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Benefits of Video Games in Multidisciplinary Scientific Research

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Dedication

To my parents, my coworkers, my adviser who had to put up with me, and anyone who has ever believed that I could go this far with video games, I say thank you. If I can change, and you can change — everybody can change.

Acknowledgments

I would like to acknowledge the hard work of all the people I have had the privilege of working with during these years. Without their gracious professionalism none of this would have been possible.

Abstract

In recent years, computer-based games have been shown to be effective both as a tool for conducting research in a variety of domains and for research on games itself. In this work, we show that implementing games that have a basis in theory and that are combined with the most recent gaming practices result in effective research tools. We demonstrate this via game implementations for three domains. The first implementation is based on new theories in speech pedagogy, and demonstrates the effectiveness of our approach. The second implementation shows that using a game that simulates therapeutic speech practices can aid in the study of rehabilitation. The third implementation shows how using game practices with a large-scale visualization could potentially result in scientific breakthroughs in the biologic community. All three of these implementations show the multidisciplinary use of games in scientific research.

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Chapter 1

Introduction

Games have always been an integral part of our culture. These structured forms of play have been used to entertain but also teach useful skills throughout the ages. Some of the earliest recognized games were used to teach important survival skills in a safe and structured way. Often referred to as "folk games", these historical games are still taught to children today. A game such as *tag* can condition the body and mind for hunting and survival. The simplest form of this game starts with a person as "it" which can be thought of as the hunter, and the remaining players are the prey. The goal is for the player who is "it" to touch another player, and when this occurs the tagged player then becomes "it". The game finishes when every player has been tagged. Similar games like *hide and seek* trained a person in both tracking and also stealth. In this game, a person is nominated as "it" was tasked to find the other players. The game begins with "it" counting down from a given number while the other players find ways to disguise themselves. The game is over when the player, "it", finds all the other players or gives up when they cannot find one or more of the remaining players. It is easy to conclude that from the game-play games taught historically needed abilities to function and thrive.

As time progressed more advanced games developed, which were used to foster critical and strategic thinking. Simple games that have existed in many cultures such as *Rock, Paper, Scissors* contain at its core strategic elements. Two players are pitted head-to-head, and the must count down and then choose a hand gesture that represents a rock, a piece of paper, or a pair of scissors. A winner is determined by who picks the winning gesture against their opponent's gesture. The winning configurations are rock beats scissors, scissors cuts paper, and paper cover rock. While its game-play is very simple learning how to predict the patterns of one's opponent while also trying to trick the opponent becomes essential to victory. As time went by, more complex games that had boards and pieces were developed. Much of these games had more intricate rules and strategies compared to folk games. Early board games that have survived since the ancient times, such as *Uhr*, were remnants of royal families' belongings, and are thought to have taught military strategy to their heirs. One game from the ancient era that was used to teach strategy was the game of *Weiqi* otherwise known by its Japanese title *Go*. The pieces and assembly for this game are very simple, but the strategy to win becomes incredibly complex. The board is broken into a several small squares. Each of the two players have a set of uniquely colored stones, and they take turns by placing a single stone on the corner of a square as seen in Figure 1.1. If one or many of the player's stones are completely encompassed by the other player's stones then those stones are removed. The game ends when both parties mutually agree it is over, and the player with the largest collectively occupied space wins. The vast number of possibilities and approaches players can take continue to make this a popular and compelling game.

In the present time where most games are played on a screen. The early days of video games started humbly as recreations of existing games. In 1952, Alexander "Sandy" Douglas developed the game "OXO" otherwise known as "Naughts and Crosses" on the EDSAC as a part of his dissertation thesis on human-computer interactions (Figure 1.2). This game was a recreation of "Tick, Tack, Toe" where two players take turns strategically placing "X's" and "O's" on a three-by-three game board. The game is finished when either a player has three of their symbols in a row or there are no other moves to make. What made this game unique (other than it was played on a screen) was the player competed against an artificially intelligent

