: Furniture Finder, BR-S: Block Rock Swipe and BR-G: Block Rock Grab)**

| Game | Infringement | Dyads Mean(SD) | Triads Mean (SD) | p-value |
|---|---|---|---|---|
| **FF** | Tangible Placer | 3.33(0.500) | 6.17(0.753) | **0.043** |
| | Gesture Controller | 0.56(0.726) | 2.50(0.837) | 0.292 |
| **BR-S** | Tangible Placer | 1.78(0.441) | 4.00(1.09) | 0.089 |
| | Gesture Controller | 1.89(0.601) | 6.50(1.76) | **0.005** |
| **BR-G** | Tangible Placer | 3.00(0.500) | 5.17(1.329) | 0.132 |
| | Gesture Controller | 0.78(0.667) | 3.17(1.417) | ***0.058*** |

**Table 17. Means and the standard deviations for the normalized territorial infringement occurrences for FF, BR-S and BR-G for dyads and triads. (FF: Furniture Finder-S: Block Rock Swipe and BR-G: Block Rock Grab)**

### 5.3.4 Impact of Group Size on Communication

We compared the means of both explicit communication and implicit communication (information gathering) between the two group sizes using a one-way ANOVA. The ANOVA indicates that there are significant differences in visual evidence across dyads (M=11.09, SD=9.32) and triads (M=46.27, SD = 16.53) and basic awareness in dyads (M=47.641, SD=19.314) and triads (M = 24.348, SD=7.668)) in the BR-S game. In Furniture Finder, verbal shadowing was done more by triads as compared to dyads (p=0.083). Though this is not statistically significant, it worth considering for further exploration. Table 18 and 19 summarize the means and standard deviations for verbal and nonverbal communication for dyads and triads.

| Game | Communication | Dyads Mean(SD) | Triads Mean (SD) | Comparison |
|---|---|---|---|---|
| FF | Conversational Communication | 46.769(21.953) | 49.245(13.291) | F (1,13) = 0.61; p=0.809 |
| | Verbal Shadowing | 20.786(17.474) | 36.068(11.429) | F (1,13) = 3.531; p=0.083 |
| | Deictic Reference | 32.444(28.206) | 14.270(9.152) | F (1,13) = 2.279; p=0.155 |
| BR-G | Conversational Communication | 48.101(29.560) | 37.967(16.822) | F (1,13) =0.572; p=0.463 |
| | Verbal Shadowing | 21.921(33.240) | 39.341(22.993) | F (1,13) =1.237; p=0.286 |
| | Deictic Reference | 18.865(16.307) | 22.691(21.537) | F (1,13) =0.154; p=0.701 |
| BR-S | Conversational Communication | 39.618(25.659) | 37.143(6.040) | F (1,13) = 0.053; p=0.822 |
| | Verbal Shadowing | 39.675(15.400) | 45.722(14.290) | F (1,13) = 0.586; p=0.458 |
| | Deictic Reference | 20.706(16.148) | 17.134(13.061) | F (1,13) = 0.212; p=0.653 |

**Table 18. Means and the standard deviations for verbal communication for dyads and triads across the three games.**

| Game | Communication | Dyads Mean(SD) | Triads Mean (SD) | Comparison |
|---|---|---|---|---|
| **FF** | Basic Awareness | 18.307(18.86) | 37.178(12.23) | F (1,13) = 2.723; p =0.123 |
| | Feedthrough | 34.972(26.716) | 19.993(8.205) | F (1,13) = 1.736; p=0.210 |
| | Visual Evidence | 45.899(15.353) | 42.828(5.029) | F (1,13) =0.219; p=0.647 |
| **BR-G** | Basic Awareness | 29.018(15.401) | 29.918(9.750) | F (1,13) =0.13; p=0.901 |
| | Feedthrough | 32.416(26.968) | 24.288(14.284) | F (1,13) =0.452; p=0.513 |
| | Visual Evidence | 31.155(31.541) | 45.7933(17.330) | F (1,13) =1.060; p=0.322 |
| **BR-S** | Basic Awareness | 47.641(19.314) | 24.348(7.668) | **F (1,13) =7.745; p=0.016** |
| | Feedthrough | 34.967(15.105) | 26.878(11.658) | F (1,13) =1.223; p=0.289 |
| | Visual Evidence | 11.094(9.325) | 46.271(16.531) | **F (1,13) =28.083; p=0.000** |

**Table 19. Means and the standard deviations for nonverbal communication for dyads and triads across the three games (FF: Furniture Finder, BR-G: Block Rock Grab, BR-S: Block Rock Grab).**

### 5.3.5 Impact of Group Size on Completion Time

We compared the completion times of both dyads and triads across the three games. There were no statistically significant differences between the completion times for both group sizes across the three games as summarized in Table 20.

| Game | Dyads | Triads | p- value |
|---|---|---|---|
| Furniture Finder | 140.11(55.339) | 158.67(97.920) | 0.645 |
| Block Rock - Grab | 111.78(104.820) | 73.83(33.630) | 0.411 |
| Block Rock - Swipe | 125.00(58.737) | 79.83(32.171) | 0.112 |

**Table 20. Mean (SD) time (secs) for dyads and triads**

## 5.4 Age Range

For this analysis, we consider only triads. This is because we have a balanced number of triads in the two age groups (16 in Concrete Operational(CO) vs 6 in Formal Operational(FO)) as compared to dyads (4 in Concrete Operational(CO)vs 9 in Formal Operational(FO)).

