

An Augmented Reality Prototype for Investigating Tangible and Virtual Components in a Gaming Environment

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Abstract

In recent years, button-based controllers for gaming consoles have evolved into dynamic, sensor based controllers that track movement and mimic real life instruments. The sudden popularity growth of this novel and interactive sensing technique has led us to consider whether realistic motion controllers will become the standard of future entertainment. This notion inspired us to investigate the preferability of physical interaction techniques over their virtualized equivalents. To accomplish this, a multi-user prototype was developed and designed using affordable and portable commercial hardware components. Our system features an overhead camera as the main form of input, coupled with a vibration sensor for touch-detection, and a projector for graphical output. Three gaming applications, an augmented tower defense game, roll-and-move board game, and augmented Settlers of Catan, were implemented to test the hypothesis that physical components will be most suitable for social situations while digitization is preferred for mundane tasks. Additionally, two formal experiments were conducted in the context of the last two gaming applications to determine the overall effects on player enjoyment. Our findings suggest that while it is possible to use either physical or digital implementations of game components, scenarios involving more than two simultaneously interactive players benefit from tangible components.

Sommaire

Depuis quelque temps, les contrôleurs de jeux vidéo évoluent en instruments à bases de capteurs qui suivent les mouvements dynamiques et naturelles, et imitent les instruments utilisés dans la vie de tous les jours. La popularité soudaine de ce type de contrôleurs nous mène à considérer si cette nouvelle manière d'interaction naturel va devenir la norme pour l'avenir du divertissement électronique. Cette notion nous a inspiré à investiguer la préférence de l'interaction physique versus les modes virtuels conventionnels. Pour accomplir ceci, un système prototype multiutilisateur a été développé en utilisant des composantes matérielles commerciales à prix modiques. Notre système comprend une caméra montée sur le plafond, qui sert de capteur principal, couplé avec un capteur de vibration pour la détection tactile et finalement un projecteur servant à projeter des graphiques sur une table. Trois applications de divertissements on été créés: un jeu de défense de tours augmenté, un jeu de dés et un jeu Settlers of Catan augmenté. Ces jeux ont été développés pour tester notre hypothèse que les modes d'interactions physiques sont préférés dans des situations sociales, tandis que les modes virtuels sont plus adaptés pour des tâches banales. De plus, deux expériences ont été menées dans le contexte des deux derniers jeux pour déterminer l'effet sur le plaisir des joueurs. Nos résultats démontrent qu'il est possible d'utiliser les modes physiques ou virtuels d'interaction des jeux, mais que les modes tangibles procurent plus de bénéfices lorsqu'il y a plus de deux joueurs simultanés.

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List of Acronyms

AR	Augmented Reality
GUI	Graphical User Interface
HMD	Head-mounted Display
RBI	Reality-Based Interaction
SRE	Shared Reality and Environments
TAR	Tangible Augmented Reality
TUI	Tangible User Interface
VR	Virtual Reality

Chapter 1

Introduction

In the last few decades, digital games have been revolutionized by the fast-evolving trend of technology. Beginning with keyboard-only ASCII text games, the gaming industry has developed into a motion-sensitive, vivid multi-player environment for all types of games. A pioneer of this modern game trend is the Dance Dance Revolution dance pad. Although not motion sensitive, this interface allowed people to play a game using whole-body physical motion. Shortly after the release of this product, companies realized the potential of using natural motion for game controllers.

One of the first well-known, defining devices of the gaming controller revolution is the Nintendo DS. This device allowed players to interact using a stylus and thus radically changed the way digital games could be played. For the first time, people were able to apply a learned motor skill to play a game. Following the success of this device, Nintendo developed the popular motion-sensitive Wii Remote, which was followed by other movement controllers from competitors, such as the camera-tracked Sony Move controller and Microsoft Kinect system. The continued presence and popularity of these interfaces leads us to believe that there is an audience for natural interactive techniques in the gaming

industry.

Another well-received branch of natural gaming interfaces uses physical “props” to engage players. Two example interfaces include the guitars from Guitar Hero and the drum set from Rockband, a popular music video game available for many console systems. The musical “instruments” in these systems retain the general look and feel of their real counterparts, but are simple enough for the average gamer to learn, even if not already a musician. When used with video games, these devices simulate real instruments and thus immerse the players in a realistic scenario of participating in a rock band. The sense of engagement created by using natural, tangible objects shows us that physical components play a large part in creating a rich, realistic experience for any type of game.

The current generation of game interfaces has extended the capabilities of traditional hand-held button controllers by using familiar physical objects and employing some form of motion sensing. Apart from using a unique sensing mechanism and being novel, these techniques allow players to enjoy games and ways of playing that were previously not possible. When tangible objects are used as the primary method of interaction in a digital context, such as for video games, they are also known as tangible user interfaces (TUIs). Although these new game interfaces promise to enrich the physical gaming experience, their full potential can only be realized with appropriately designed software. This software-enhanced physical interaction environment is also considered to be a type of augmented reality (AR).

Augmented reality has many qualities similar to modern computer games. For example, AR uses the digital world to enhance the physical interaction experience. In this situation, physical objects have additional digital capabilities allowing them to interact with other components in the virtual world. This allows complex or fictional scenarios to be modelled that may be otherwise impossible in real-life. Moreover, the use of a computer can automate

repetitive, mundane tasks such as shuffling, point-counting, and memorizing rules, factors that may detract from the enjoyment of certain games. By combining TUIs with AR, we are able to create an augmented reality environment that has benefits from the physical and virtual world. This environment is also known as tangible augmented reality (TAR)[1].

To better understand how TAR can improve the overall gaming experience, we briefly discuss the capabilities, also known as affordances, of TUIs and AR in their distinct categories.

1.1 Tangible User Interfaces

Tangible user interfaces are often created by coupling physical pieces to the computer through some sensing mechanism. These physical components afford manipulation, allow spatial reasoning skills to be exercised while parallel operation and collaboration is supported between single and multiple users [2, 3]. As an example, imagine TUIs as wooden blocks, each corresponding to a specific digital document on the computer. Patten and Ishii discovered that participants used spatial organization techniques with TUIs including stacking, grouping, and orienting, to help memory and recall of the digital document contents while those employing graphical user interfaces (GUIs) did not [4].

Familiar physical objects used as TUIs minimize learning time and allow users to complete tasks efficiently. People naturally understand the affordances of new physical objects if they mimic similar, known objects encountered in life. For example, if a TUI object is designed similar in shape, size, and behaviour to a die, it will be perceived as one with the same physical affordances. This transfer of knowledge allows people to understand that faces of the new cube object are distinct and only one cube face is active at any time, as it is with dice. Designers may use this transfer effect to create interfaces that are easily

understood by users.

The biggest challenge in the design of a TUI is determining its physical structure. It is important to design the shape and structure of a TUI such that it elicits physical actions valid to the digital system.

1.2 Augmented Reality

Using physical elements to interact with the digital world implies that the virtual elements are in some way, linked to the physical objects. The concept of augmented reality modifies the perception of physical objects by overlaying digital information, such as graphics, without physically changing the object. This is often accomplished using projectors and camera technology. Augmented reality is highly appropriate when information has a spatial relationship with the objects in the scene. Spatially linked digital-physical elements means that manipulation of physical components causes a direct change to the digital elements. With digital augmentation, complex information that would otherwise be difficult to memorize can be associated with physical objects to make this possible.

To track physical game pieces in an AR environment, fiducial markers¹ [5] are used in some cases. These are portable, versatile, and extremely inexpensive to implement, providing a simple, tether-free solution, even for complex objects. Fiducials have been used in conjunction with head-mounted displays in a shared space game in which users match together projected 3D virtual objects [1] and with hand-held devices such as cellular phones in various TAR applications. For the latter, games such as *Bragfish* [6] and *Art of Defense* [7] have demonstrated the portability aspect, but the requirement for players to hold and focus on the hand-held device hindered face-to-face communication and use of

1. A pattern or object that is uniquely marked and used in the field of view of an imaging system. This often acts as a point of reference for digital projections.

hand gestures for interaction.

1.3 Tangible Augmented Reality

When combined with TUIs, augmented or mixed reality techniques can provide real world interaction in a more integrated manner than traditional video games. Typically, this is achieved by projecting graphics into the same space where the tangible interfaces are used, e.g., on a table. Tangible Augmented Reality enhances face-to-face communications of multi-player games, while allowing players to interact in a natural manner. This idea of merging pre-existing, everyday knowledge with digital interaction techniques arises from the *Reality-Based Interaction* (RBI) framework, which provides techniques for analyzing and comparing components used for this style of interaction [8].

Previous studies of tabletop games with tangible objects [9, 10] investigated the support of such technology for natural and social interaction. These prototypes led to the formulation of a set of guidelines for effective collaborative systems [11] and to methods for evaluating such systems [12, 13, 14, 15]. The latter describe the limitations of efficiency and productivity as an evaluator of success and propose instead the use of physiological signals and subjective reports, such as Likert-scale² questions, as a more accurate technique. The described prototypes and methods of evaluating enjoyment have inspired us to consider their techniques for investigating interaction paradigms in the system implemented as part of this thesis.

To support the investigation of tangible augmented reality systems used in a gaming context, we have created a prototype that facilitates the use of tangible components as the primary method of interaction in a virtual environment. Several games have been devel-

2. A type a psychometric scale used in survey research. The scale corresponds to the respondent's level of agreement to each questionnaire item.

oped and used in formal experiments to test the appropriateness of physical and digital game components in this setting. We are most interested in whether tangible or virtual components should be used in various gaming situations based on their impact on enjoyment. We hypothesize a preference for tangible components in multi-player interactions due to their rich physical affordances and preference for digital components for their ability to automate mundane tasks. Following the results of our study, we hope to establish design guidelines that may be used to determine choice of tangible or physical components in generic gaming situations.

1.4 Literature Review

The idea of using physical components to enhance interaction with the digital game world has been explored in previous research. The goal of this section is to describe the important discoveries and shortcomings of related augmented reality projects and how they have inspired our work. These previous research efforts may be categorized into three distinct hardware groups: capture-projection technology, hand-held devices, and touch-sensitive surfaces.

1.4.1 Capture-Projection Technology

One technique of merging digital output with tangible components is to use coupled capture-projection technology. Cameras or microphones are responsible for capturing input information, such as the spatial location of TUIs, while output information is projected onto the physical components using projectors or head-mounted displays. Projectors allow for a large number of viewers, constrained only by physical space. Unfortunately, top-down projection technology suffers from occlusion issues where the user's shadow obstructs the

projection. This is easily resolved with a bottom-projected setup. Head-mounted displays offer the advantage and disadvantage of providing a private view of the merged digital-physical space. This restricted view allows private information to be conveyed but requires multiple head-mounted displays if more than one person wishes to view the augmented scene.

Pingpongplus was one of the first systems to augment an existing game, ping pong, with digital projections and sound. Location of the tangible object, the ping pong ball, is determined using eight microphones mounted beneath the table. Each microphone records the time at which an impact is heard to interpolate the position of the ball, accurate within a few inches. This sound information is used to create a variety of digital effects that are projected onto the playing surface [16].

Several game applications in the Pingpongplus paper show how digital enhancement affects gameplay. The first involves treating the ping pong ball as a “paint ball” where the impacted location adopts the paint color digitally associated to the ball. The second uses impacted locations to trigger musical sounds, varying based on the origin. Both of these applications modify the traditional ping pong game into a cooperative, artistic application that is not focused on winning. The third application uses digital effects to encourage collaboration between the two players. As players rally the ball, digital effects such as static and lightning became increasingly intense with each return. The designers discovered that the build-up of digital effects also raised agitation and nervousness in the players, demonstrating the capabilities of computer augmentation as an experience enhancer in an otherwise repetitive, simple game. The next two applications show the importance of adjusting digital features to supplement physical components. Pac-Man mode added digital graphics to each side of the table, challenging players to target specific items while avoiding others. Because the physical activity of playing ping pong demanded most of the

player's attention, it was difficult for players to distinguish between good and bad items based on fine detail. This was resolved through simplification of digital elements such that only quick glances were needed to discern item differences. Learning from the Pac-Man mode, Ishii et al. designed the school of fish mode that featured ripples and scattering of fish on the impact of the ball. This was the most preferred mode of all; digital elements simultaneously held player interest and enhanced the simple nature of ping pong.