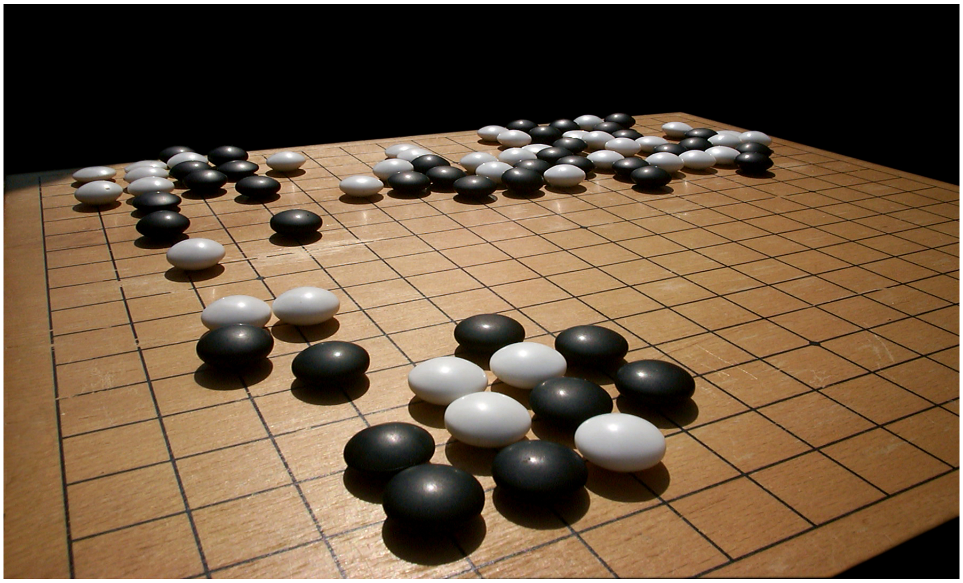


Figure 1.1 The game Go. This early board game is thought to have taught militaristic strategies.

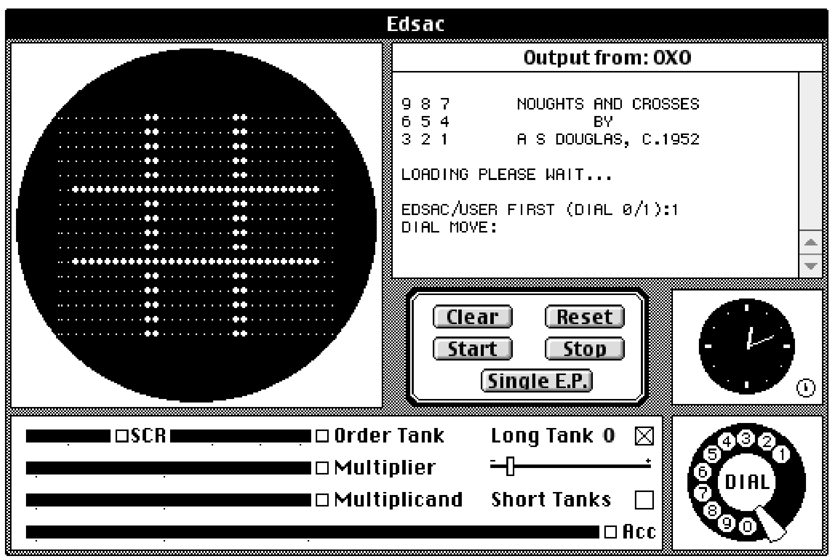


Figure 1.2 *OXO* on an EDSAC Emulator. This is considered the first video game and was a part of Alexander "Sandy" Douglas' dissertation thesis as research in human-computer interactions.

system. This was not only recognized as the first video game; it was the first time a video game was used in research. As such, the genesis of video games was in research.

From the humble and research based beginnings to now, video games have shown to be more than just an entertaining escape. Games looked at in a more serious light they have shown to be an effective tools in many different fields. Games like *Oregon Trail* have been used in classrooms to not only teach about the American westward travelers in the 1800's but also convey the hardships of their exodus. Other games like *Tactical Iraqi* have been shown to be an effective teaching aid for the Arabic language, but also useful to train a level of understanding of a culture and the use of their gestures. Experimental games like *Fold It* have been vital to protein folding discoveries[43]. Video games are far more than just entertainment; they can can be used as integral instruments in many different disciplines.

1.1 Research Contribution

The field of gaming research is ever emerging, and as such there are still many avenues that have not been discovered that could benefit from the use of gaming techniques and practices. The following chapter gives foundation for not only what games are, but how they have already been used in research. Next, we will be exploring three different subjects that all use gaming to aid in their study. The first work teaches languages in a modern way. Using past games and techniques as a foundation, we then explore aligning contemporary language pedagogy with game mechanics to create an effective system. We then tested the effectiveness of the game on a few different populations, and present our results.

The next section focuses on rehabilitation of speech with games. We focus on one type of language disorder, that is usually caused by strokes, called aphasia. By examining a popular and effective rehabilitation technique, we then detail the creation of a game where its design mirrors the fundamental therapeutic concepts. Next we discuss the results of testing this game on a variety of people affected by this condition.