### 5.4.1 Impact of Age Range on Gameplay Strategy Adoption

As compared to the CO, we observed that FO were more focused on completing the game in the allocated time. Participants often referred to the countdown timer and reminded their group members the amount of time they had left. We find no distinct differences between CO and FO triads for FF. We see evidence of more parallel play in FO than in CO triads for BR: in BR-G we see 4/13 cases where interaction roles were strict in CO vs. 0/6 in FO, and in BR-S 13/16 CO triads divided responsibilities or took turns vs 3/6 FO. In FF Strategy 1 is more prevalent in FO while Strategy 2 is more common in CO. In BR-G, Strategy 2 is more prevalent in FO while Strategy 3 is more common in CO. In BR-S, Strategy 4 is more prevalent in FO while Strategy 2 is more common in CO.

| **Strategy** | **FF** | | **BR-S** | | **BR-G** | |
|---|---|---|---|---|---|---|
| | **CO** | **FO** | **CO** | **FO** | **CO** | **FO** |
| **1** | 2.75 | 5.00 | 1.25 | 1.17 | 1.38 | 1.67 |
| **2** | 6.06 | 4.33 | 5.56 | 3.17 | 4.06 | 4.50 |
| **3** | 1.06 | 0.67 | 0.25 | 1.17 | 2.69 | 0.50 |
| **4** | 0.13 | 0.50 | 1.38 | 3.17 | 0.44 | 0.17 |
| **5** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table 21: Normalized distribution of gameplay strategies for CO and FO (FF: Furniture BR-S: Block Rock Swipe and BR-G: Block Rock Grab)**

We compared the percentage of gameplay strategies adopted by CO (7-11 years) and FO (12+ years) across the three games: FF, BR-S and BR-G, using one – way ANOVA. We found that there was a statistically significant difference in the two age groups in BR-S for strategy 2 (p=0.005). CO (7-11 years) age group adopted strategy 2 significantly higher as compared to FO (12+ years). Furthermore, strategy 4 was marginally significant in FO as compared to CO age group (p=0.055) in BR- S. Table 22 summarizes the mean and SD for gameplay strategies adoption across CO and FO age groups.

| **Game** | **Strategy** | **CO (7-11 years) Mean(SD)** | **FO (12+ years) Mean (SD)** | **Comparison** |
|---|---|---|---|---|
| **FF** | 1 | 23.75(21.25) | 46.66(33.26) | F (1,20) = 3.724, p=0.68 |
| | 2 | 62.50(20.81) | 33.33(26.58) | F (1,20) = 7.400, p=0.13 |
| | 3 | 6.25(12.58) | 11.66(11.69) | F (1,20) = 0.837, p=0.371 |
| | 4 | 1.87(4.03) | 3.33(5.16) | F (1,20) = 0.492, p=0.491 |
| **BR-S** | 1 | 13.88(14.34) | 12.96(12.98) | F (1,20) = 0.19, p=0.892 |
| | 2 | 62.50(21.42) | 24.07(34.00) | **F (1,20) = 10.175, p=0.005** |
| | 3 | 7.63(16.58) | 20.37(31.75) | F (1,20) = 1.543, p=0.229 |
| | 4 | 15.97(17.19) | 42.59(45.76) | **F (1,20) = 4.148, p=0.055** |
| **BR-G** | 1 | 15.27(27.77) | 18.51(21.84) | F (1,20) = 0.066, p=0.800 |
| | 2 | 48.61(32.42) | 61.11(23.04) | F (1,20) = 0.400, p=0.400 |
| | 3 | 22.22(21.46) | 20.37(24.76) | F (1,20) = 0.30, p=0.864 |
| | 4 | 13.88(18.81) | 0.00(0.00) | F (1,20) = 3.171, p=0.090 |

**Table 22: Means and standard deviation of gameplay strategies for CO and FO (Furniture BR-S: Block Rock Swipe and BR-G: Block Rock Grab)**

### 5.4.2 Impact of Age Range on Participation Equality

We compared the means between the two age ranges using a one-way ANOVA. The ANOVA indicates that there are no significant differences in work distribution across CO and FO across the three games.

| Game | Work | CO (7-11) Mean(SD) | FO (12+) Mean (SD) | Comparison |
|---|---|---|---|---|
| FF | Tangible | 0.4464(0.2317) | 0.3001(0.1207) | F (1,20) = 2.126; p=0.160 |
| | Gestural | 0.2171(0.1484) | 0.2017(0.1123) | F (1,20) = 0.532; p=0.820 |
| BR-G | Tangible | 0.4150(0.2712) | 0.3513(0.3436) | F (1,20) =0.209; p=0.652 |
| | Gestural | 0.1725(0.1545) | 0.3205(0.2498) | F (1,20) =2.852; p=0.107 |
| BR-S | Tangible | 0.3865(0.2829) | 0.1968(0.1221) | F (1,20) =2.461; p=0.132 |
| | Gestural | 0.4050(0.1919) | 0.2694(0.1117) | F (1,20) =2.606; p=0.122 |

**Table 23. Means and the standard deviations from the normalized standard deviation dataset, for Concrete Operational and Formal Operational age groups.**

### 5.4.3 Impact of Age Range on Territorial Infringement

We conducted a paired-samples t-test to test the impact of age range on infringement made by tangible placer and gesture controller and each role (i.e. tangible placer and gesture controller). Both CO and FO groups show more territorial infringement by tangible placer as compared to gesture controller in FF, with the FO groups showing more overall. In BR-S there was a marginally significant (p=.059) increase in territorial infringements by gesture controller for the FO groups, but not the CO groups, with the FO groups again showing more infringement overall. In BR-G, there was no significant difference in CO and FO for infringement by both tangible placer and gesture controller. Furthermore, in FO group there is more infringement by tangible placer(s) in FF and BR-G, while in BR-S, FO have more infringement by gesture controller as compared to CO group.

| Game | Age Range | Role | Mean (SD) | p-value |
|---|---|---|---|---|
| **FF** | CO | Tangible Placer | 2.31(0.873) | **0.000** |
| | | Gesture Controller | 0.94(0.574) | |
| | FO | Tangible Placer | 6.17(0.753) | **0.001** |
| | | Gesture Controller | 2.50(0.837) | |
| **BR-S** | CO | Tangible Placer | 1.50(0.730) | 0.16 |
| | | Gesture Controller | 2.44(1.459) | |
| | FO | Tangible Placer | 4.00(1.09) | *0.059* |
| | | Gesture Controller | 6.50(1.76) | |
| **BR-G** | CO | Tangible Placer | 1.94(1.81) | 0.18 |
| | | Gesture Controller | 1.19(0.750) | |
| | FO | Tangible Placer | 5.17(1.329) | 0.12 |
| | | Gesture Controller | 3.17(1.417) | |