To support the display of private information, see-through head-mounted displays are used in place of projectors. Szalavari et al. demonstrated the capabilities of this setup with an augmented reality Mah-Jong game. Private information, such as the player's tile rack, was projected onto a personal information panel. This panel assists players by providing instant in-game help for the tiles currently held, a type of digital affordance that is difficult to support by its physical equivalent.

Head-mounted display devices have also been used with fiducials. Several prototypes developed by Billingham et al. show the potential of a HMD-fiducial setup for creating collaborative AR environments [1]. A simple multi-player game in this setup, SharedSpace, found users with varying levels of experience were able to collaborate effectively without problems. The second application, Tiles, demonstrated the HMD-fiducial coupling as a viable prototyping platform. Fiducial markers could be used physically as placeholders for ideas or concepts organized on a white board while digital augmentation allowed information, such as graphs, charts, and detailed documents, to be stored virtually.

1.4.2 Hand-Held Devices

Hand-held devices are used when portability is prioritized over other TAR qualities. Often, digital augmentation is handled entirely by the portable device, such as a mobile phone or personal data assistant (PDA), and viewed on its display screen. While the small

size of these devices offers the advantage of being mobile, they are disadvantaged by the small display area.

Huynh et al. explored the use of hand-held devices for augmenting physical board game tiles in the context of a tower defense³ game. The purpose of this research was to determine the affordances and constraints of using hand-held AR interfaces for collaborative games. This was tested on a custom-made game called Art of Defense. Physical components that were player-drawn or pre-printed with unique symbols were camera-tracked with a hand-held device and acted as game towers. This device served as the augmented viewport for the physical board components. The limited viewing resolution was utilized as a game challenge to encourage players to actively explore the game space and communicate with other players [7].

Findings from this study indicate that players desired a larger screen area and found viewing occasionally obstructed by others. Players resolved both issues by communicating and cooperating with each other. It is interesting to see that while face-to-face interaction was not required, players opted to do so if it increased their chances of winning. Separate augmentation screens also created difficulties in communication when players tried to refer to a virtual element. This was resolved by pointing to the corresponding physical location. Although not explicitly mentioned in the paper, pointing may obstruct certain viewing angles. Social interaction was evident in the study as players frequently communicated with their partner. They also reported enjoying the game when played with either a stranger or friend.

Another hand-held AR prototype created by the same group, Bragfish, explores the use and effects of shared physical spaces on interactive social gaming [6]. In this game, players share a physical board printed with AR sensitive markers. Each player uses a personal hand-

3. http://en.wikipedia.org/wiki/Tower_defense

held device to view the game space and is allowed to physically move around the board. The goal of the game is to collect the most fish by competing for the most advantageous fishing spot. Fishing boats are controlled using hand-held devices while multi-player interaction is encouraged by enabling boats to ram into others, stealing fish in the process. This style of play allows passive or aggressive behaviours depending on the nature of participants.

The results of this study explain that game mechanisms are required to encourage player-to-player interaction in any co-located environment. Without encouragement, people playing in the same space would not interact with each other. They also found preference for playing with friends and family over strangers. Although not indicated in the study, we considered this to be a possible bias and acknowledged it in the design of our experiments. While players did not complain about the small screen size, ergonomic issues related to leaning forward or staring down at the hand-held device were raised, a common problem for hand-held AR devices. Because viewing angle is dependent on device positioning, the player must orient him or herself to the device instead of playing in a preferred comfortable position. In the discussion, the authors described the interaction benefits of linked tangible-virtual components and suggested their inclusion would encourage more social and physical interaction than an exclusively hand-held prototype.

1.4.3 Touch-sensitive Surfaces

The last category of devices encompasses varieties of touch-sensitive table-top technology. These systems range from custom-prototype tables to commercial touch-sensitive screens, for example, the DiamondTouch and Microsoft Surface. The heavy technical requirements of these devices allow the precise detection of objects but imply a high investment cost. Large screens also reduce the portability of these systems.

One example of a custom-made prototype is the game board used for Wizard's Appren-

tice [17]. This touch-sensitive surface tracked player tokens and dice rolls on the table using RFID technology. Unlike many other augmented reality systems, digital graphics were displayed on a screen adjacent to the game board. Post-experimental discussion revealed that players viewed this prototype as a regular board game and not a computer-augmented board game. We hypothesize that this was caused by the separation of the interaction and display space. Disconnecting the input and output space may have led players to view physical elements apart from the digital effects they elicited. Although the game had two roles, moderator and player, to encourage interaction, participants found social interaction in this game to be underdeveloped and shallow. This may have been an issue of game simplicity and lack of social motivators.

Another specialized hardware setup is the STARS platform created by Magerkurth et al. The main component of this setup is the touch-sensitive screen. Additional input and output devices such as hand-helds and large vertical displays are used to facilitate private game information or enrich presentations, respectively [9]. The first game implemented on this platform, KnightMage, allows players to explore an adventure game with tangible player tokens. The digital table surface detects tokens and dynamically changes the virtual setting during gameplay. Hand-held PDAs are used to support the display of private information. Informal studies for KnightMage found social interactions and method of displaying private information to be enjoyed adequately by players.

In addition, Magerkurth et al. created STARS Monopoly, an adaptation of Parker/Hasbro's Monopoly game. This mixed-reality game eliminated mundane tasks such as shuffling and randomizing game elements through digitization. Furthermore, statistical data pertaining to purchases and money exchanges were displayed on adjacent screens to visualize the flow of game events. Physical elements such as dice rolling and hotel placement were retained as they were considered essential for interactive gameplay. A private money exchange system

was also implemented for the hand-held PDAs. This added a new dynamic to the game and allowed secret alliances to be forged, encouraging more social interaction between players.

The False Prophets prototype is another custom sensor-tabletop interface system. The setup is comprised of a projected surface and physical pieces mounted with infrared light emitting diodes that are detected through phototransistors. Private information is handled with portable computers. The purpose of this prototype was to combine the flexible, interactive nature of board games with the dynamic capabilities of computers. To encourage physical interaction, player-to-player exchanges or communications were not supported by the hardware system. Unlike traditional board games where static turn-taking moderates game flow, this prototype uses an energy-based system that depletes through player token movement and is replenished over time, a digital capability that is not easily replicated in a physical setting.

Microsoft has also explored a variety of augmented board game prototypes on the Microsoft Surface system. This is a touch-sensitive screen that contains a built in, bottom-up projector and an array of five cameras used to detect objects and fingertips through the infrared spectrum. Specific game implementations such as SurfaceScapes and Settlers of Catan have been made for this platform. SurfaceScapes appears to be based off of a pen and paper role-playing game called Dungeons and Dragons. This digitized format eliminates the use of paper, automates hand-calculations, and provides dynamic visual elements to the game. While many of these qualities, such as automating mundane tasks, are desired by players, anecdotal evidence has suggested that imaginative capabilities of the game are reduced due to limited action support. The highly variable and open-ended nature of Dungeons and Dragons makes complete implementation extremely difficult. The second game, Settlers of Catan, resembles the board game equivalent but without physical cards and playing tokens. Instead, virtualized cards are displayed on-screen and covered from

other players using a physical shield. This is another method for dealing with privacy in the absence of extra hand-held devices.

1.5 Game Applications

Discussion of existing tangible augmented reality systems led us to consider the suitability of this platform for a variety of multiplayer board and strategy games in which gameplay is centered around spatial information. The table-top surface that doubles as the projection surface could be used as a game board for tangible pieces. To test its suitability, we developed three game applications on a TAR prototype.⁴ In each of these games, players interacted on the table surface using game pieces that were tracked by an overhead camera. Additionally, surface contact was sensed through vibrations generated from touching the table. The details of this setup are discussed in Chapter 2. In general, development involved designing and creating suitable tangible objects, determining methods for detecting these components, programming the game applications, creating dynamic graphics, and managing input/output data.

To determine whether specific components in our game applications should be tangible or virtual, experiments were conducted on our prototype test bed. We believed that tangible components would be favored due to their affordances for natural interaction. However, digital equivalents were considered if they greatly improved efficiency, ergonomics, or decreased cognitive load. From a gaming perspective, computerization was used to reduce the number of fatiguing or menial tasks and provide passive assistance such as organization and notification in strategic situations. The results from this research helped us establish a set of guidelines that may be used to determine whether specific game components should

4. See <http://www.cim.mcgill.ca/sre/videos/game/GameTop.m4v> and <http://www.cim.mcgill.ca/sre/videos/game/ARBoardGames.m4v> for examples

be tangible or virtual.

In this context, we set out to investigate the interaction tradeoffs between tangible and virtual objects, both in single- and multi-player settings. We sought to discover their effects on specific game mechanics requiring different levels of strategy and player-to-player interaction. Our hypothesis was that non-strategic (or “set”) actions such as game setup and piece sorting will favor automation through virtualization. Moreover, for situations where strategy or multi-player interaction was required, we expected that tangible objects would be preferred due to their assistance with planning through spatialization [4, 18, 19] and support of parallel actions between multiple people [2].

To test these hypotheses, we designed a TAR prototype that facilitates the use of tangible objects in addition to automating and assisting players on low-cognition tasks. Using this system, experiments tested whether the TAR paradigm was most appropriate for board games and if so, which components should remain tangible and others virtual. The first experiment, described in Chapter 3, informally explored the affordances and designs of tangible components used for an augmented reality game. Chapter 4 describes the second study that compares the effects of tangible vs. virtual objects in a simplistic, single- and multi-player computerized board game. Following the inconclusive results from this study, we designed a third AR game and conducted more experiments in the setting of an established board game, *Settlers of Catan*, that encourages single- and multi-player interaction with realistic and complex game mechanics. The results from this final study are described in Chapter 5. Our analysis revealed that tangible components were preferred for complicated social gaming situations while digitization was desired for routine tasks such as board setup and score counting.

1.6 Overview

The augmented reality games described above have been shown to be highly capable of supporting various social gameplay situations featuring multiple players. Common themes such as digital assistance, digital enhancement of existing physical games and facilitation of social interaction with digital elements have been demonstrated on an assortment of platforms including capture-projection technology, hand-held devices and touch-sensitive systems. Unfortunately, evidence of social and physical interactivity of augmented reality board games has been preliminary or informal. Our research aimed to establish guidelines that can be used to create a social, interactive and dynamic gaming environment for all genres. Specifically, we were interested in discovering whether game components should be tangible or virtual in various game situations. In addition, our prototype was designed to serve as a test bed for the investigation of physical and digital affordances of components in AR games.

The remainder of this thesis is organized as follows. In Chapter 2, we explain our rationale for choosing a capture-projection setup using a set of design principles we have defined. Detailed descriptions of hardware components used for our prototype will be separated by functionality. Our three gaming applications, augmented tower defense, a roll-and-move augmented board game, and augmented Settlers of Catan, along with the corresponding experiments, are described in Chapters 3, 4, and 5, respectively. Finally, conclusions and future work drawn from our prototype design and experimental results are presented in Chapter 6.

Chapter 2

Hardware and Software

This chapter describes the rationale behind our hardware decisions following the discussion of capture-projection technology, hand-held devices, and touch-sensitive surfaces in our previous literature review section. Specifically, we explain our choice of a capture-projection setup stemming from a set of design objectives. Technical details of these components are organized by functionality as an input or output component. Finally, the related software components supporting this hardware are described in Section 2.4.

2.1 Design Objectives

We decided to select a capture-projection setup using a camera and top-down projector as the primary input and output components. Since it is difficult for a camera to capture surface contact, we have incorporated a vibration sensor for this purpose. In this section, we explain our strategy for choosing each hardware component based on available technology and how well it satisfies our design principles.