Finally we discuss a system developed like a game to explore genomes. This work, by definition, does not qualify as a game, but it borrows techniques and technology used commonly in large, open-world video games. We then discuss the creation of a 3D viewer that's capable of real-time exploration of the vast amount of data in a genome. We then compare the construction of this application with a similar one that was created without gaming technology and techniques by administering a set of tests. Finally we discuss the results of the comparison.

The final chapter is a discussion of all of the results, and a look into future endeavors. All the studies and facts are summed together, and a theoretical methodology is proposed. It is shown in the broad body of work that using games as an instrument for research is a wide open field with many possibilities that have yet to be explored.

Chapter 2

The Importance of Games

In order to first understand why using games can be useful for research, we must examine what a game is, and historically why it is important. We first look at the role of play; as these were the foundational examinations that lead to games. Next we define what is a game. Seemingly simple on the surface the definition of a game is still debated. We explore historical and modern definitions, and then finally conclude with the definition we find the most contemporary and accurate. Finally we then explore the roles of games in research. We give a provisional taxonomy and give examples of each.

2.1 The Importance of Play

Before we begin our discussion on games we must understand play. One of the most famous explorations of this concept was by Dutch historian Johan Huizinga in his work, *Homo Ludens*[38]. First he decomposes the different explanations for play in both psychology, biology, and physiology, and concludes that not one of them are sufficient explanations. He realizes that there must be more to it as he defines that play as not an element "of" culture, but an element "in" culture. This powerful statement demonstrates the fundamental importance of play. Furthermore he defines play having the following attributes:

1. Play is free.

2. Play is not "ordinary" or "real" life.

3. Play is distinct from "ordinary" life both as to locality and duration.
4. Play creates order. It demands order absolute and supreme.
5. Play is connected with no material interest, and no profit can be gained from it.

This idea was elaborated on in the 2000's with Mary Flanagan's, *Critical Play*[28]. In her work she examines how play can be used to convey ideas. She defines "critical play" as an exercise in creating alternative play spaces by carefully examining social, cultural, political, and even personal themes. She also goes further to talk about games and defined the term *activist games*, which can be thought of as a game-like essay. A main idea in her work is the concept of critical language play. Through different modern artistic movements, she explored and demonstrated the importance of language, and even how it is applied to games. This concept becomes one of the stepping stones of this idea which we will explore further, which is serious games.

2.2 Definitions of Games

With an understanding of play, and the furthered exploration of how play can be serious we can now expand how these then apply to games. One of the early attempts to understand games comes from Ludwig Wittgenstein, in his exploration of the mind[81]. In a portion of this work, he struggles to define what a game is, and finally concludes that simply trying to assign rules, play, and competition to this terms fails to adequately define it.

Around the same time period the French sociologist Roger Caillois explored the idea of games in his famous work, *Les Jeux et les Hommes* or *Man, Play, Games* [13]. Caillois created a rigid definition of games where they must be:

1. fun: the activity is chosen for its lighthearted character

2. separate: it is circumscribed in time and place

3. uncertain: the outcome of the activity is unforeseeable

4. non-productive: participation does not accomplish anything useful

5. governed by rules: the activity has rules that are different from everyday life

6. fictitious: it is accompanied by the awareness of a different reality

While each of the points definition are valid, we believe it limits what qualifies as a game. Furthermore, many modern games, and even entire genres break many of these qualifications. For instance, serious games are games that are created for other reasons than just entertainment. By this definition the entire genre breaks the non-productive criteria.

A 1980's game designer and creator of "Scram" — an Atari 800 game about managing a nuclear reactor — Chris Crawford later defined a game through a series of decisions in a tree. The tree also defined many other terms surrounding games[22]. First it is art if it is created for beauty and entertainment if created for monetary gain. Next entertainment can be defined as a plaything if it is interactive, while books and movies are non-interactive forms of entertainment. Then if there are no goals then the plaything is a toy. After that if there is no adversarial agent in which to compete with then it is a puzzle. Finally, if the player is only to outperform or outshine their opponents, and not allowed to interfere with the adversaries then it is a competition. However if this action is allowed then this finally qualifies as a game. These decisions can be seen in Figure 2.1.