**Table 24. Means and the standard deviations for the normalized territorial infringement occurrences for CO and FO made (FF: Furniture Finder, BR-S: Block Rock Swipe and BR-G: Block Rock Grab)**

| **Game** | **Infringement** | **CO<br>(7-11 years)<br>Mean(SD)** | **FO<br>(12+ years)<br>Mean (SD)** | **p-value** |
|---|---|---|---|---|
| FF | Tangible Placer | 2.31(0.873) | 6.17(0.753) | **0.004** |
|  | Gesture Controller | 0.94(0.574) | 2.50(0.837) | 0.19 |
| BR-S | Tangible Placer | 1.50(0.730) | 4.00(1.09) | 0.072 |
|  | Gesture Controller | 2.44(1.459) | 6.50(1.76) | **0.000** |
| BR-G | Tangible Placer | 1.94(1.81) | 5.17(1.329) | **0.021** |
|  | Gesture Controller | 1.19(0.750 | 3.17(1.417) | 0.23 |

**Table 25. Means and the standard deviations for the normalized territorial infringement occurrences for CO and FO (FF: Furniture Finder, BR-S: Block Rock Swipe and BR-G: Block Rock Grab)**

### 5.4.4 Impact of Age Range on Communication

We compared the means of both explicit communication and implicit communication (information gathering) between the two group sizes using a one-way ANOVA. The ANOVA indicates that there are no significant differences in communication across CO and FO across the three games.

| Game | Work | CO<br>(7-11 years)<br>Mean(SD) | FO<br>(12+ years)<br>Mean (SD) | Comparison |
|---|---|---|---|---|
| FF | Conversational Communication | 39.518(12.838) | 49.245(13.291) | F (1,20) = 2.461; p=0.132 |
|  | Verbal Shadowing | 33.524(6.890) | 36.068(11.429) | F (1,20) = 0.414; p=0.527 |
|  | Deictic Reference | 26.956(13.909) | 14.270(9.152) | F (1,20) = 4.229; p=0.53 |
| BR-G | Conversational Communication | 40.295(20.475) | 37.967(16.822) | F (1,20) =0.061; p=0.807 |
|  | Verbal Shadowing | 41.607(21.239) | 39.341(22.993) | F (1,20) =0.048; p=0.830 |
|  | Deictic Reference | 18.097(15.408) | 22.691(21.537) | F (1,20) =0.313; p=0.582 |

|  |  |  |  |  |
|---|---|---|---|---|
| BR-S | Conversational Communication | 40.509(14.920) | 37.143(6.040) | F (1,20) = 0.218; p=0.602 |
|  | Verbal Shadowing | 37.898(15.650) | 45.722(14.290) | F (1,20) = 1.138; p=0.299 |
|  | Deictic Reference | 21.594(13.582) | 17.134(13.061) | F (1,20) = 497; p=0.489 |

**Table 26. Means and the standard deviations for verbal communication for CO and FO age groups across the three games.**

| Game | Communication | CO (7-11 years) Mean(SD) | FO (12+ years) Mean (SD) | Comparison |
|---|---|---|---|---|
| FF | Basic Awareness | 31.148(5.138) | 37.178(12.23) | F (1,20) = 1.040; p=0.320 |
|  | Feedthrough | 25.439(7.981) | 19.993(8.205) | F (1,20) = 0.440; p=0.182 |
|  | Visual Evidence | 43.414(9.784) | 42.828(5.029) | F (1,20) = 0.223; p=0.883 |
| BR-G | Basic Awareness | 28.901(15.965) | 29.918(9.750) | F (1,20) = 0.212; p=0.886 |
|  | Feedthrough | 33.499(21.300) | 24.288(14.284) | F (1,20) = 0.946; p=0.342 |
|  | Visual Evidence | 37.031(18.355) | 45.7933(17.330) | F (1,20) = 1.022; p = 0.324 |
| BR-S | Basic Awareness | 29.558 (12.410) | 24.348(7.668) | F (1,20) = 0.910; p = 0.352 |
|  | Feedthrough | 29.977(14.156) | 26.878(11.658) | F (1,20) = 0.227; p = 0.639 |
|  | Visual Evidence | 39.965(11.236) | 46.271(16.531) | F (1,20) =1.065; p = 0.314 |

**Table 27. Means and the standard deviations for nonverbal communication for dyads and triads across the three games.**

### 5.4.4.1 Breakdown in communication

We observed an instance of breakdown in communication in a triad (participants in Concrete Operational Stage) while the group was playing the Furniture Finder game. At start of the game P55 and P56 both performed the grab gesture concurrently, while p57 stood on the side. P56 was in control of gesture and he opened a box. P55 then placed the tangible. They did for 2 more tangibles. At this point p57 said that he did not get to go anything yet. So P55 asked p56 to stop performing the gesture. P56 however continue to perform the grab gesture. To stop him, P56 moved closer to P57 and performed the grab gesture and again asked P55 to stop performing the gesture. While doing so P56 got pushed a little by P55. P56 got visibly upset and said, "*Hey stop pushing I am just trying to grab the box*" and then moved to the side of the tabletop. P56 then decided to not the play anymore. P55 and P57 completed the Furniture Finder game. For the next two Block Rock games, P56 came back but P55 left the game. Thus, only P56 and P57 played the block rock games.

### 5.4.5 Impact of Age Range on Completion Time

We compared the completion times of both CO and FO across the three games. There were no statistically significant differences between the completion times for both group sizes across the three games.

| **Game** | **CO (7-11)** | **FO (12+)** | **p-value** |
|---|---|---|---|
| Furniture Finder | 182.44(63.368) | 158.67(97.920) | 0.507 |
| Block Rock - Grab | 87.44(48.622) | 73.83(33.630) | 0.538 |
| Block Rock - Swipe | 126.75(70.880) | 79.83(32.171) | 0.138 |

**Table 28. Mean (SD) time (secs) for concrete and formal operational in triads**

## 5.5 Observed Behavior to Overcome Kinect Tracking Issues

We observed participants coordinated with each other to overcome tracking issues of Kinect. When it was not clear to participants as to who was in control of the gestures, participant communicated with each other to overcome the issue. This behaviour included participants putting both their hands on their sides and at their back. It became clear from observation that participants did this as they had the perception that hiding their hands from the tracking area would not detect their hands. Then each member in the group would perform the gesture to find out who was in control. Also, participants moved to the side of the tabletop (east or west zone) to stay out the tracking area while the other participant tried the gesture. Only the participant who was trying to perform the grab gesture would stay directly in front of the Kinect. Another observation was the participant who tried the gesture stood in front of the Kinect while the other two participants ducked down thus getting out of the tracking area. For example, group 30 had difficulty in figuring out who was in control during the gameplay in Furniture Finder game. To resolve this, participant followed different mechanisms. At start of the game, p77 grabbed p78's hand and put it down. He did this because p76 was performing the grab gesture at that time. Also at one point in the game when p78 was trying the grab gesture p77 also tried to grab. P78 asked to put his hand down saying, "*Quit distracting the thing, and just put your hand down*".