We identified the following objectives as general considerations for the design of our TAR

Summary of Components by Objective			
Objective	Capture-Projection	Hand-Held	Touch-Surface
Affordable	Camera and Projector	4 Cell Phones	Tablet Devices
Lightweight	Camera and Pico Projector	PDA's or Cell Phones	Tablet Devices
Unrestrictive	Camera and Projector	PDA's or Cell Phones with one-hand interaction	Tablet Devices

Table 2.1 Listed are devices deemed as being the most suitable for each corresponding objective.

prototype. Several of these were addressed in existing research but were rarely considered together in a single prototype. To determine the most appropriate hardware setup, we compared the devices available for capture-projection, hand-held use, and touch surfaces, according to the guidelines described below. We rationalized our choices based on how well each setup addressed the evaluation criteria that characterizes each objective.

Since hand-held devices and touch-surface technology such as iPhones and iPads share many features, we will restrict the definition of hand-helds to include only palm-sized devices that are single- or multi-hand use. Touch-surface technology will be classified as anything larger than palm-sized systems, for example, iPads and large table setups such as the Microsoft Surface.

Affordable. To support a wide range of users, cost of components should be minimized without sacrificing functionality. This can be accomplished by choosing ubiquitous hardware components. Whether there will be increased hardware costs or requirements for multiple users should be considered as well.

We limited our choice of hardware components to approximately \$500 USD, a rough estimate that we deemed affordable for the average consumer. Eligible systems were also required to support at least four players in a multi-player setting. Ubiquitous components were chosen whenever possible to decrease the potential for additional costs in cases where

consumers already own the required device.

The most suitable setup for the “capture-projection” category would be a camera-projector system. The large interaction area supported by these components facilitates four users interacting simultaneously. Although video projectors are not as ubiquitous as hand-held devices such as cellular phones, cameras, in particular webcams, may be considered equally pervasive to hand-held systems. As such, the average cost of a camera-projector setup depends predominately on the projector price. Current units within the stated price budget do support our requirements.

The hand-helds option would involve the use of four personal palm-sized systems similar to iPod Touch or Blackberry devices. Although the actual cost of the described hand-helds is on average \$200 USD per unit, in reality, given the ubiquity of these devices due to the sheer number of sales of iPod Touch¹ and Blackberry² units, we argue that it is reasonable to assume an average cost per unit closer to half of that price, i.e., \$100 USD, after subsidized phone costs and provider fees.

Finally, given the high cost of touch-surface systems such as table setups, we are limited to smaller tablet devices such as the iPad. Although tablets allow a variety of uses, facilitating four players simultaneously may be difficult due to limited screen size.

Following the imposed cost and multi-player requirement, both camera-projector and hand-held systems appear to be suitable choices for a TAR gaming platform. Since we are interested in providing an integrated environment that seamlessly blends virtual components with real objects, we decided that a camera-projection setup would be the most appropriate option. This effect cannot be achieved with hand-held systems because augmentation is displayed on a separate view that is spatially isolated from the physical space.

1. iPod Touch sales: <http://www.macworld.com/article/140165/2009/04/ipodtouchsales.html>

2. <http://wirelesscanada.blogspot.com/2010/01/iphone-android-blackberry.html>

Lightweight. A portable, lightweight system that allows interaction in a variety of social and physical environments would be highly favored. To maximize portability, smaller, lighter components should be favored over larger, cumbersome pieces whenever possible.

Since portability is associated with size, the smallest hardware setup, hand-helds, is ranked highest in this category. Next are capture-projection setups using laser pico projectors coupled with cameras. The specific requirement for laser pico projectors is necessary to provide sufficient luminance for this setup. In the touch-surface category, tablet systems are considered to be the most lightweight option. Although tablet devices are an improvement to the bulky touch-surface tables, they are the least lightweight among the three categories due to their larger hardware screens.

Unencumbered. In many social gaming situations, players usually communicate using hand and body gestures to complement verbal discussions. Hardware components should aim to encumber players as little as possible to provide players the freedom to communicate with their entire body.

As the name suggests, players must hold hand-held devices at all times during use. This restricts the range of hand gestures to a single hand. Both touch-sensitive surfaces and capture-projection technology do not require holding, making them acceptable choices as they, in theory, allow for a wider range of hand gestures.

Following our three design objectives and the available hardware options for each, we decided that a camera-projector setup was the most suitable TAR gaming platform. Since our research deals with investigating social and physical interactions, we decided to choose a platform that would provide maximum support for social interaction, namely, one ranking favorably in the “unencumbered” objective while considering the affordability and lightweight objectives as well. The following section describes the specific hardware pieces and technical details, separated by input or output functionality.

2.2 Input

Our choice of a camera-projector setup resulted in a configuration that features a single camera and projector mounted above our interaction space. Since it is difficult to detect surface contact with cameras alone, we included a lightweight, affordable vibration sensor that recognizes touch through surface reverberations. We also describe the use of biosignal sensors as a technique to gather physiological data from the user to determine emotional responses. Below, we discuss the particular hardware components used in our research and software specifications required to support the physical components of our TAR gaming system.

2.2.1 Camera Input



Figure 2.1 Point Grey Flea-2 Camera.

The input for our system consists of a single ceiling-mounted Point Grey Flea 2 Model FL2-08S2C camera with maximum resolution of 1032×776 pixels with color in YUV or RGB format. This is a Firewire B camera that produces a maximum bandwidth of 800 Mbps as limited by the bus. Despite these camera specifications, our applications only used

black and white images in a reduced area of 1024×768 pixels. This was the maximum supported resolution by the third-party software libraries used for our camera.

Our camera is mounted 2 meters above the capture surface and has a field of view of approximately 1.5×1 meters using a 8 mm monofocal lens. After several rounds of pilot testing, we found approximately 15 frames per second to be sufficient for our game applications; a lower frame rate resulted in perceivable delay during gameplay. It is important to note that this is a minimal requirement and higher frames per second would suffice as well.

To support camera detection of physical objects, game pieces are tagged with fiducial markers from reacTIVision³, an open source software package used for camera recognition. ReacTIVision is a cross-platform vision framework for fast and robust tracking of fiducial markers designed for rapid development of table-based tangible user interfaces. Multi-touch finger tracking is also supported. Game applications are implemented in Processing, a Java-based open source programming language used to create images, animations, and interactions quickly.

2.2.2 Vibration Sensor

The vibration sensor is a piezoelectric transducer built following the Signal Conditioning Piezoelectric Sensors Application Report [20]. The vibration signal captured by the piezoelectric sensor is transmitted to a connected Arduino Diecimila board⁴ with 10-bit ADCs that communicate output signals to the main computer over a USB interface.

3. <http://reactivision.sourceforge.net>

4. www.arduino.cc, www.wiring.org.co

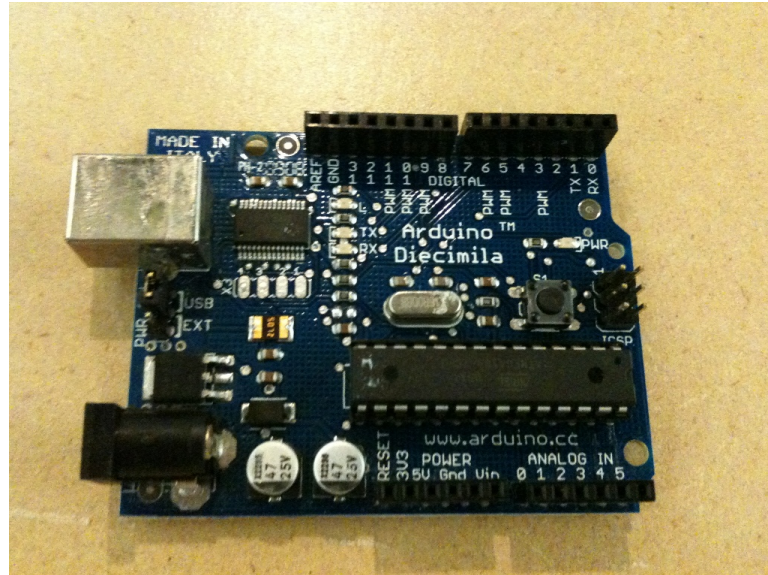


Figure 2.2 Arduino Diecimila board.

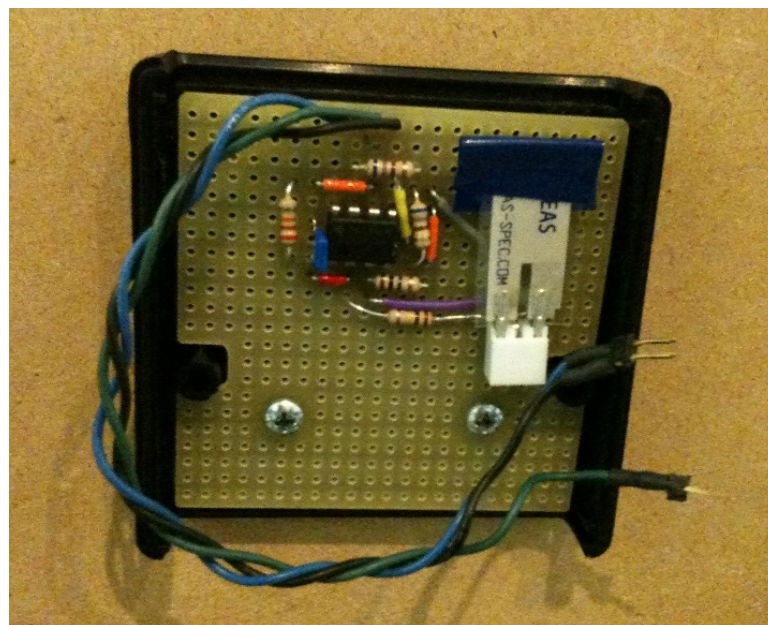


Figure 2.3 Our custom-built piezoelectric sensor.

2.2.3 Biosignal Sensors

To acquire live data from the participants, we used medical-grade biosignal sensors from Thought Technologies ProComp Infinity. These were attached to one hand to collect blood pulse, heart rate, and galvanic skin response at a sampling rate of 2048 Hz. The sensors were relayed to a hardware hub, shown in Figure 2.4, connected to the computer by fiber optic cable.



Figure 2.4 ProComp Infinity Hub.

2.3 Output

Without HMDs, our capture-projection setup must use either a front or back projector as the main display output. To refrain from making a custom table surface for back projection, we used a top-down front projector arrangement.

A Hitachi CPX-5 projector with maximum resolution of 1024×768 was mounted next to our input camera 2 meters above the table surface. At this height, the maximum projected

image was approximately 1.35×1.80 meters with brightness of 161 candelas per square metre (cd/m^2), viewable in a room with maximum brightness of 250 lux equivalent to a moderately lit indoor room as determined by the Hitachi CPX-5 Projection Calculator.⁵ Our largest tested game board occupied approximately 50×50 cm at a resolution of 500×500 pixels when projected on the table, roughly the same size as Parker/Hasbro's Monopoly game board. For lighting conditions of more than 250 lux, the projector throw distance must be reduced proportionally to the increase in lux.

2.4 Related Software

Each hardware component has a corresponding software program for translating raw data into useful game information. A diagram illustrating the flow between software and hardware components is shown in Figure 2.5. Details of the physical die detection mechanism and the algorithm used to filter capture data is explained below. In addition, a technique for sensing and initiating a virtual die using physical gestures such as knocking is described.

Interactions such as dice rolling were initiated with either a real die or knocks on the table to simulate tangible and virtual interactive techniques, respectively. The former required a black die with white pips for tracking through the reacTIVision software. Because reacTIVision received input in black and white, the white pips on a black background resembled finger tips, allowing artificial tracking of dice numbers through the finger tracking mechanism of this program. To avoid erroneous tracking due to noise or accidental covering of the dice, we implemented several filter algorithms to verify tracked "fingers".

Detected pips from a real die were considered a dice roll only if it passes a set of criteria.

5. See <http://www.projectorcentral.com/Hitachi-CPX5-projection-calculator-pro.htm>

First, the pips must remain within the same spot for a minimum user-specified number of frames. In our experiment, this was set to 15 frames and equates to approximately 1.0 seconds of detection time with a camera recording at 15 frames per second. This provided us with an ample number of frames to ensure the robustness of counting the correct number of pips. We found one second to be the maximum tolerable detection time for users. Next, if an identical set of pips was detected in the same position as in the previous dice roll, this suggested that the die was occluded and revealed rather than re-rolled. In this case, the detection result was rejected. We found these two filters to be acceptable for eliminating noise and identifying dice rolls.