By Crawford's definition games are entertainment (this is made for money), interactive, goal oriented, competitive, head-to-head challenges, and video games are not art, non-interactive, goal-less, puzzles, or are not simple competitions. According to many of today's standards of games, this definition does not hold well. First,

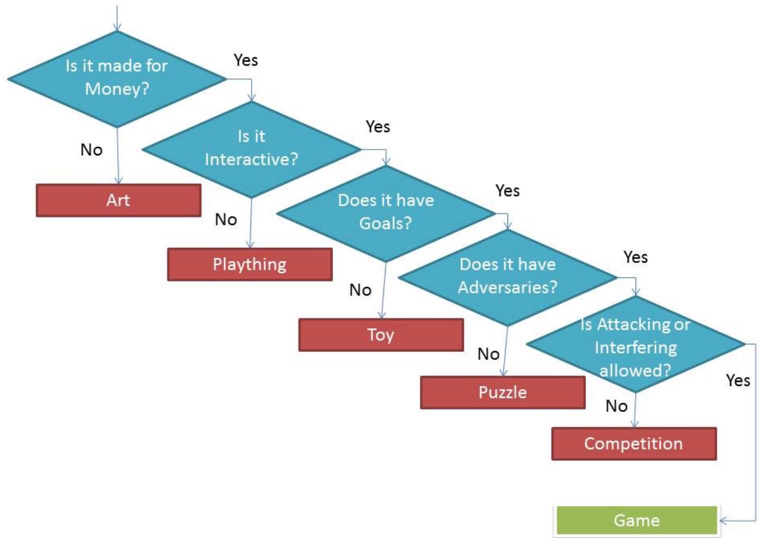


Figure 2.1 Crawford's explanation of games. Through defining many terms that do not qualify as a game, he then recheached what he considered to be the correct definition.

and probably the most easy argument, that games are not art and are created for money can be broken by looking that the popular Apple's App Store. Many of these games are available for free, thus by his definition cannot be a game. Furthermore, claiming that games are not an art form is simply an outdated notion. For the sake of brevity, we will not go into that argument in this work. However, later in his most famous lecture, "The Dragon Speech", he calls games an artistic medium, which is in contrast with what he stated before. We do not believe this strict definition of games is correct.

In the book *Serious Games* [2], Clark C. Abt defines games as such,

> "Reduced to its formal essence, a game is an activity among two or more independent decision-makers seeking to achieve their objectives in some limiting context. A more conventional definition would say that a game is a context with rules among adversaries trying to win objectives."

This rather simple but concise definition states that games must be interactive, contain adversaries, have goals defined by the system, and rules to govern the interactor's actions. Furthermore this idea has been echoed since this work from other sources [67].

With all of these definitions in mind, we use the concept that a game must be interactive, have adversaries, goals that are defined by the system, and rules to strictly define the term. While it is important to know what a game is, it is now time to explore how games have been used in research by examining an important sub-genre: serious games.

2.3 Serious Games

A game is generally classified by its play mechanic whether it be action, adventure, rhythm, simulation, shooter, etc. Some game researchers have taken it upon themselves to help clarify these variances by creating a taxonomy [51]. For the most part, the gaming industry is interested in creating games solely to please the consumer, so that they can generate revenue. However there is an interesting set of games that are created for other purposes than just entertainment value; these games are called serious games. Traditionally, if a game was created to teach, train, or persuade then it falls into this classification.

Some serious games are developed to teach a player. These types of serious games have been around for a long time and have been shown to effectively teach a variety of subjects [57] [20]. One early video games that was created to teach was *Oregon Trail*. Placed in the role of pioneers venturing out into an unknown wilderness, the player must make difficult decisions and face immeasurable hardships through their journey to the west coast. In order to simulate these hardships, the game had a complex number of systems at the core of its game play. One of them was how to manage and distribute food after a hunt. Another was to make decisions of which path to take depending on the stability of the wagon and also the time of year. It

Figure 2.2 Oregon Trail. A teaching game that used a sophisticated, underlying simulation in order to convey the hardship of westward travelers in the 1800's.

was inadvisable to try to cross a mountain range in the dead of winter, or fjord a dangerous river with a rickety wagon. Using, at its core, a sophisticated simulation along with wrapping everything up in historically accurate accounts, this created a popular teaching tool which conveyed the hardships of these westward travelers.

Effective training has been demonstrated through several types of games. A very popular one is *Microsoft's Flight Simulator*. The player is put in the role of a pilot and they must manage flying and landing a plane safely. There are several different types of aircraft, environments, and weather conditions they must take into account. This has also been considered a serious game by some and has shown to be an effective learning tool[45]. A similar game in this categories is *Densha De GO!*, which is a Japanese train simulator game. This game with its special controller that simulated the levers of a Japanese locomotive, works similarly to *Microsoft's Flight Simulator*. The player is tasked with starting and stopping the train within a certain time and location and is awarded points for successfully doing so. Other games such as *MineCraft* have been shown to train people in the fundamentals of programming. In this game, there are no set rules and the player is free to roam around the blocky

Figure 2.3 *Flight Simulator X*. A game that has been used to train people to fly various aircraft.

environment constructing buildings and monuments, while also battling enemies like the "creeper". However people have managed to create intricate circuits used to control certain operations in the game as seen in Figure 2.5. By demonstrating this, people found out that one could teach sequential programming basics at this level[85]. By making training drills fun and interesting, these games have communicated the importance of gaining a skill to succeed in a field.