## 5.6 Interview Results

At the end of the game, all participants in every group to rate the system, their desire to win the game, what features they liked and disliked in the games, what changes they would like to see in the current system and what other games can be fun to play in this system setup.

### 5.6.1 Inverse correlation between age of participants and rating of the game.

Participants in formal operational age group (12+ years) gave lower rating to the overall experience of playing the games as compared to participants in concrete operational age group (7-11 years). We investigated the relationship between age and rating of game was using Pearson product-moment correlation coefficient. Preliminary analyses were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity. There was a strong, negative correlation between the two variables, $r = -0.317$, $n = 92$, $p = 0.002$, with higher rating associated with lower age. The main reason for participants giving a lower rating was that participants did not find the games challenging enough. They found them too easy to play and did not like the repetitive nature of the games, and the aspect of having to figure out who was in control of gestures. Some of the recommendations made by participants included adding more levels to the games to make them more challenging, giving less time to complete a game, introducing bonus level if game was completed in a certain time frame. As participant p19 said, "*Smaller time frame, so hurry more. If you take this game and apply it to whole console thing, then I would definitely play it many times. This is fairly simple so would get boring.*"

Participants giving a higher rating for the game stated that they liked to interact with the 3D model using just their hands and not needing a controller, also having the game setup as a puzzle, liked the 3D avatars on the screen, among some of the reasons. As participant p42 said, "*I really like it because you don't have to use any controllers, which needs batteries, because you need to look over the whole house for the batteries. You can just use your hands. And you are learning too.*" Also, participants stated they felt nostalgic playing with the tangibles specially the dollhouse furniture in the Furniture Finder game.

We also asked participants which games they though would be fun to play in this system. Though many games were suggested by participants, Minecraft was one game, which was commonly recommended by participants. A common idea stated by participants for Minecraft (n=11) was placing a block on the tabletop would introduce it in the virtual world on the wall display and then using gestures to manipulate the 3D object e.g. using smashing gesture to break the object. Many games were suggested by participants such as building blocks to build models, duck hunting, fishing, shooting etc. Participants' stated it that it would be fun to play these games without using a controller.

# CHAPTER 6 DISCUSSION

In this chapter, we present a discussion of our results. Firstly, we present a discussion of our experimental factors (game type, orientation control, age group size and age range) on gameplay strategy adoption, participation equality, territorial infringement, communication and game completion time. Secondly, we present our recommendation for the design of such systems. Thirdly we present limitations of our study and finally future work.

## 6.1 Interpretation of Results

Our main objective was to explore how do small groups of youths, playing together interact in a multimodal configuration (tangible and gestural). We designed two games and studied the impact of our experimental factors such as game type, orientation control, group size and age range on collaboration We identified five commonly observed strategies across all groups.

Hornecker et. al. [7] noted that embodied constraints, shared transaction space and access points, can be considered for defining game rules. These factors can be used to promote collaboration and limit individual play [7]. In our system, players around the tabletop had access to specific objects that could be used to achieve game's goals and objectives. Each object (e.g. tangibles) can be considered as an access point to the game. Accessibility to the game's objects increases the power of players and influences the way they play the game. In addition, the nature of accessibility rules creates a sense of competition or collaboration among players. For example, insufficient access points increase the sense of competition between players, while sufficient and simultaneous access points promote collaboration between players [7]. The sequential nature of Furniture Finder was designed to promote collaboration. In this game, only one box could be opened at a time to reveal the hidden furniture. Thus, the tangible placer had to wait for the gesture controller to open the box. In Block Rock games, the 3D model presented more information, as compared to Furniture

Finder, albeit limited to canonical orientations. In Block Rock Grab, viewing the model from bird's eye view, allowed participants to see position of all the blocks in the 3D model. However, getting the optimal view, required precision from the gesture controller. However, once the model was rotated to the desired view, tangible placer(s) could place tangibles without waiting for the gesture controller. As compared to grab based games (FF and BR-G), BR-S was designed to offer more scope parallel play since as opposed to grab based, switching views in the swipe game was comparatively easy.

Participants adopted different gameplay strategies. Our experimental factors such as game type, orientation control, group size had an impact on gameplay strategies adopted by participants. The most commonly observed strategy was Strategy 2 with one player performing gesture while the other(s) placed tangibles. When compared across game type, in Furniture Finder Strategy 1 was adopted significantly higher. Furniture Finder required frequent gesture control as only one box could be opened at a time. Also, some groups chose a turn taking approach. Each participant placed exactly half of the tangibles while the other participants waited for their turn. In the Block Rock games, participants could see more than one tangible at a time depending on their orientation of the 3D model. Thus, tangible placer(s) were less dependent on the gesture controller as compared to the Furniture Finder game. One of the factors identified by Yuill and Rogers [18] to promote collaboration is information provided to the users about the resources in the system. The amount information visible to the participants (in terms of 3D content) at a time thus influenced the nature of collaboration.

In Furniture Finder and Block Rock Grab, we found that Strategy 1 (both interactions performed by the same person) was common. In Furniture Finder, we observed a more turn based approach wherein participants performed both tangible and gestural interaction individually for some of the tangibles while the other participant(s) watched over whereas in Block Rock Grab we observed that gesture controller placed tangibles along with other tangible placers. Furniture Finder required frequent interactions with the 3D model to open each box whereas in Block Rock Grab rotating the 3D model in an optimal view allowed the participants to view the position of all the tangibles in the 3D model. Thus, frequency of interactions required with each modality to complete any task (tangible or gestural) has an impact on single person interaction.