For the knocking mechanism, the signal received from the Arduino microcontroller was handled using the Serial package native to the Processing programming language. This package converted the USB signal into an integer that increases with the strength of detected vibrations. A reasonable threshold was tested and set to prevent accidental bumps or shuffles from triggering the virtual dice roll.

2.5 Overall Environment

After careful consideration of the available technology for the three design objectives described in Section 2.1, we came to the conclusion that a camera-projector setup would be most appropriate. In general, our TAR prototype, pictured without physical game pieces in Figure 2.6, may be separated into three distinct categories: input, output, and game pieces. Visual input is captured using an overhead camera while a pizoelectric sensor attached beneath the table detects surface contact. Output is projected top-down onto a regular table surface with a minimum size requirement of 90×90 cm to support the maximum game board size and extra table space for game pieces. All input and output

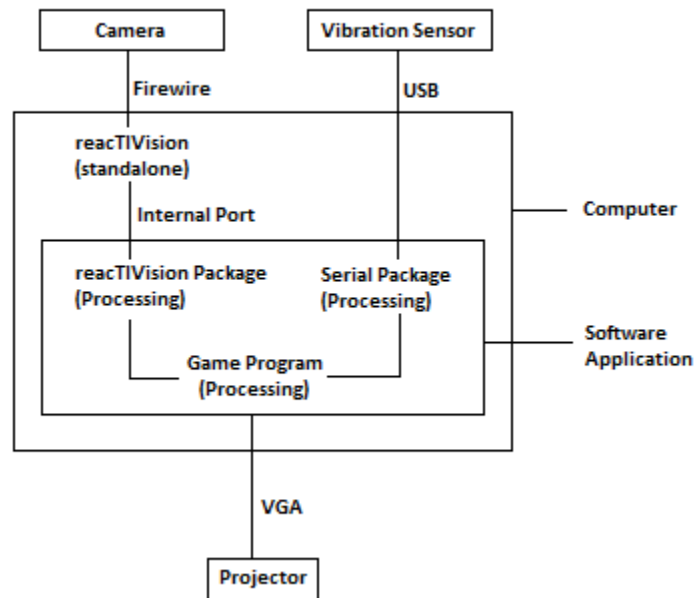


Figure 2.5 Hardware and Software Flow Diagram.

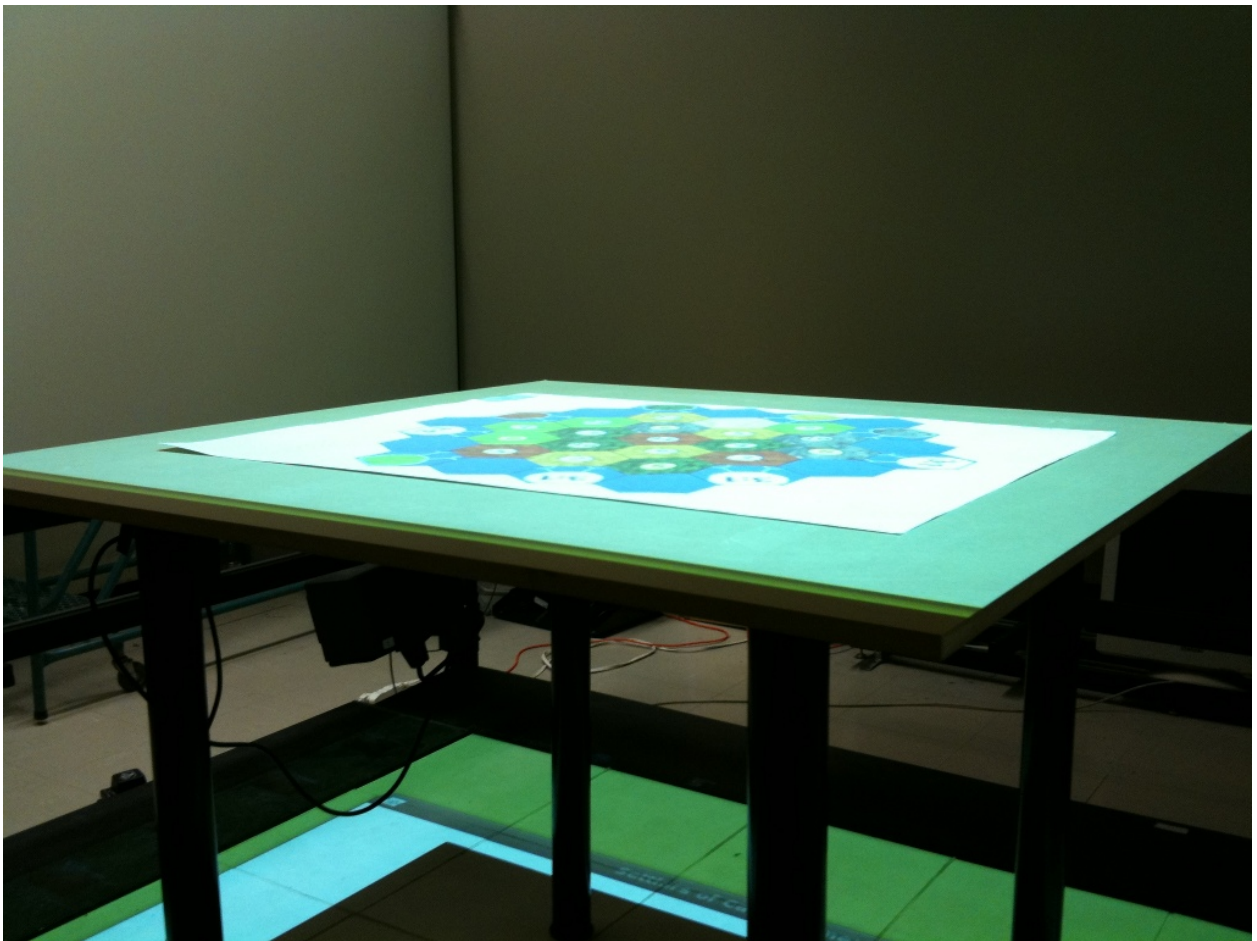


Figure 2.6 The game environment, consisting of an augmented game board projected onto a sheet of paper from above.

is controlled by a single computer that also drives the software developed to support the hardware components as described in Section 2.4.

Our choice of generic hardware components allows each device to be used for other purposes when not needed by our applications. Since projectors and cameras are mainstream technologies, our setup is easily available to anyone interested in deploying it.

Chapter 3

Tower Defense

The tower defense application, tau, was the first implementation used to explore the affordances of tangible components in an AR gaming environment. Tower defense falls under the genre of real-time strategy games. The goal is to prevent a steady stream of computer-controlled invaders from reaching the player's home base, a location defined at the start of the game. In order to stop the constant flow of marching opponents, artillery towers capable of firing projectiles must be placed in various strategic positions on the map to destroy invaders. Tower placements always cost resources, such as gold, that are collected when invaders are killed. The emphasis on spatial information renders this game highly suitable for testing the design of different tangible interaction components.

In this chapter, we discuss the software specifications of tau and the development process of the physical interaction components from a user-centered perspective.

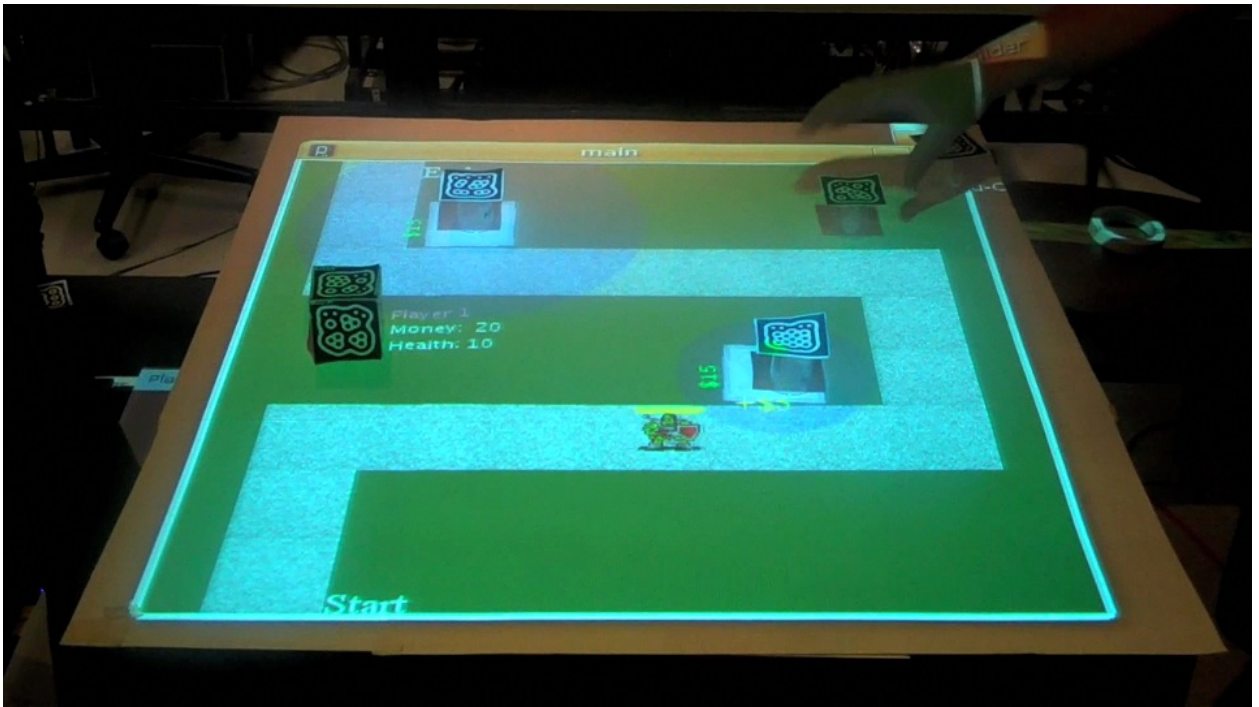


Figure 3.1 Augmented Reality Tower Defense

3.1 Software

The game program is responsible for five major tasks: tracking and identifying fiducials, generating corresponding digital effects, creating and moving invaders, keeping track of the player's score and producing the game board. Two types of physical playing pieces, tower tokens and status cards, are used in this setup. When placed in the game area, tower tokens respond digitally by firing virtual bullets at advancing invaders within a specified range that is marked with a translucent circle. At the same time, status cards are used to control game flow and allow the following actions: play, pause, reset, and stats. Play begins or resumes the game, allowing invaders to move towards the destination. Pause saves and freezes the game state and requires the play card to resume. Reset restores the player's life and gold to its initial state and moves the invaders back to the starting

location. Stats projects the player's current health and gold next to the physical marker, which dynamically rotates and moves according to the marker's position.

Game play is similar to most tower defense games. Once loaded, a grassy field with a pre-defined, twisting gravel path is displayed on the table. The two ends are marked as either start or finish. The game begins when the play card is placed in a trackable location on the board. As the invaders walk down the gravel path, the player must place towers in the surrounding grassy areas to prevent them from reaching the end destination. If towers are placed on the path, a red circle is projected around the tower to indicate incorrect placement. Misplaced towers need to be moved to grassy areas or they will not fire projectiles at incoming invaders. If players are unsuccessful at stopping the invaders, one life is lost per invader reaching the end. The game terminates when all lives are lost or when all invaders are destroyed. Players have the ability to pause, reset, and view stats any time during the game by placing the appropriate card in the playing space.

3.2 Iterative Development

To determine whether our unique, tangible objects are appropriately designed for a TAR prototype, we went through an iterative development process that allowed us to evaluate and improve the tangibles according to user feedback. This specific development process was chosen because it allowed us to test and revise physical components several times to ensure design goals were met. In addition, testing helped us verify whether the designed tangibles were adequate as interaction components in a TAR setting. The lessons learned from this development process are then considered in subsequent applications and experiments described in the following chapters. Below, we list the usability improvements for both tangible and digital components.