Finally there are some games that are used to convey ideas or make a point. In the work "Critical Play" Mary Flanagan demonstrated how play can be structured in such a way that the players will take more from it than just entertainment [28]. By exploring different avenues in her surveys, she showed how it is possible to create play that delves into activism and the humanities. Furthermore she delved into the creation of games that have serious meanings. This idea was furthered in Ian Bogost's *Persuasive Games* by introducing the concept of "procedural rhetoric". This concept claims that messages are not just in the narrative or other assets in the game, but are more importantly tied to the mechanics[8]. Messages can be conveyed by the rules, goals, and the interactions of the game, and should be done so to effectively

Figure 2.4 *Densha De Go!* This Japanese game simulated the operations of a commercial locomotive, and even was bundled with a specialized controller which replicated the train's controls.

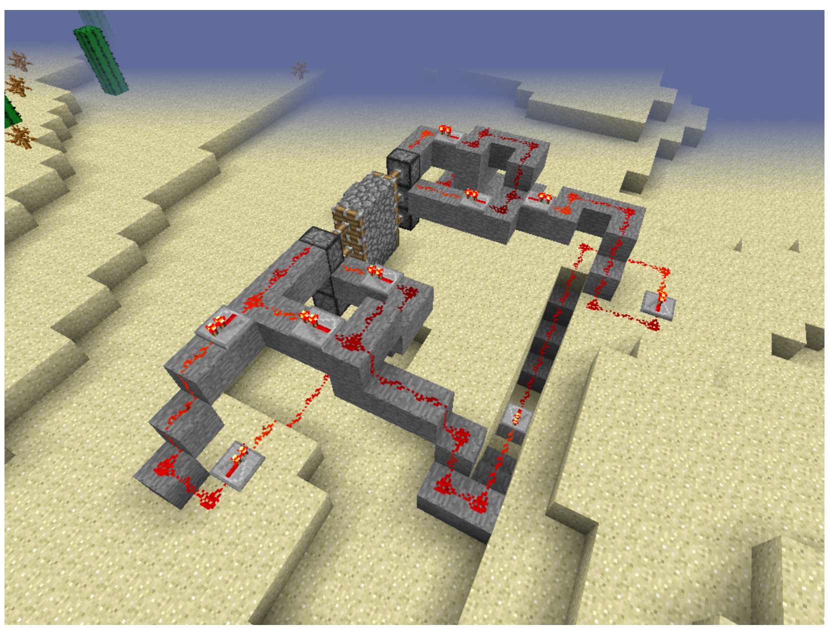


Figure 2.5 *Minecraft* Circuits. An open world exploration game was used to teach basic circuit design through one of their resources.

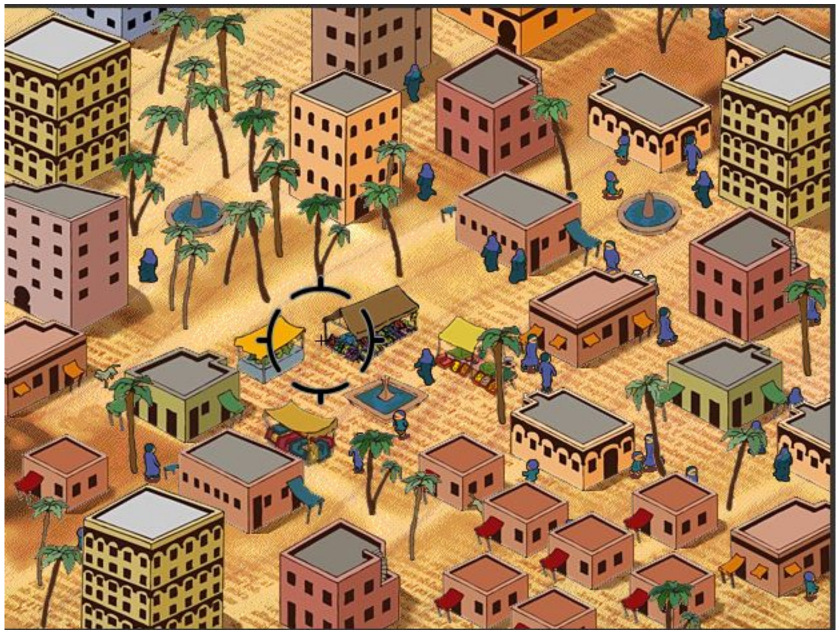


Figure 2.6 *September 12th*. A game which through its mechanics demonstrated how violence only leads to more violence.