Prior work [19, 37] found that orientation of game elements had an impact on collaboration specially in terms of how participants coordinate their actions. In our system, BR-S afforded discrete canonical orientation whereas BR-G offered continuous 360 view the 3D model. In terms of orientation control, for the two games, BR-S and BR-G, we observed that strategy 4 was more prevalent in BR-S, wherein both the gestural control and placing tangibles was shared. While in BR-G, strategy 3 was more prevalent wherein only placing tangibles was shared. In BR-G, a virtual hand represented the movement of the gesture controller, which allowed the gesture controller to move over the handle and grab it. Thus, participants were explicitly made aware of who controlled the gesture. Furthermore, in BR-G, we observed there were variations as to how Strategy 3 was adopted. The gesture controller would keep the model grabbed with one hand while placing tangibles with other while in another approach, the gesture controller would rotate the model to desired view, stop performing the grab gesture and placed the tangibles, rotating the 3Dmodel as and when required. In BR-S, there was no virtual hand to indicate the mapping of gestural actions. Combined with the ease of swipe with its atomic nature, participants swiped as required, at times, simultaneously, until the actions were tracked by the Kinect. .

In terms of group size, we found that Strategy 1 was significantly adopted more in Block Rock Grab in triads. In BR-G, gesture controller could orient the 3D model to the desired view and place tangibles. We observed gesture controller holding their hand mid-air to perform the grab gesture while placing tangibles with other hand. Furthermore, though not statistically significant, in Furniture Finder strategy 4 was more prevalent in Furniture Finder in triads (p=0.070) and Strategy 3 was more prevalent in Block Rock Swipe (p=0.071). We had a comparatively small number of groups to compare. This is an interesting aspect to investigate further in future work. In our results, we found that their dyads had significantly more unequal tangible work distribution while triads had more equal tangible work distribution. Dyads adopted a more distinct division of labor approach wherein each participant performed either gestural or tangible interaction. Thus, equal number of participants in a group and interactions supported by the system leads to a stronger mapping of roles among users.

We observed that dyads adopted a more distinct division of labor approach as compared to triads in FF. The dichotomy of interactions coupled with the sequential design of the game, allowed dyads to easily divide the gestural and tangibles interactions than triads. In BR games, in the swipe variant dyads adopted a more parallel play approach as compared to triads wherein both the tangible and gestural interactions were shared. In Furniture Finder, we observed statistically, more equal distribution of tangible placement while a low-level distribution of tangible placement in dyads. Dyads observed a more distinct division of labor approach and combined the sequential nature of the game lead to each participant focusing on one interaction (tangible or gestural).

In terms of age range In Furniture Finder, we observed statistically, more equal distribution of tangible placement while a low-level distribution of tangible placement in dyads. Dyads observed a more distinct division of labor approach and combined the sequential nature of the game lead to each participant focusing on one interaction (tangible or gestural). In BR games, in the swipe variant we observed that participants in FO age range we more focused on finishing the game as fast as possible choosing a parallel play approach whereas participants in CO adopted more division of labor approach. This was converse in the grab variant with participant in FO age range exhibited more division of labor approach whereas participants in in CO shared the tangible interactions.

We studied territorial infringement made by participants to gain a resource. Due to the inherent design of the game and as expected, the infringement done to for tangible interaction was more than that of gestural interaction. Overall, we observed that participants were not hesitant to take a tangible, which was near another participant. Participants reached over, moved, reached under other participant arms to retrieve the tangible. Ryall et. al. [10] had observed that participants were reluctant to grab a resource, which was close to another participant. While in their system, participants performed only tangible interactions, they recommended how the addition for an additional vertical display might affect the group dynamics in terms of infringement. In our system, we observed that for the grab based games, territorial infringement was done significantly higher by tangible placers. In the swipe variant of the BR game, the infringement was done more by gesture controller than the tangible placer. In grab based games, gesture controller mostly focused on the gestural interaction. Even in BR-G, when the gesture controller placed tangibles, he/she would still have to control the 3D model. In BR-S game, participants did not have the visual hand indicator on the screen. Also, BR-S provided canonical orientation of the model. Thus, the gesture controller could more quickly map the position of the 3D to the position of the tangible in the tabletop as compared to others.

In terms of groups size, territorial infringement in triads was higher as compared to dyads. In Furniture Finder, tangible placers infringement was more by tangible placers, while in BR-S and BR-G gesture controller infringed more. Across the two age ranges, Formal operational age group infringed more than Concrete operational age group. Infringement was more by tangible placers in FF and BR-G, while more by gesture controller in BR-S. We observed that participants on the CO we more focused on each participant doing their designated task (place tangible or control gesture) more than in FO age group.

In term of communication, we found that there was significant impact of group size on visual evidence in BR-S with triads relying on visual evidence while dyads relied more on basic awareness. This observation is along the lines of prior work by Xie et. al [46] who found that even when playing in parallel, participants observed each other's actions. Furthermore, participants communicated with each other to overcome tracking issues of the Kinect and coordinated their actions to resolve the issue. Behaviour such as staying out of tracking area, ducking down to prevent tracking required participants to be aware of each other's actions. Perceptual mapping (relationship of look of an object and its behavior) is an important to factor to consider when considering the affordances provided by tangible and spatial interactions [36]. We also observed participants holding their hands close to their chest and putting hands in the back to "hide" from the system. The participants had a notion that hiding hands from the Kinect will prevent tracking. Game type and orientation control had significant impact on completion times. As expected, FF with its significant nature took more time as compared to BR games. However, BR-G took statistically less amount of time than BR-S. Though participants adopted more parallel play approach in BR-S, they at times took more times to get the right view of the 3D model whereas BR-G allowed them optimal view after precisely rotating the 3D model.

### 6.2. Design Implications

Prior work [7,11,14,36] has shown that while designing systems for children, it is important to consider children's understanding of what elements mean in their various representational form.

We designed two games, which allowed us to understand the impact of multimodal interfaces and interaction constraints on collaborative gameplay. In this section, we discuss these factors and their implications for designing games for such multimodal interfaces.

### 6.2.1 Shared interaction space v. group size

Successful collaboration using multimodal interfaces depends on strategies used for deploying elements such as gestural and tangible interactions, and on the design on interaction spaces and points where group members can access the shared interaction space (access points). Our implementation featured a design where the interaction spaces for both gestural and tangible interaction overlapped. We felt this was necessary in our system design because one person is always controlling the 3D model using gestures, and because the orientation of the 3D model was critical for successful tangible interaction, we wanted to allow any member of the group to perform this action and believed that this would introduce interesting behaviours as participants compete for control.