1. **Status Cards:** The physically separated status cards were understood as distinct game events that were activated one at a time. However, players found the remove-replace process tedious and unnatural as they would forget to remove the card on the table before placing another. In addition, players were uncertain about where unused status cards should be placed. Since players were often occupied with moving token towers and walking around the play area, excess status cards needed to be placed down in an accessible location that was outside of the detection area to prevent unintended activation. To address this issue, we decided to adapt the design of a die. Its faceted design allows status cards to be mounted on different faces of the same object, reducing space requirements. By simply rotating the control cube, players were able to transition between game states more smoothly than with the status card remove-and-replace procedure. One drawback of this technique is the need to explore multiple sides of the cube to locate the next mode.
2. **Tower Tokens:** These were originally designed as flat fiducial tokens. Although portable, it was difficult for players to distinguish between different towers and grasp the flat token. To resolve this, we used color-coded cylinders top-tagged with fiducials. The cylinder allowed players to distinguish tower types on first glance and move towers more easily due to the increased area of the object.
3. **Error Feedback:** Invalid tower placements, such as on the gravel path, were initially marked by a red “X” projected onto the tower’s fiducial marker. Since the projection was partly obscured by the fiducial marking, players found it difficult to see the error. To increase visibility of errors, we replaced the red “X” with a translucent red circle projected over the fiducial and a small surrounding area to indicate incorrect placement.



Figure 3.2 Left: Status cards are glued to faces on a cube; Middle: Color-coded towers; Right: Invalid and valid placement of token.

3.3 Summary

Lessons learned from developing tau may be generalized into two concepts:

Use specific object shapes to encourage specific physical actions. The physical affordances of the status cube naturally facilitated a specific set of actions. The dice design allowed game states to be separated and activated one at a time. Cylindrical tower tokens allowed for easier grasping and moving.

Use shapes and colors to distinguish between elements. Tower tokens and error circles of different colors were used to convey messages such as invalid or valid placement. These color and shape differences were easily discerned by the player on first glance, reducing cognitive load for other tasks.

Overall, this implementation allowed us to explore the interaction benefits of tangible components in an augmented reality setting for a game centered around spatial information. These initial findings encouraged us to investigate whether tangible or digital components are more suitable for common game tasks such as token placement and dice rolling. The next two chapters describe applications that were developed to compare tangible vs. virtual components in different game scenarios. Formal experiments were conducted to support our comparisons.

Chapter 4

Olympic Dice

This chapter describes our second AR implementation, Olympic Dice, a basic roll-and-move board game with a layout similar to games including Sorry!, Monopoly, and Parcheesi. The findings from our tower defense application inspired us to consider whether tangible or virtual components would be preferred in a simplistic game setting.

4.1 Experiment

With our Olympic Dice application, we set out to investigate the tradeoff between interacting with tangible vs. virtual objects, both in single- and multi-player settings. We also hoped to determine whether the player's gaming history and preferences are useful predictors for favouring a particular interaction technique. As such, we asked participants to list the genres of games they have played and their preference between single- or multi-player game types. If a significant correlation between these player preferences and the research results can be found, this study may have implications for the design of new computer-enhanced games meant for specific demographics.

To assist our investigation, we implemented variations of virtual and physical interaction elements that are vibration-sensed and fiducial tracked, respectively, into our TAR system. To ensure that our tangible interaction components comply with standard HCI principles, we identified a number of prerequisites following guidelines provided by Norman [21] and Fitzmaurice [2]:

- Direct manipulation of virtual game objects through a physical object.
- Attempt to use descriptive physical controls in place of buttons.
- Facilitate direct communication between players.
- Parallel operation of single or multiple game pieces.
- Physically descriptive components that elicit behaviours such as grasping, pulling, twisting, etc.
- Allow natural spatial reasoning skills to be used through the presence of physical objects on a table surface.

Our experiments were designed to test whether the TAR paradigm would be appropriate for board games and if so, whether interaction with tangible objects would be preferred over purely virtual game objects in a computer-enhanced board game. Our hypothesis for the former question was that this would be the case for the following reasons:

- Board games often do not have a fixed number of players. Sometimes players may choose to play in teams and interact simultaneously on the system. Unlike traditional controllers, tangible objects allow people to operate in parallel in the multi-player and multi-handed sense.
- Individuals interact in the same game space while facing each other. This is necessary for many board games because players must communicate with others as part of the game.
- Many board game genres involve spatial planning, which has been shown to be better

suited for tangible objects [4, 18, 19].

- Physical components have always been used for board games.
- Player-to-player interaction is encouraged when components need to be passed and shared between people.

4.2 Game Tasks

To examine player preferences for the fundamental action of dice rolling and piece movement in roll-and-move board games, we set the task of collecting various items to earn points. This served as a realistic, albeit simplistic, scenario for testing different methods of interaction. Upon each game load, items were randomly placed on board tiles. Players rolled a virtual or physical die to determine the next destination tile for their game piece. Destinations were highlighted in a lighter color once the roll was acknowledged and players were allowed to move to any one of the marked locations. If the reached destination contained an item, the system recognized the player token, removed the item, and indicated the scored points for the player while playing a jingle. Three types of items with different values were used for the game. Cheese was worth five points, appearing only 10% of the time, strawberry was worth three points, appearing 30% of the time, and grapes were worth one point, with a 60% chance of appearance. Each tile had a 50% chance of generating an item when the board was initialized. We found that players often steered movements towards the cheese due to its scarcity and high value.

Two sample game configurations are shown below. In single player mode, the game continued until a pre-defined number of rolls were reached. When the player collected an item, another was randomly generated and placed in a free location. The multiplayer version contained a predetermined number of items and players competed to acquire the

most points. Although the game board is only shown in perspective for one player in Figure 4.1, the simple nature of the game allows players to view the board from any angle. Instead of using text to convey meaning, we opted to use symbols and pictures that are viewable from any perspective.

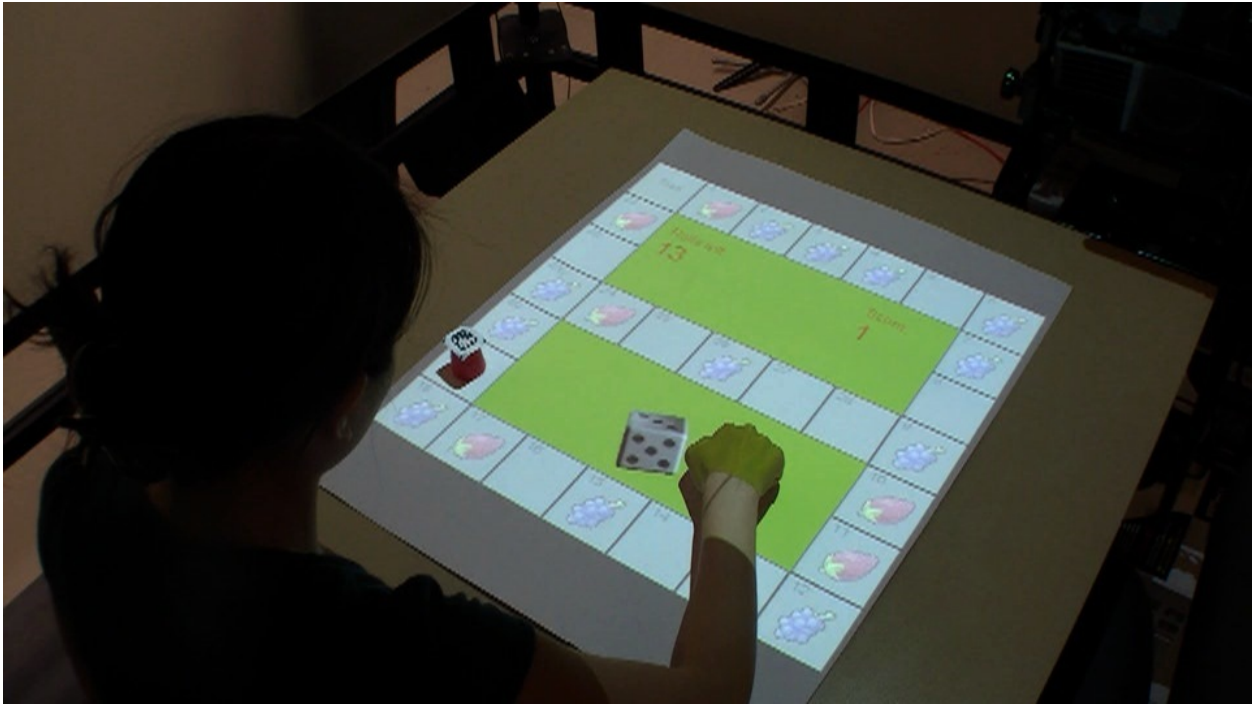


Figure 4.1 Olympic Dice Single Player

4.3 Experimental Conditions

To compare the effects of varying levels of game object augmentation, we designed our experiments around all 2×2 pairings of game die and player token, seen below. The former were either a physical, black die with white pips or an animation of a rolling die that was initiated with tapping or knocking on the table surface. The latter consisted of a player token that was either a physical cylindrical player piece or a virtual token, whose position



Figure 4.2 Olympic Dice Multi-Player

could be moved by placement of the player's hand over the designated square. Fiducial markers were used for identification and tracking of the token pieces.



Figure 4.3 Virtual Die, Virtual Token, Real Die, Real Token

4.4 Affective Evaluation

To determine the affective responses to the various game conditions, we collected biosignal measurements from players during the sessions and administered a post-test questionnaire after each condition. The recorded biosignal data was averaged across participants and the trend over time was observed for each condition, separated by type of sensor measurement: galvanic skin response (GSR), heart rate (HR), and blood volume pulse (BVP) amplitude. A rise in GSR is interpreted as increased arousal or engagement if found near the start of each session and as anxiety or boredom if at the end of the trial [22]. Differences in HR are likely to indicate physical exertion and emotional investment. A drop in BVP is usually related to adrenaline release, which causes constriction of the capillaries [23]. This may be interpreted as arousal or excitement. After each experiment session, participants were asked to rank enjoyability of the condition from 1 to 5, 1 being least enjoyable and 5 being the most. They were also encouraged to provide written comments regarding this experience, such as emotional reactions to the condition.

4.5 Design

As this was our initial study to compare methods of interaction, we were careful to keep our game basic to prevent genre bias from affecting interaction preferences. We were interested to see the players' reaction to the core qualities of each interaction paradigm in a neutral situation that favoured no particular characteristic. For example, a strategy game centered around spatial information may find that users prefer TUIs over gestural control because physical objects help with spatial planning and recall [4].

We conducted two separate experiments, one as a single-player game and the other as a two-player competition game. Our subject pool consisted of 32 participants, five female and 27 male, ranging from 23 to 40 years of age. These were divided between the two experiments into separate groups of 16 people for each experiment. For both experiment configurations, biosignal sensors were attached to one hand per participant for the duration of the session. In the single-player experiment, each subject performed a total of 12 sessions, divided into three sessions per condition. These consisted of one practice and two formal trials. Once a condition was finished, participants completed a questionnaire regarding their emotional reactions to the interaction technique. When all 12 sessions were completed, a final questionnaire was provided to determine overall preference and reactions to the experiment. The two-player experiment had a similar format except that subjects were paired against a new opponent for each condition.

To prevent learning and ordering biases, we divided the 16 subjects in each experiment into four groups. Each group cycled through all four conditions in a different order. A modified Latin square was used where each condition appeared in every slot of the ordering. Before beginning the experimental trials, participants were asked to fill out a pre-test questionnaire used to profile their gaming preferences and experience. Once completed, we

attached biosignal sensors to the participant's hand to measure their baseline signals.

4.6 Results and Analysis

In both the single- and multi-player conditions, no significant differences were observed, either in the physiological measurements or the preferred method of interaction as determined from the questionnaire responses. Despite this, the additional comments provided by participants were informative and perhaps explain the lack of significance. Below, we list the summary of the additional comments collected from the completed post-test questionnaires. Negative traits items in bold; all others are positive qualities.