deliver the message. Throughout the remaining parts of his work he gives examples of how procedural rhetoric succeeded and failed. An example of a persuasive game is *September 12th* which demonstrated how war and violence only perpetuates more war and violence. This game presents the player with a middle eastern village and a cross hair. When the player clicks the mouse a missile is launched which destroys buildings and kills people as seen in Figure 2.6. The people then turn against the player, and begin attacking. The only way to win this game is by not participating. This sends a strong message that only by not causing violence will we avoid more violence. Other games like "Cow Clicker" have shown satirically (or arguably not) how social games at that present time can be boiled down to just clicking on cows [75]. In this game, the player clicks on a cartoon cow and then it posts to their Facebook page a message saying they clicked a cow as seen in Figure 2.7. By obnoxiously posting about a mundane action in a game it shows how most social games work and are viewed by some people. These games through their procedures demonstrate an idea.

Figure 2.7 *Cow Clicker*. By obnoxiously posting about the mundane task of clicking a cow, this game showed the failing points of social games.

2.4 Research and Games

Using games in scientific research is still a budding discipline. Through our literature reviews we have determined there are three categories most gaming research falls into: research about games, research for games, and research using games. These different categories are not mutually exclusive as there are some studies that overlap two or all of the different classifications as seen in Figure 2.8. Using this provisional taxonomy we will explore each one of them and give examples of each.

Figure 2.8 Research and Games. All research involving games fall into at least one to all of these categories.

A large amount of gaming research generally dealt with how a person was affected by a game or by playing games in general. Social and psychological ramifications are the corner stone of most of these studies. Some studies have supported or refuted that games have a sinister element to it. For instance a prime topic that has been in the media majorly since the 1990's was whether or not games make people violent. While it has been shown to increase aggression temporarily[27], the claim that video games make people gravitate faster toward violence has never been proven. Some other studies have shown that certain games like MMORPG's could possess addictive properties. Like other addictions, people's obsession with games would ultimately become detrimental [74]. Also some studies have shown that people who play games habitually run the risk of being overweight and depressed [80]. On the other side of the spectrum, it was shown that some games have beneficial properties. For instance some games could have relaxing and therapeutic properties[63]. Another was determining if and why serious games were effective tools for teaching and training. Many scholars pointed out that games are engaging, and the user is intrinsically motivated to play the games. A game that is engaging has been shown to induce a mindset that is both focused and happy. "Flow theory" described this concept, and became the basis of creating engaging games [23][54]. Furthermore, motivation was effective in learning [65]. Through the play of games it has also been shown that even children display and expert mastery of the skills the game has taught [78].

Another example of games in research is exploring new ways improving elements of game-play. One of the easiest game-play elements that has benefited from research is improving graphics in games. Any type of near real-time graphics are generally added to game engines in order to stay on the cutting edge of beauty. Another game-play component that is commonly explored is artificial intelligence. Most modern games require smart adversaries in order to keep the game interesting. Typically path-finding [72] and optimal decision making[61] are two crucial areas that game-play has benefited from. While there is many more examples one newer research area that has appeared that focuses on a unique element of game-play is procedurally generating compelling narratives. More often than not when a game has a story it remains static and the player's action have no real bearing on the outcome except for following along. Some researchers has taken it upon themselves to create systems that create new narratives based on the actions of the player.

Finally, games have been used to drive research in other fields forward. This type of work remains mostly unexplored. In some examples games have been used to visualize and work in conjunction with simulations[70]. Simulations and games go hand-in-hand, since most of the game mechanics rely on some form of simulation. Due to this, work involving simulations have benefited from the use of games. In other cases they have been a source of radical discoveries for research such as in the case of "Fold It"[43]. This game about protein folding solved a near decade old problem about the HIV virus, by having users manually fold proteins in an optimal way. Along with the ideas of using games to drive research other gaming elements have been used in research. For instance the use of motion controllers in rehabilitation analysis[15]. Despite these examples using gaming techniques and tools to drive research is still a relatively new concept.

In the following work, we focus on the lesser explored research using games, by using three different examples. The first is a game to teach a foreign language in a more modern way. We detail the construction of this game which uses contemporary pedagogical theories as the core inspiration of game-play. After that we detail the studies used to determine whether or not it was effective, which either helps support or refute those theories. The next study focused on a game created to aid in speech rehabilitation. In this game, we pioneered many different techniques in the creation of a game; its core mechanics are based on a popular speech therapy. Then we detail studies which determined the game's effectiveness. The last study was not on a game, but a system that was developed to explore genomes by using game making tools and principles. We explain the design and implementation, and then compare that to a similar tool. Finally, we discuss the all of the studies and give some insight on some future work in the ever evolving field.