If orientation is not critical in systems and one person is always performing gestural interaction, it would be wise to move that person away from the tabletop interface, so that they do not use space required for tangible interaction. We focus a paradigm where we have one point of control for the gesture control. Future work would be interesting to see how an access model, which allow simultaneous access would work out. We don't have data how his would work out but we can look on this in future.

When designing systems with multimodal interfaces, it is also important to consider breaking the shared interaction space constraint by allowing people to choose to participate in either modality. This would mean moving away from enforcing overlapped interaction zones in a fully shared (or, mixed) interaction space (as discussed above about our implementation), to separate interaction spaces for tangible- and gesture-based interactions. While a mixed interaction space would allow people to interact with any modality and might facilitate contention for control/access to specific interaction modes, using separate interaction spaces would reduce chaos and allow for clear separation of responsibilities. It would be interesting to study the impact of such a change in interaction spaces on collaboration, as communication changes from visual observation and simple gestural messages to explicit often verbal instructions and direction. The collaboration mode could change from self-directed interaction to that involving a separate and clearly defined actor with the responsibility of a director.

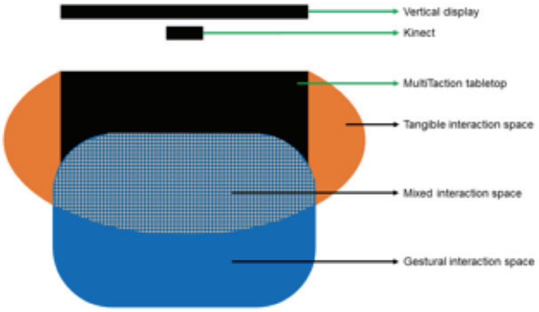


**Figure 23. Interaction spaces.**

### 6.2.2 Height of vertical display

The placement of the Kinect in our system implementation and the height of participants introduced the possibility of a genuine attempt at a tangible interaction (e.g. holding the tangible in the hand) was recognized as a gestural action (e.g. grab). Furthermore, placement of tangibles would sometimes be misconstrued to be gestural work, and would cause transfer of control that is unintentional. This behaviour was the result of the overlapped interaction space discussed previously. Depending on the nature of interaction in systems, it might be worth considering increasing the height of the wall mounted display to not detect gestures below a certain threshold (e.g. in cases where role switching is important in interactions).

### 6.2.3 Tracked v. untracked areas around the tabletop

An important aspect to consider in designing collaborative games using multimodal interactions is clearly demarking zones that are tracked by the Kinect. This helps people understand how they can collaborate and perform tangible interactions without being tracked by the Kinect. Although we did not have explicit indication of tracking zones, we observed that participants used the visual indicator (3D silhouettes of persons in the tracking zone) as a reference to temporarily leave the tracking zone, in cases when they were not sure as to who was being tracked. This is an important design aspect to consider as children may not always fully comprehend the implications of staying in or moving out of tracking zones. Clearly demarking zones offers clarity, which zones are tracked, and this would also explicitly make them notice such areas and understand their purpose in supporting successful collaboration.

### 6.2.4 Level of coupling and collaboration

From our observations, we recommend using atomic gestures such as swiping to facilitate shared control of one of the gestural interaction mode (e.g. gestural control of the reference 3D model). This keeps each gestural action discrete, allowing more than one person to perform the action, making them compete for control, and thereby making group members more independent (i.e. loose coupling). On the other hand, if the game requires role-specific actions (e.g. one person acting as the director or controlling the reference 3D model), we recommend that designers consider using continuous gestures, such as grab and hold. This would increase dependency among group members and create a more tightly coupled collaboration environment. While it is important to consider supporting rapid changes in gestural control - both in atomic and continuous gesture modes - designers should be careful of how they facilitate such control transfers/changes, as it will impact collaboration.

From our observation, we recommend considering the following design factors while building tangible and gestural multi-display game interfaces.

- The task of the game plays a major role in the division of labor among users.
- When working in collaboration, users prefer having control over some aspect of the game. Users don't want to be left out, preferring been part of game at least to some extent.
- Proper division of labor leads to more coordination and better performance.

A multimodal system (supporting tangible and gestural interactions) can be deployed in school or museum setting. In a museum setting, the users generally a limited time to interact with the system. Thus, while designing such a system different factors such as the number of interactions afforded, access points available to the users playing in a group, number of users in a group, age range can be considered to offer more enriched experiences.

## 6.3 Limitations

To answer our research questions, we designed our study methodology accordingly, however our study has the following limitations.

### 6.3.1 Population Sample

We recruited participants from SuperNova [81], due to which we had no control over participant's number. Also, we had instances where participants preferred to play with their friends, which lead to a skewed number of dyads and triads. Due to this, during analysis to remove the confound of age and group size, we had to counter balance the groups accordingly. Furthermore, the we conducted the study with youth only. Thus, the reported behaviour cannot be extrapolated to adults or compared with adults.

### 6.3.2 Tracking Issues

We observed instances of the gestural tracking been not detected by the Microsoft Kinect. This led to participants having to try the gesture multiple times. Also, since participants played in groups, specially in triads, participants had to spend time to figure out the interaction controller in the group. This affected the time taken by participants to due complete the game. Though we observed interesting mechanisms from participants to overcome the tracking issues, however it affected their overall experience of playing the game and might have influenced their perception of the multimodal setup.

## 6.4 Future Work

We explored the use of multimodal interfaces (gestures and tangibles) to study collaborative behaviour in small groups of youths. Following are the considerations for future to improve on the study.

### 6.4.1 Gesture Control Indicator

Participants had to spend time in figuring out whose actions were recorded by the Kinect. Participants took turns performing the gesture to find the interaction controller in the group. A better way would be to have a gesture control indicator in the system. In our system, the silhouettes of participants were shown on the LCD screen in the form of depth maps of their body. An improvement to this feature is to highlight in some way (such as color of depth map, visual cue etc.) which will help participants to know who is in control of the gesture.

### 6.4.2 Multimodal Setup

In our multimodal setup, position of the vertical display and the tabletop was such that it created an overlap of interaction space for tangible and gestural interaction. In the future, it would be interesting to have the setup, which there is no overlap of tangible and gestural interaction. This can be done by having the LCD display adjacent to the tabletop instead of having it exactly in front of it. Also, in terms of interaction, instead of gestures, touch based interaction to interact with the reference 3D model. This can be done in two variations. The 3D model can be projected on wall display, which is touch enabled. Alternatively, the 3D reference model can be projected on the tabletop. Thus, the tabletop display can be divided to have both 3D reference model, which can be manipulated by touch and support the tangible interactions.