4.6.1 Questionnaire Results

Virtual Objects:

- Cannot cheat
- Novel die is faster; allows more intensive play
- Cannot roll die into other objects or off the table
- Token does not obstruct game board; cannot be knocked over
- Can reach destination with one natural reaching/grabbing gesture
- **Token blends with other objects; hard to track**
- **Automation makes players feel less engaged**

Real Objects:

- Affords cheating; requires players to moderate game
- Familiar experience
- Tangibility increases active feeling, “illusion” of control enjoyable
- Die is sensitive to manner in which it is rolled
- Token marks location clearly; helps with spatial planning and tracking

- **Token can be rolled into; die can roll into objects or off the board**

4.6.2 Analysis

In retrospect, we realized that the deliberate genre-neutrality of our game design, as noted above, in addition to limited game complexity, may have contributed to the lack of significance. While TUIs provided players a rich physical interaction experience, we were unable to demonstrate that this experience would also induce a positive physiological and verbal response when compared to virtual techniques. This may have been caused by the simplistic nature of our game.

Despite the lack of significance, there is considerable information in the questionnaire responses that can guide our analysis of the results. The reasons expressed for liking and disliking each condition were fairly consistent with each of the listed positives and negatives reported by at least two participants. This may help game designers understand the player's expectations and inform the creation of natural, engaging interfaces allowing absorbing gameplay.

4.6.3 Preference for Familiarity

Preference may have been biased by personal experience as demonstrated by the positive “familiar experience” comment for the real objects. People are comfortable with devices they have used before, such as the physical die, and often prefer to stick with familiar interaction techniques such as that for dice rolling. This may have caused people to prefer the tangible components for nostalgic reasons rather than interaction benefits. Designers may leverage this familiarity when creating a new game to ensure that their product will at least capture the interest of players who have been exposed to similar games.

4.6.4 Intensity and Speed

Use of our virtualized die resulted in faster games because only one gesture was required to initiate dice rolling. This was reflected in the players' comments where they mention that the novel die allows more intensive play. With the physical die, players were required to reach and pick up before rolling, which added considerable delay, especially since the players were often concerned about the die rolling into other objects or off the table. This issue is also common in traditional board games. Depending on the target audience and desired game speed, the designer should consider the number of actions required to activate recognition of either physical or virtual game pieces. Given that developers are only interested in natural interaction techniques, fast-paced games may benefit from simple, quick gestures while physical objects might help slower games engage users.

4.6.5 Illusion of control

The idea of being in control of your actions to affect the outcome of a game is appealing. Even for random events, such as dice rolling or revealing cards, people enjoy adding variations to the motions to affect the result, despite the fact that such acts have no actual influence on the outcome. This claim is supported by players preferring the real die, citing this exact explanation. As such, some players reported a lower preference for the virtual die, since the level of separation between variability in the players' gestures, e.g., how hard they knock the table, and the outcome of the dice roll, made it less likely that they would be prone to any such belief. This factor should be considered by game designers who wish to virtualize real objects. To retain the desired illusion of control, the game should support and acknowledge these "arbitrary" motions even if they do not directly affect the result. As an example, our virtual die could be made sensitive to knocking strength or types of

knocks, such as finger tapping vs. fist pounding, responding in a convincing manner, as described in the following section.

4.6.6 Level of physical engagement

Many people complained about the lack of physical actions when using the virtual components and felt they were not actively engaged in the game. Specific comments were critical of the reduction of fun in the game resulting from automation of the dice. This may well be due to our implementation of the virtual die, for which the necessary gesture (knocking the table) had little to do with physically rolling an object. In contrast, some players mentioned that they enjoyed the virtual token because it simulated reaching and grabbing objects on the board, which was thus perceived as a less mundane or arbitrary gesture.

Unfortunately, not all physical affordances can be virtualized. Some people enjoy the sensation of tangible objects and consider them more legitimate due to their physicality. For example, anecdotal evidence suggests that there are those who enjoy playing poker online but prefer watching a dealer through a live video feed physically dealing and revealing cards, because they distrust the artificial, virtual equivalent. Regardless of whether game designers choose to use tangible components, it is important to consider the realism of the interaction technique and its sufficiency to create a sense of active engagement. For virtual components, one way of achieving realism is to design virtual interactions that comply with simple laws of physics. Applying this to our virtual die implementation, we could animate the die to “jump” in response to each knock, more closely simulating the equivalent real world behaviour.

4.7 Discussion

We should be cautious about inferring that the lack of significance in our experimental results suggests an equivalence of enjoyment between the use of physical and virtual objects. As noted above, the simplistic nature of our game likely played an important role in these findings. However, the lessons learned from the player comments can be generalized easily to more complex situations. Player feedback from our study suggests that perceived affordances are just as important as actual affordances [24] when designing interaction methods for augmented reality games. It is essential for designers to understand the player's perception of the game if they wish to create systems that facilitate the desired method of interaction and expectation of game behavior.

Our next objective was to conduct a similar experiment with an existing board game of higher complexity, such as *Carcassonne* or *Settlers of Catan*. This allows us to utilize the full potential of the proposed interaction paradigms and determine whether genre is a factor for interaction preference. The next chapter describes such work, continuing our testing with games that require spatial reasoning to challenge our hypothesis of tangible components being superior for spatial tasks.

Chapter 5

Settlers of Catan

We now turn to our final experiment, which was informed by the issues and results of the study described in the previous chapter. Our assumption that the lack of significance was caused by limited game complexity motivated the use of a more demanding, German-style board game. This style of table-top gaming emphasizes strategy and involvement of more than two players, fitting our complexity requirement for both individual and group interaction. More specifically, we chose the Settlers of Catan game as it encourages, but does not enforce, multi-player interaction in addition to single-player strategy. For example, the choice of players to engage in trades with others helps us determine whether people enjoy exercising the different trade mechanisms implemented for each condition.

The goal of the game is to be the first player to reach ten points accumulated by constructing buildings or purchasing special cards. In order to do so, players must spend resources that are generated by dice rolls and traded from other players or the bank. Balancing the advantages and disadvantages between trading with others and relying on oneself is the most important and complex strategic component in this game.

The comparison study for Settlers of Catan is presented on the classic board game

version, our developed TAR version, and a digitized version on the Apple iPad. As we move from the classic to the digitized version, the number of tangible components decreases as the amount of automation and rule enforcement increases. Fewer rules are enforced when tangible components are present to accommodate rich object manipulation techniques. For tasks where no tangible handle is available, computer automation and rule enforcement are used to guide and inform the player of the actions available.

The classic version of Settlers of Catan demonstrates an abundance of tangible components and player-rule enforcement. Self-moderated game play facilitates house rules and other exceptions that may not be allowed in the enforced-rules versions. This is desirable to accommodate player customization and self-learning but also undesirable because it allows cheating and forgetting. Since automation is not present in this condition, comparison with the TAR and digitized version demonstrates the strengths and weaknesses of virtualizing components.

The TAR system was designed to accommodate the flexibility of tangible components while assisting players with automation and digital cues. Tangible game pieces and resource cards are used to facilitate natural interaction. One method of digital assistance is the process of randomizing and setting up the game board. Although this task may appear to be trivial, it may take up to five minutes for shuffling, sorting, and organizing of game components. Because our specific TAR implementation of Settlers provides instant setup, players may reset the board if desired, an option that is possible but not practical with the traditional version. In addition, this platform assists players by illuminating the appropriate game components corresponding to each dice roll, reminding players of the effects for the particular game action. Our hypothesis is that tangible components are ideal for making strategic decisions while virtual equivalents are preferred for non-strategic, tedious tasks.

The digitized version demonstrates the effects of full automation and rule enforcement

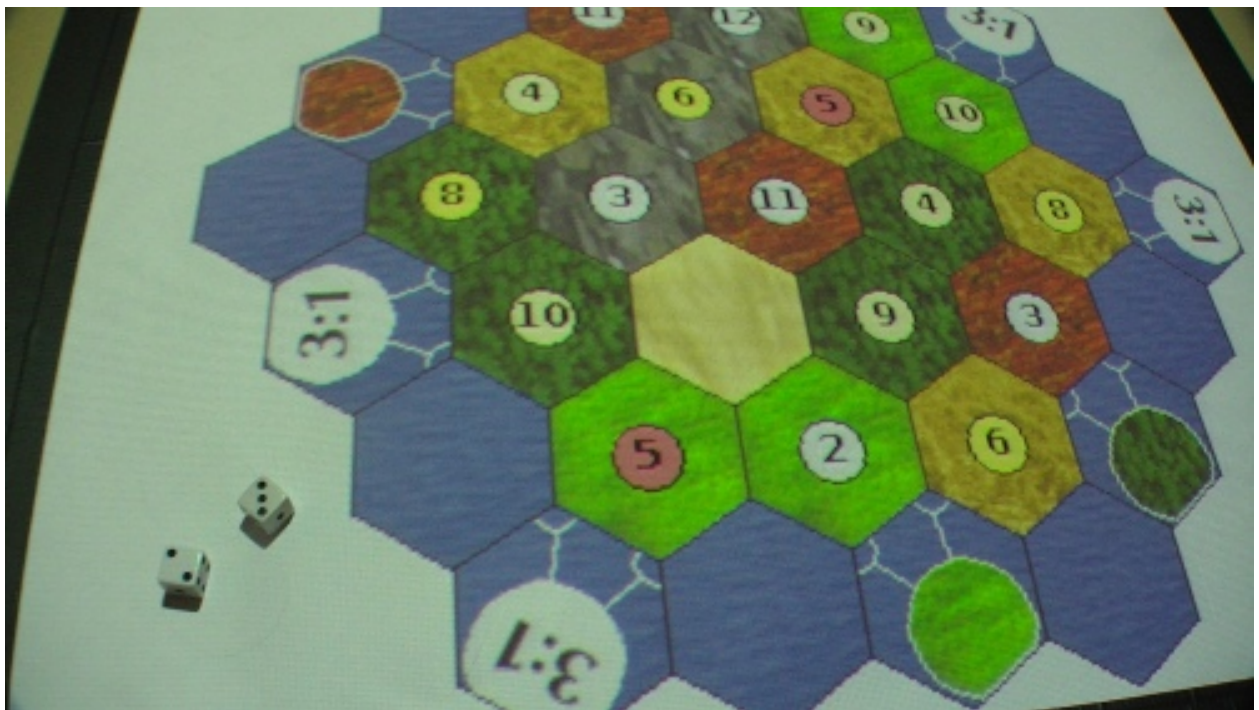


Figure 5.1 Value of the dice roll is detected; corresponding number lights up.

in the absence of tangible components. Game flow is governed by software implementation as actions are presented in the form of on-screen buttons. Unlike the other versions, the number of points, resources, and other statistical data pertaining to the game is readily available to the player. By comparing this to the TAR implementation, we determine the effects of automation and strict rule enforcement on player enjoyment.



Figure 5.2 Settlers of Catan Classic Mode

5.1 Measurement

The fundamental goal of our experiments is to determine the level of enjoyment for each interface condition. To measure fun, we compiled a post-test questionnaire comprised of questions from FUGA’s Game Experience and Social Presence in Gaming Questionnaire (GEQ and SPGQ) [14, 15] and O’Brien’s User Engagement Scale [13]. The FUGA GEQ



Figure 5.3 Settlers of Catan TAR Mode

and SPGQ aim to classify enjoyment of video games into different categories of emotions to better understand how games affect players psychologically. The O'Brien's User Engagement Scale is used to determine how immersed players feel during the gaming experience. Questions pulled from either questionnaire are organized by their categories as described from the source. In addition, we reduced the number of questions per section to allow completion in a reasonable amount of time. For the User Engagement Scale questions, re-wording was necessary to fit the gaming context of our study. We retained the five-point Likert scale from both questionnaires and score responses as described in the respective sources [25, 14]. Qualitative data was also gathered through video recordings and written observations for each experimental session.