Chapter 3

Language Game

From the days of computer assisted language learning (CALL) [50], using computers as a means to acquire a new language has been a long standing research field. Chinese is a notoriously difficult language to learn, and teaching methods that have been used take a long time and can be tedious[46]. However, these techniques have been shown to be effective[55]. We believe that by creating a serious game that used newer second language acquisition techniques, the learning process can be expedited and enjoyable. Moreover it is our research goal to provide an effective and inviting learning experience. Our approach employed theories of language pedagogy research that is integrated into a fun and interesting game. This exposed the player to an abundance of simple, comprehensible target language input, which provided an engaging, motivating, and low stress setting. Implementing this research into the game allowed the player to naturally acquire the language, since the underlying system is based on said research.

3.1 Introduction

Computer assisted language learning (CALL) [50] has been studied for many years, and several programs have been developed using this methodology as an augmentation to standard teaching techniques. As effective as the techniques such as word lists and word drills are [55], they can be monotonous and highly time-consuming [46]. New CALL programs have emerged using serious video games to teach languages which we will explore later. Along with serious video games, new language learning techniques have also been developed that could be used in these serious games. We will now expand on both serious video games, language learning methods, and finally introduce our game which merges the two.

3.1.1 Educational Computer Games

Serious video games have been around for a while, and have started to become respected, and a highly profitable industry. Unlike commercial games where their sole intent is to entertain people, serious games' primary motivation is to convey information while also entertaining the user [64]. Educational video games are one of the corner stones of serious games, and there have been three generations of these games [25]. The first focused on the player's behavior during game-play and how to achieve a target behavior. The second was focused on how the player learns and adapts to the game. The third focuses on incorporating culture into the game and allowing social interaction to benefit learning via game-play. The most effective educational games employed all three of these.

3.1.2 Second Language Acquisition

In one second language acquisition (SLA) theory, the learner was immersed in the language in such a way that they gain an intuitive feel for it. This is in contrast to being taught the language's syntax and semantics by relating it to the learner's native language. Stephen Krashen created several key points that make this particular SLA theory a powerful method in teaching a second language [47]. Some of these points include: acquisition must be implicit and subconscious, acquisition is attitude dependent, present informal situations, use grammatical "feel", and have a stable order of acquisition.

The input hypothesis of the SLA theory states that the learner gains an intuitive feel for a second language rather than learning the formal structure and grammar rules

[48]. The main component of the theory was an abundance of comprehensible input of the target language. This in turn was screened through an affective filter, which is then processed by a theoretical portion of the brain known as the language acquisition device (LAD). Finally after it has gone through the LAD, the input became acquired knowledge [19]. Formed from the learner's emotions, the affective filter is a barrier that inhibited learning. This acquired knowledge was then used by the learner to produce output in the target language.

Task-based language teaching (TBLT) utilized "tasks" as a method for teaching a foreign language [58]. Tasks were actions such as solving a puzzle, conversing with people, reading a map, etc. In order to complete a task, the learner must have utilized the target language. Following directions to find a destination is a simple example.

Content-Based Instruction (CBI) is a language acquisition approach where the learner acquired language based on the specific subject matter they were focused on [12]. For example, if a person read a Spanish article about gardening, they would have likely acquired vocabulary about gardening.

The goal of our project was to develop a language learning video game using new elements of SLA theory: the input hypothesis, TBLT, and CBI. TBLT is employed in the game as an example of targeted behavior. CBI is utilized as a way to incorporate culture and simulated social interactions using AI. *Lost in the Middle Kingdom* used dynamic teaching techniques as well as an array of multiple level options as a way to customize learning, so the player is self-motivated and has a low affective filter to capitalize on the input hypothesis. This project required research in language teaching, effective game design, and the target second language's culture. The reason we choose Chinese is because it is a notoriously difficult language to learn. It has its own character system which is different from the Roman alphabet, and also listening and speaking requires knowledge of the four tones.

3.2 Related Work

Serious computer games could change the way we learn [32][33]. Learning a foreign language using video games has been explored in many different ways, and early examples were fraught with problems. Common drawbacks to first generation educational games include: halting game-play to teach a topic; boring game-play; game-play which is unrelated to learning material; and poor or no story [60]. Recently, a new wave of second language educational games (and related research) sought to overcome many of the drawbacks of the first generation of educational games, by retrofitting commercial games with second language material. This educational material is then intertwined with game-play.