### 6.4.3 Population Sample

Antle et.al [5] reported that adults mostly focused on winning a game whereas children were more interested in having fun. Since, we have conducted our study only with youth, we do not have data about adults. In future, having a study with adults collaborating in multimodal setup will help to evaluate in detail the impact of age on collaboration dynamics in multimodal setup.

# CHAPTER 7 CONCLUSION

In this this, we conducted an initial exploration of multimodal (tangible and gestural) interfaces for collaborative gameplay. We performed our evaluation with a sample of children between the ages 8 – 15 years. Some of the key factors that influenced collaboration were group size, age range, game type and orientation control. Based on our observations, we deduced five collaboration strategies used by users when interacting with our system, and present impact of our experimental factors on collaboration. In tightly coupled game such as Furniture Finder with its sequential nature, participants were dependant on each other actions while in loosely coupled game such as Block Rock with swipe, we found that participants were actions were more independent of each other. We tested the impact of game type, orientation control, group size and age range impact om collaboration. Our study suffers from the limitation of small numbers to compare age range and group size. In our future work, it would be interesting to see how adults interact in such a configuration, socially how perceptions about personal space differ than in youth. Furthermore, while our system supported only one person gestural interaction at any time, in future we can analyze system, which both tangible and gestural interactions are shared.

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# APPENDIX A

## Informed Consent

### Using 3D gestures to support physical interaction

Principal Investigators: Aniruddha Waje, Faculty of Computer Science, an246533@ dal.ca
Dr. Derek Reilly, Faculty of Computer Science, reilly@cs.dal.ca

Co Investigators: Dr. Gary Hu, Faculty of Computer Science
Majid Nasirinejad, Faculty of Computer Science
Khalid Tearo, Faculty of Computer Science

Contact Person: Aniruddha Waje, Faculty of Computer Science, an246533@ dal.ca

We invite your son/daughter to take part in a research study being conducted by Aniruddha Waje at Dalhousie University. Your son's/daughter's participation in this study is voluntary and he/she may withdraw from the study at any time. The study is described below. This description tells you about the risks, inconvenience, or discomfort which your son/daughter might experience. Participating in the study might not benefit him/her, but we might learn things that will benefit others. You should discuss any questions you have about this study with Aniruddha Waje.

The purpose of the study is to evaluate an application, which combines tangible interaction and 3D gestures with 3D content projected on LCD display. Your son/daughter will be asked to participate in the study lasting for 15 – 17 minutes, where he/she plays two games with other students in a group of three. The games involve manipulating physical blocks to correspond with a 3D model. Interaction can be made with the 3D model by use of gestures which allow rotation and grabbing the model. There is no compensation for participation in this study. Your son/daughter will be video recorded while playing the game. Note that this video is only for analysis purposes. The video will be viewed only by the investigators of the study. Kinect Tracking data, software logs and display screen captures will also be recorded. The study is funded by Natural Sciences and Engineering Research Council of Canada (NSERC).

The entire session should take approximately 15-17 minutes. Researchers are available to answer any questions your son/daughter may have or address any problems that he/she may experience while playing the game.

All personal and identifying data will be kept confidential. Using pseudonyms will preserve anonymity of textual data. The informed consent form and all research data will be kept in a secure location under confidentiality. As your son/ daughter will be playing the games and giving the interview in a group with other two students, there is lack of anonymity within the group.

In the event that you have any difficulties with, or wish to voice concern about, any aspect of your son's / daughter's participation in this study, you may contact Catherine Connors, Director, Office of Research Ethics Administration at Dalhousie University's Office of Human Research Ethics for assistance: phone: (902) 494-1462, email: catherine.connors@dal.ca.

"*I have read the explanation about this study. I have been given the opportunity to address any questions. By signing below, I hereby consent to let my son/ daughter take part in the study.*

*xHowever, I understand that the participation is voluntary and that my son/daughter is free to withdraw from the study at any time.”*

**Guardian Signature**
Name: ___________________________
Signature: _________________________
**Date:** ________________________

**Researcher**
Name: ________________________
Signature*:* _____________________
**Date:** ______________________

Please answer yes/no to each of the following questions:

| | |
|---|---|
| “*I agree to let you directly quote any comments or statements made by my son/daughter in any written reports without viewing the quotes prior to their use and I understand that the anonymity of textual data will be preserved by using pseudonyms.*” | ☐☐Yes<br>☐☐No |
| *“I agree to let you use video and photos taken of my son's/daughter's for analysis purposes.”* | ☐☐Yes<br>☐☐No |
| *“I would like to be notified by email when results are available via publication”*<br>If yes, provide an email address: ____________________________________ | ☐☐Yes<br>☐☐No |

## APPENDIX B

## Assent Form

## ASSENT SCRIPT

**Project Title:** Using 3D gestures to support physical interaction
**Principal Investigator:** Aniruddha Waje, Faculty of Computer Science

**Supported by:** Natural Sciences and Engineering Research Council of Canada (NSERC)

I want to tell you about a research study we are doing. A research study is usually done to understand how things work. In this study, we want to find out more about how people play a game together that involves moving objects and using hand movements to control a 3-D image on a large screen.

You are being asked to take part because you are attending the Super Nova camp in a large group, which means we can have several groups of campers play the game. In any study, only people who want to take part will participate. You do not have to participate if you don't want to. You can still play the game if you don't want to participate in the study.

If it is okay with you, I will ask you to play two games with other campers in a group of three. The games involve placing physical blocks on the tabletop in similar position as with a 3D model which is displayed on the screen in front of you. Interaction can be made with the 3D model by use of gestures, where you move your hands in a way, which allow rotating and grabbing the 3D model. You will be video recorded when you play the two games. Also after the game we will ask you some questions about the game which will also be video recorded. If you don't want to be video recorded then you don't have to participate.

Sometimes while playing the game you may have some difficulty. But, I am here to help you any time you want any help. Just ask me. Since you will be playing with other campers, you will be asked questions in group. I will ask the questions to each one of you so you will get chance to answer every question.