Figure 5.4 Settlers of Catan Digital Mode

5.2 Hardware Configuration

Hardware decisions in this study were balanced for cost and accessibility to provide a fair comparison. Components used in each experimental condition were within the price range of the average consumer. The classic condition for Settlers of Catan used the original board game as is. The TAR system required an overhead mounted projector and camera, a computer, and a table for projection. For the digital version, we decided to use a readily available commercial software implementation of the game, running on an Apple iPad, instead of considerably more expensive alternatives such as Microsoft Surface.

5.3 Software Specification

Software specifications for the TAR setup were similar to the Olympic Dice prototype, excluding the reacTIVision package. A diagram of the hardware and software flow process is shown in Figure 5.5. Since reacTIVision, OpenCV and Processing were all compatible with Java, it was easy to integrate the three components together in our software design. Camera input was handled by an OpenCV package that is integrated into our Processing-based application. The received video input was filtered using image processing techniques to isolate dice pips. To increase robustness of detection, we limited detection area to the white background space around the game board.

A new game board of 500×500 pixels or 50×50 centimeters was generated automatically on each execution of the program. The tileset and board setup algorithm were based on JSettlers, an open source Java Settlers application.¹ Color and code modifications were made to improve visibility and suitability for our setup. Once loaded, the camera captured a snapshot of the initial game board for background subtraction.

Next, each video frame was subtracted from the saved background image, converted to black and white, contrast adjusted, and thresholded to remove noise and shadows. The contrast and threshold values require manual adjustment for proper detection in various lightning conditions and were determined empirically in our game for generic black and white dice. To increase robustness of detection, blobs with less than three pixels or more than 15 pixels were rejected. The resulting processed image contained circular blobs corresponding to the tracked dice pips. The number of blobs were counted and sent to the main game application for highlighting the associated numbers on the projected game board.

1. <http://sourceforge.net/projects/javasettlers/>

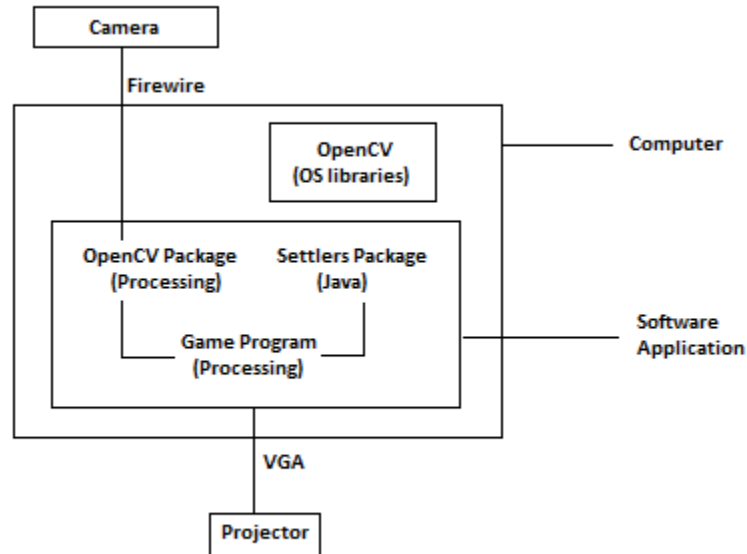


Figure 5.5 Data Flow for TAR Settlers of Catan

5.4 Design

The experiment comprised the three conditions as described above. Our subject pool consisted of nine participants, two female and seven male, ranging from 23 to 30 years of age. The participants were randomly assigned to one of three groups of three players. Eligibility criteria included prior experience with the game and familiarity with the other players to avoid learning and stranger biases, and to ensure a realistic board game playing situation. The groups were presented with every condition, with each group experiencing the conditions in a different order. A modified Latin square was used where each condition appeared in every slot of the ordering. The post-test questionnaire was completed immediately after each gameplay session. Once all three conditions were complete, players were asked to choose what they considered to be the best overall condition.

5.5 Results and Analysis

The questionnaire was comprised of two high level categories: personal game experience and social experience. These reflect the single-user experience and between-player experience, respectively. The former measure the player's mental and emotional state on items such as level of frustration and comprehension (perceived usability), look and feel of the interface (aesthetics), gameplay immersion (focused attention), sensory stimulation (sensory and imaginative immersion), willingness to play again (endurability), fatigue and attentiveness (negative affect), and level of enjoyment (positive affect). Social experience questions deal with the enjoyment of playing with others (empathy), competitive and aggressive feelings towards others (negative feelings), and acting or reacting to other players (behavioural involvement). One or more questions make up each of the listed sections in both personal and social game experience. The full questionnaire is provided in Appendix A, along with the rank definition for the answer scales.

The responses within each category were averaged to form the associated mean score, as shown in Table 5.5, separated by subject and condition for analysis. Since the multiple questions under each heading were equally relevant to the evaluation of enjoyment, we were able to justify the use of averaging to calculate an overall score. Significant difference between the conditions was determined using one factor repeated measures ANOVA. A post-ANOVA multiple comparisons test was performed on the data from Table 5.5 to determine which means exhibited significant differences.

As seen, the TAR condition was rated the highest most frequently in the questionnaire, an overwhelming preference that was also reflected in the qualitative feedback. All players chose TAR as their favorite condition in the final questionnaire. In general, players found tangible components essential for complex interaction tasks such as negotiation and resource

Questionnaire Results			
Section	Mean		
	Classic	Digital	TAR
Personal Game Experience			
Perceived Usability ²	3.04	2.11	3.59
Aesthetics	3.94	3.56	4.28
Focused Attention	3.67	2.89	4.44
Sensory and Imag. Immersion	3.78	2.94	3.83
Endurability	4.33	2.83	4.50
Negative Affect ²	2.78	1.78	3.00
Positive Affect	4.17	3.28	4.50
Social Experience			
Empathy	3.33	3.19	3.83
Negative Feelings	3.37	3.22	2.96
Behavioural Involvement	3.85	3.26	3.89

Table 5.1 Mean score averaged over all subjects.

trading. At the same time, players preferred the efficient, automatic board setup for its organized presentation where the board components could not be disrupted. The computer-assisted task of illuminating dice rolls was also desired because it located and reminded players to collect resources.

The significant difference in empathy [$F(2,16)=5.16$, $p<0.05$] was an unexpected finding. Because players played the same game with the same people for each condition, one would expect the between-player interaction to be similar in all conditions. As predicted, this was the result for the other two social experience categories. Further means comparisons revealed that players preferred the TAR version over digital while preference for the classic condition was not significantly different from either. The significance in empathy may have been affected by the single-user “positive affect” experience since they both relate to desirable emotions.

5.5.1 Settlers of Catan Trading Mechanism

Further qualitative feedback and written observations demonstrated that players were strongly averse to the trading mechanism in the digital version. Specifically, players disliked the implementation constraint that precluded negotiation with multiple players in parallel, or jumping in immediately with a counter-offer. Another factor weighing against the digital version was that once players agreed verbally to trade, they were required to repeat the process through the computer interface. Other observations noted differences in quality and complexity of trading interactions between the digital and tangible representations. The physical components facilitated sophisticated trades and greater eye contact as shown in Figure 5.6. Often, instead of strictly requesting a resource in exchange for another (the only technique available in the digital version), players would first request a specific resource then ask what others would like in return. Judging by the reactions and responses based on qualities such as willingness and response time, the requester is able to gather more information to negotiate in their favor. We also found players offering others the option between multiple resources during trades, a technique that is unsupported in the digital version unless specifically implemented. We also noticed that there were more counter-offer and trade revisions in the classic and TAR conditions. While possible in the digital implementation, doing so was more time consuming and tedious.

Another difference in trading related to player-bank exchanges, which, during normal gameplay, are usually executed immediately before purchases were made. Instead of conducting this transaction “properly” in two steps, first exchanging, then picking up the desired resource from the bank, players often employ a shortcut of leaving the traded resource in the bank and completing the purchase by depositing the remaining resources into the bank. Such “shortcut” behaviors, which are afforded naturally by tangible components



Figure 5.6 Tangibles facilitate greater eye contact during trades.

with no further implementation effort, must be implemented explicitly in the equivalent virtual environment. Regardless of feasibility, there is considerable risk of feature overloading, increasing complexity, and impacting usability. Despite the fact that the fundamental trading mechanism in both the tangible and digital conditions accomplishes the same end goal, the rich affordances of physical components seem to contribute to significant differences in usability [$F(2,16) = 9.83, p < 0.01$], sensory stimulation [$F(2,16) = 8.49, p < 0.01$], endurability [$F(2,16) = 13.24, p < 0.001$], negative affect [$F(2,16) = 6.51, p < 0.001$] and positive affect [$F(2,16) = 10.82, p < 0.01$]. In all these categories, multiple comparison of means found the digital version significantly less preferred than either the classic or TAR conditions.



Figure 5.7 Stealing becomes more personal with Tangibles.

5.5.2 Screen Size Concerns

We also considered the possibility of a bias in the results stemming from the difference in screen resolution between the digital and other two conditions. While the classic and TAR versions had the same board size, as seen in Figure 5.8, the screen size for the digital version was proportionally smaller. This led us to include a question on user preference for screen size. One-way repeated measures ANOVA verified significance between the conditions [$F(2,16) = 7.49$, $p < 0.01$], which appears to confirm our suspicion of bias. Further mean comparisons revealed that a significant difference was only found between conditions TAR and digital.

Since the TAR and Classic setups are identical in physical size, we would expect the scores from both conditions to be nearly identical as well. Our results indicate otherwise,

Screen Size Results - Mean				
	Classic	Digital	TAR	p
Enjoyed Screen Size	3.78	2.89	4.44	<0.01

Table 5.2 Mean values for screen size preference.

suggesting that unaccounted factors may have affected these findings. Upon further investigation, we discovered that players ranked the screen size question using additional criteria such as “neatness” and “contrast”. While these comments were insightful, they demonstrate that our findings do not confirm or disprove our hypothesis of a screen size bias.



Figure 5.8 Superimposed classic tiles are the same size as the TAR projected tiles.

5.5.3 Privacy Concerns and Existing Implementations

Another reported issue with the digital version is the problem of privacy. With a single screen, it is difficult to conceal personal cards from other players. In our experiment, players had to look away when someone wanted to inspect his or her cards privately. A superior alternative to supporting private information would be to use mobile devices, such as PDAs or cellular phones, or shields to cover portions of the screen, the former being more dynamic albeit at the expense of higher cost and additional hardware requirements. Both of these techniques have been demonstrated by existing augmented reality games such as KnightMage [9], and the Microsoft Surface version of Settlers of Catan, respectively.

While both techniques appear to facilitate privacy well, one should consider whether these implementations afford the same, desired actions as their tangible counterparts. In the Microsoft Surface Settlers of Catan game, the player's hand, i.e., collection of cards, is displayed on the digital screen and concealed by a physical shield. While this appears to function similarly to physical cards, there is a constraint of screen space, in particular when displaying a large hand of cards. In addition, the need to drag each card from the concealed area to the trading area implies that trading must be executed serially, card-by-card. In contrast, in the non-virtual implementations, players can quickly reach and deposit one or more physical cards. However, virtualized implementations offer other benefits such as the sorting and organizing of cards. The choice between physical affordances and digital assistance thus involves a usability tradeoff on different aspects of the game.

5.6 Discussion

The study described in this chapter tested different implementations of Settlers of Catan to determine the appropriateness of digitizing various physical elements commonly used in

board games. Our approach in this regard is to retain tangible components used for making strategic choices while digitizing pieces used for simple, mundane tasks such as the ones required for board setup. These qualities resulted in the TAR condition being the highest rated in many portions of the survey and unanimously chosen by players as their favorite. Preference of tangible components over digital equivalents for complex interaction tasks such as card trading was demonstrated by the significant differences between the virtual and tangible (identical in both classic and TAR) conditions in many areas of the questionnaire. However, the high degree of similarity between the classic and TAR conditions in terms of multi-player interaction led to no significant differences between these two.

Despite two possible biases that may have affected our results, we note the lack of a parallel in the digital version of the game for the rich physical affordances provided by the tangible components of our TAR implementation. Notwithstanding its attempts to mimic the behavior of physical objects, the purely digital implementation cannot easily support the same emergent behaviours that result from the use of physical pieces for trading. In contrast, tangible components naturally facilitate the same object manipulation skills that we exploit in physical implementation. Unfortunately, tangible interfaces are not always the best solution. Designers should consider the tradeoffs between reality and virtualization, favoring the option that is more practical, affordable, versatile, etc., as described in the reality-based interaction framework. While available resources and requirements may heavily influence this decision, consideration of digitization and its impact on enjoyment should be of utmost importance.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Important discoveries regarding the affordances of tangible and digital components for augmented reality games have been realized through investigations and experiments conducted using our three AR gaming applications: tau, Olympic Dice, and TAR Settlers of Catan. Our tower defense game, tau, served as the initial foray into tangible augmented reality for games. Important physical design principles were learned from this first investigation. This led to the design of our second prototype, Olympic Dice, that was used to determine whether the physicality of gaming components affects enjoyment in a formal experiment. The inconclusive findings from this study resulted in the development of a third prototype, TAR Settlers of Catan. The experiment conducted on this last application revealed the importance of using physical components for complex social situations.

From the Settlers of Catan study, it was interesting to see the differences in the quality of interaction for tangible and digital components that were designed to accomplish the same goal. Examples of the rich interaction techniques afforded by physical objects in our studies

provided strong justification for the inclusion of tangible objects in any game that requires a high communication bandwidth between multiple players in an effective manner. For example, tangibles may be better suited for collaborative tasks where efficiency is required to meet game-imposed time constraints. While the benefits of tangibles were formally tested only in our final Settlers of Catan experiment, we believe that other activities, such as debating with several people, requiring the same level of social complexity, will find tangible components best suited for interaction.

The lessons learned from this research allowed us to design components that are usable, ergonomic, and suited for multiplayer games. Considerations of cost, portability and ubiquitous components were acknowledged in each stage of our research by using non-specialized hardware such as cameras, projectors and computers. Our design choice of merging the input and output spaces into a single interaction area has allowed a smooth integration of the physical and digital world. This allowed us to create an indulging gaming environment that also facilitates integration of private viewing panels such as hand-held devices. Unfortunately, using an overhead projector occasionally occluded the scene. In the future, bottom-up projection and camera capture should be used to prevent this issue and allow for increased robustness in tracking.

Given that technology is becoming smaller but increasingly powerful, the hardware requirements for future generations of our TAR system are being rendered insignificant. With devices such as laser pico projectors where the image is always in focus regardless of size, restrictions of camera resolution and light intensity posed by our current setup are likely to disappear.

The benefits of both virtual and physical domains demonstrate the importance of their inclusion in the design of future game platforms. The tangible augmented reality paradigm offers the best of both worlds by combining the desired elements from each to create an envi-

ronment that emphasizes a rich experience from a social, sensory, and cognitive perspective. In such a setting, players are able to indulge their physical senses through complex, natural interaction techniques and fulfill high level cognitive needs without being hindered by menial tasks. By combining this concept with affordable, practical technology, the possibility of TAR gaming becoming mainstream may soon be realized.

6.2 Future Work

While many discoveries regarding TAR game interactions have been made in this research, further studies and improvements related to the automation of trivial tasks, player privacy and robustness of our system may be conducted to broaden the scope of our findings in the area of gaming. Below, we describe how each of these issues may be addressed in future studies using our prototype.

While we were able to justify the use of tangible objects for complex tasks, we were unfortunately unable to show that mundane tasks, such as setting up the board, were significantly preferred in a digitized format. Evidently, further testing is required to determine whether players indeed prefer to automate such tasks. This might be investigated in the context of a subsequent TAR implementation that includes a greater number of digital enhancements such as turn designation, score tracking, and valid piece placement options.

Continuing this study to investigate more thoroughly the options related to support of privacy in game-play, we plan to implement the shield method, score tracking, and valid placement, described in the Settlers of Catan experiment, in our next iteration. Possible implementations include detecting the presence of pre-made shields on the table before personal information is displayed, or by attaching private information to a tangible anchor that hides the information when tucked along the edge of the game board. In addition, we

will compare the use of shields versus physical cards in different multi-player scenarios that vary in interaction complexity to determine their effects on usability and enjoyment.

With the improvement of a bottom-up projection system, fiducial markers may be positioned faced down on the table to prevent distraction from other physical elements. Finger tracking would also be possible given appropriate camera detection methods for surface contact. To remain within our affordability goals, a bottom-up projection surface could be created using a glass table and a translucent film sheet. These improvements would greatly improve the quality of our prototype.

Although our research has been centered around new forms of entertainment, many of our discoveries could be applied to other types of activities. Other similar AR prototypes, like those from Billingham et al. [1], demonstrate that this platform is suitable for several types of collaborative tasks. This AR format may be used in a work setting to encourage discussions and facilitate collaboration on projects with minimal setup and cost. The spatial and multi-user affordances of this setup also facilitate teaching and instructing given that tangible components are used. Similarly, varying levels of digital assistance afforded by the AR setup may be used to teach young children important concepts while providing a practical, hands-on learning experience.

Appendix A

User Documents

Consent Form

Hello,

Today, you will be taking part in a study investigating interactive techniques for virtual board games conducted by Jessica Ip (Master's student) under Professor Jeremy Cooperstock's supervision at McGill's Shared Reality Lab.

In this study, we would like to determine the level of enjoyment for two different dice rolling techniques applied in a virtual board game context. Your actions will be logged throughout the test, and any comments you have will be noted by the investigator. Please do not hesitate to ask for help, verbalize any thoughts or comments you may have and let us know if you need to take breaks. The experiment should last about 20-30 minutes each session for a total of four sessions, and you will be compensated \$10 for your time once all the sessions have been completed.

For analysis purposes, we will ask you for your age and gender. This information and your identity will remain completely confidential in any report(s) of results of this study. All personal data will be password-protected and locked within the research facilities, accessible only to the experiment investigators. Please note that you are free to withdraw from this study at any time, and that you are entitled to have the researcher explain to you the purpose of the study after you have completed it. There will be no repercussions if you choose not to participate. We intend to disseminate the results of this research to relevant journal, conference publications and/or to future augmented board game designs.

In order to better understand your manipulation of the interface, we also request your permission to capture video recordings and physiological readings of you with medical-grade sensors during the experiment. These recordings will not be shared with anyone, and will only be used for analysis purposes. If you authorize us to capture this data, please initial here: _____

Finally, should you have any questions about this study, you may the research supervisor, Professor Cooperstock at email@email.ca. Concerns or complaints should be directed to the McGill Research Ethics officer at 555-555-5555.

I have read and understood this consent form. I agree to participate in this study.

Participant's name: _____

Signature: _____

Date: _____

Research Ethics Board Office
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Fax: (514) 398-4644
Ethics website: www.mcgill.ca/researchoffice/compliance/human/

Research Ethics Board I
Certificate of Ethical Acceptability of Research Involving Humans

REB File #: 416-0510

Project Title: Interaction Techniques in Augmented Reality Games

Principal Investigator: Jessica Ip

Department: ECSE

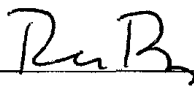
Student Status: Master's Student

Supervisor: Prof. J. Cooperstock

Funding Agency/Title: Centres of Excellence: Graphics, Animation and New Media

This project was reviewed on 7/5/2010 by

Expedited Review x
Full Review



Rex Brynen, Ph.D.
Acting Chair, REB I

Approval Period: May 18, 2010 to May 17, 2011

This project was reviewed and approved in accordance with the requirements of the McGill University Policy on the Ethical Conduct of Research Involving Human Subjects and with the Tri-Council Policy Statement: Ethical Conduct For Research Involving Humans.

-
- * All research involving human subjects requires review on an annual basis. A Request for Renewal form should be submitted 2-3 weeks before the above expiry date.
 - * When a project has been completed or terminated a Final Report form must be submitted.
 - * Should any modification or other unanticipated development occur before the next required review, the REB must be informed and any modification can't be initiated until approval is received.

Olympic Dice Pre-Test Questionnaire

Alias:

- 1) How many hours a week do you play board games?
- 2) List a few of your favorite board games.
- 3) How many hours a week do you play video games?
- 4) What platform(s) do you play video games on? List them all.
- 5) List a few of your favorite video games.
- 6) Suppose you and your friends decide to play a game. Out of the following options, which game(s) would you suggest? Circle all that apply.
 - Wii Sports/Wii Fit
 - Guitar Hero/Rockband
 - Halo, or similar FPS (shooter) game
 - Charades
 - Monopoly
 - Go/Chess/Checkers
 - Card Game: _____
- 7) Do you enjoy competing against other players? (multiplayer only)

Not at	1	2	3	4	5	Very much so
all						

Additional Comments:

Olympic Dice Between Sessions Questionnaire

Condition:
Alias:

1) Overall, the experience was...

Not Enjoyable	1	2	3	4	5	Very Enjoyable
------------------	---	---	---	---	---	----------------

2) The dice rolling technique was...

Not Enjoyable	1	2	3	4	5	Very Enjoyable
------------------	---	---	---	---	---	----------------

3) How did you feel about the token type?

Dislike	1	2	3	4	5	Like
---------	---	---	---	---	---	------

4) Your fatigue level is...

None	1	2	3	4	5	High
------	---	---	---	---	---	------

5) How stressful was it to use this dice technique?

Not Stressful	1	2	3	4	5	Very Stressful
------------------	---	---	---	---	---	----------------

6) How stressful was it to use this type of token?

Not Stressful	1	2	3	4	5	Very Stressful
------------------	---	---	---	---	---	----------------

7) Do you feel that you were able to accumulate points to the best of your ability?

Yes No

If not, why?

8) Did you have a strategy for playing the game or rolling the die? Explain.

Additional Comments:

Olympic Dice Final Test Questionnaire

Alias:

Legend:

1 = Real Die + Real Token

2 = Real Die + Virtual Token

3 = Virtual Die + Real Token

4 = Virtual Die + Virtual Token

1) Which interaction style did you enjoy the most?

1 2 3 4 5

Why?

2) Which interaction style was the easiest to accumulate the points with?

1 2 3 4 5

3) If you had to choose one, which dice rolling technique would you use for board games?

1 2 3 4 5

4) Did you enjoy the competitive style of the game? (multiplayer only)

Yes No

Additional Comments:

A.1 Settlers of Catan Documents

Following are the two questionnaires used for the Settlers of Catan experiment.

Post-Test Questionnaire

All questions, except the final questionnaire question, follow a five-point Likert scale as follows:

1	2	3	4	5
Strongly Disagree		Neutral		Strongly Agree

Questions labelled with * are reverse coded to maintain consistency for analysis. Section headers were removed for the participants to prevent bias. The final question provided conditions classic, TAR, and digital as possible options.

O'Brien Engagement Questions

Perceived Usability

1. I felt frustrated while playing this condition.*
2. Playing this condition was mentally taxing.*
3. I felt in control of my game experience.

Aesthetics

1. The layout of this format was visually attractive.
2. This game appealed to my senses.

Focused Attention

1. I was absorbed in the game.

Sensory and Imaginative Immersion

1. I found this condition to be impressive.
2. This was a rich gaming experience.

Endurability

1. I would play this condition again voluntarily.
2. I would recommend this condition to others.

Negative Affect

1. I was distracted and thought about other things.*
2. I was fatigued after this condition.*

Positive Affect

1. This game made me laugh.
2. I enjoyed this game.

FUGA Social Experience Questions**Empathy**

1. I empathized with others.
2. I found it enjoyable to play with others.
3. When I was happy, other people were happy, vise versa.
4. I admired other players.

Negative Feelings

1. I was jealous of the other player(s).
2. I was influenced by the other player(s') mood, vise versa.
3. I felt schadenfreude (malicious delight).

Behavioural Involvement

1. My physical actions depended on the other(s') actions, vise versa.
2. The others paid close attention to me, vise versa.
3. What others did strategically affected what I did, vise versa.

Interface Questions

1. I liked the screen size. Please explain why.

Final Questionnaire

1. If you had to choose, which of the three conditions did you enjoy the most?

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