If you are uncomfortable with some of the questions, please let me know and I will stop.

I do not know if participating in this study will make you happy or benefit you in any way. However, I may learn something that will help other people.

You do not have to be in this study. It is up to you. You can say no now or you can even change your mind later. All you have to do is tell me. No one will be mad at you if you change your mind. Your parents/people taking care of you say it is okay for you to be in this study. If you have questions, please ask them now or at any time.

**DO YOU UNDERSTAND WHAT I AM SAYING AND ARE YOU WILLING TO PLAY THE GAMES?**

*End of verbal script.*

**CHECK WHICH APPLIES BELOW**:

TO BE COMPLETED BY PERSON OBTAINING VERBAL ASSENT FROM THE CHILD/SUBJECT:
Child's/Subject's response**:** ☐Yes ☐No

Do you agree to be videotaped while playing the game?

Child's/Subject's response**:** ☐Yes ☐No

**CHECK WHICH APPLIES BELOW**:

☐The child/Subject is capable of understanding the study

☐The child/Subject is not capable of understanding the study

____________________________________________
Child's/Subject's Name (printed)

# APPENDIX C
## Post-Game Interview Questions

1. How fun was the game? How much did you want to ‘‘win’’ the game?

2. Did you like working in a group to complete the game? Which part did you work on in the game, opening the box or placing furniture on the tabletop or both?

3. Did you like using the gesture to open the boxes in the game? Was it easy to use?

4. Which gesture interaction you liked? Open the box or swiping to rotate the blocks? Why?

5. Did you like the use of wooden furniture and blocks in the game?

6. Were there any times when you just wanted to give up? Why/Why not?

7. What other games you think can be fun to play with this system?

8. Do you have any suggestion(s) to improve the game?

## APPENDIX D

LETTER OF APPROVAL

**Social Sciences & Humanities Research Ethics Board**

**Letter of Approval** May 04, 2015

Mr Aniruddha Waje
Computer Science\Computer Science
Dear Aniruddha,

**REB #:** 2015-3528 **Project Title:** Using 3D Gestures to Support Physical Interaction

**Effective Date:** May 04, 2015 **Expiry Date:** May 04, 2016

The Social Sciences & Humanities Research Ethics Board has reviewed your application for research involving humans and found the proposed research to be in accordance with the Tri-Council Policy Statement on *Ethical Conduct for Research Involving Humans.* This approval will be in effect for 12 months as indicated above. This approval is subject to the conditions listed below which constitute your on-going responsibilities with respect to the ethical conduct of this research.

Sincerely,

Dr. Valerie Trifts, Chair

Post REB Approval: On-going Responsibilities of Researchers

After receiving ethical approval for the conduct of research involving humans, there are several ongoing responsibilities that researchers must meet to remain in compliance with University and Tri-Council policies.

1. Additional Research Ethics approval

Prior to conducting any research, researchers must ensure that all required research ethics approvals are secured (in addition to this one). This includes, but is not limited to, securing appropriate research ethics approvals from: other institutions with whom the PI is affiliated; the research institutions of research team members; the institution at which participants may be recruited or from which data may be collected; organizations or groups (e.g. school boards, Aboriginal communities, correctional services, long-term care facilities, service agencies and community groups) and from any other responsible review body or bodies at the research site

2. Reporting adverse events

Any significant adverse events experienced by research participants must be reported **in writing** to Research Ethics **within 24 hours** of their occurrence. Examples of what might be considered "significant" include: an emotional breakdown of a participant during an interview, a negative physical reaction by a participant (e.g. fainting, nausea, unexpected pain, allergic reaction), report by a participant of some sort of negative repercussion from their participation (e.g. reaction of spouse or employer) or complaint by a participant with respect to their participation. The above list is indicative but not all-inclusive. The written report must include details of the adverse event and actions taken by the researcher in response to the incident.

3. Seeking approval for protocol / consent form changes
Prior to implementing any changes to your research plan, whether to the protocol or consent form, researchers must submit them to the Research Ethics Board for review and approval. This is done by completing a Request for Ethics Approval of Amendment to an Approved Project form (available on the website) and submitting three copies of the form and any documents related to the change. Please note that no reviews are conducted in August.

4. Submitting annual reports
Ethics approvals are valid for up to 12 months. Prior to the end of the project's approval deadline, the researcher must complete an Annual Report (available on the website) and return it to Research Ethics for review and approval before the approval end date in order to prevent a lapse of ethics approval for the research. Researchers should note that no research involving humans may be conducted in the absence of a valid ethical approval and that allowing REB approval to lapse is a violation of University policy, inconsistent with the TCPS (article 6.14) and may result in suspension of research and research funding, as required by the funding agency. 5. Submitting final reports. When the researcher is confident that no further data collection or analysis will be required, a Final Report (available on the website) must be submitted to Research Ethics. This often happens at the time when a manuscript is submitted for publication or a thesis is submitted for defence. After review and approval of the Final Report, the Research Ethics file will be closed.

6. Retaining records in a secure manner Researchers must ensure that both during and after the research project, data is securely retained and/or disposed of in such a manner as to comply with confidentiality provisions specified in the protocol and consent forms. This may involve destruction of the data, or continued arrangements for secure storage. Casual storage of old data is not acceptable.It is the Principal Investigator's responsibility to keep a copy of the REB approval letters. This can be important to demonstrate that research was undertaken with Board approval, which can be a requirement to publish (and is required by the Faculty of Graduate Studies if you are using this research for your thesis). Please note that the University will securely store your REB project file for 5 years after the study closure date at which point the file records may be permanently destroyed.

7. Current contact information and university affiliation The Principal Investigator must inform the Research Ethics office of any changes to contact information for the PI (and supervisor, if appropriate), especially the electronic mail address, for the duration of the REB approval. The PI must inform Research Ethics if there is a termination or interruption of his or her affiliation with Dalhousie University.

8. Legal Counsel The Principal Investigator agrees to comply with all legislative and regulatory requirements that apply to the project. The Principal Investigator agrees to notify the University Legal Counsel office in the event that he or she receives a notice of non-compliance, complaint or other proceeding relating to such requirements.

9. Supervision of students Faculty must ensure that students conducting research under their supervision are aware of their responsibilities as described above, and have adequate support to conduct their research in a safe and ethical manner.