3.2.1 SLA Game Modifications

Some serious games for SLA are modifications (mod's) of existing games. Rankin et al. explored using a popular massively multi-player role playing game (MMORPG) *EverQuest 2* for SLA[62]. In order to immerse the player in the new language, they set the game's settings to the language which the learner wishes to acquire. A key component of MMORPG's is communication with other players, so they used a natural language processor (NLP) to translate the in-line chat. While this was an interesting framework, their method has not been tested fully.

A bilingual mod of *The Sims 2* was studied with the primary goal to teach a foreign language[60]. This was accomplished by exchanging or adding English and German text. A major drawback to this mod was the absence of spoken language to teach proper pronunciation. Even though the game presented a multitude of words, it lacked phrases, sentences, and other applications of vocabulary. The game also lacked a cultural aspect which can be beneficial in learning a second language. Although *The Sims 2* is played in a rich three-dimensional (3D) environment utilizing several useful words, it lacks a strong plot which can help motivate the player to continue playing.

3.2.2 Stand Alone SLA Games

While some research has gone into modifying existing games to teach a language, another large section research has been focused on creating new experiences to teach a language. Over the course of a few semesters a team of programmers lead by Kardan created and studied a language and culture learning RPG game called *Ohana*[41]. Chen and Chang explored language learning with a role playing game[17].

Tactical Iraqi is one of the most famous and well studied serious game to teach a second language. It was developed for the United States military to teach Iraqi Arabic communication skills and cultural non-verbal gestures to soldiers [66]. The game has three major modes: skill builder, arcade, and mission. Skill builder helped the learner develop speaking, listening, and reading skills through drills. In arcade mode, the learner gave his/her avatar spoken commands in the second language in order to complete a task. Finally, the learner communicated with other Iraqis to accomplish a task in mission mode. Similar products have been developed for soldiers to learn Pashto, French, and Dari. Some studies have shown that this game is effective at teaching a foreign language[39]. Especially if the learner has sufficient motivation[40].

However, this is more of a 3D instruction software and simulation to learn and practice foreign language rather than a game to learn a second language. The motivation for playing this comes mostly from the player's desire to learn the language, and not from the game itself. This is due to the software's lack of a system to reward progress, and also the lack of a strong plot. The inclusion of these game-play elements would help create a more fun and interesting game that would encourage the player to continue playing, thus learning more of the language.

Figure 3.1 *Tactical Iraqi.* A game designed to teach Iraqi Arabic communication skills and non-verbal gestures to soldiers in the United States military.

3.3 Implementation

Since *Lost in the Middle Kingdom's* primary goal was to teach Chinese, we knew the game would require several language methodologies blended with fun game-play. We envisioned a game with 3D graphics, an immersive environment, first-person style controls, fun and intuitive game-play, as well as multiple mini-games and tasks to complete. This research attempted to accomplishes three objectives:

1. fluid user interactions
2. boost the learner's vocabulary
3. promote listening comprehension

3.3.1 Immersive Environment

Lost in the Middle Kingdom utilized first-person controls. Players "scan" objects in the game with a simple left-click of the mouse, which displayed the object's Chinese character(s), pinyin representation, as well as a pronunciation button as seen in Figures 3.2 and 3.7. When the pronunciation button was pressed, the player heard the word spoken from native speaker. To aid the person understand what they were hearing, they were also shown the pinyin representation. This is a system which used the roman alphabet and special markers to denote how the word is spoken. After scanning an object, this information was stored in a "library" which can be opened at anytime to refresh the player's memory, and also aid in completing tasks in the game as seen in Figure 3.3. Scanning objects also brought up a picture association to tell the player the meaning of the character. SLA required learners to process the target language directly in contrast to first processing it in their primary language; this picture not only helped the user process the information directly, but also assists in building a total immersion game.

3.3.2 Learning Tasks

The player had to complete tasks involving words in order to progress to more advanced levels in the game. These tasks were 3D puzzles such as putting out a fire as seen in Figure 3.4 or placing the correct item on a pedestal such as in Figure 3.5. Others were figuring out dialogue with non-playable characters (NPC's) in order to solve a problem. Also some of the learning tasks were action packed game sequence in which certain acquired words become the player's weapons such as Figure 3.6.

Most video games give the player a set health amount that is reduced by taking damage from enemies or increased by collecting power-ups. When their health reaches zero the player's character dies, and the game starts over. In this game, it did not make sense to kill the player, so another way of judging the player's health was

Figure 3.2 Title Screen. A screen shot of the opening sequence of the game.

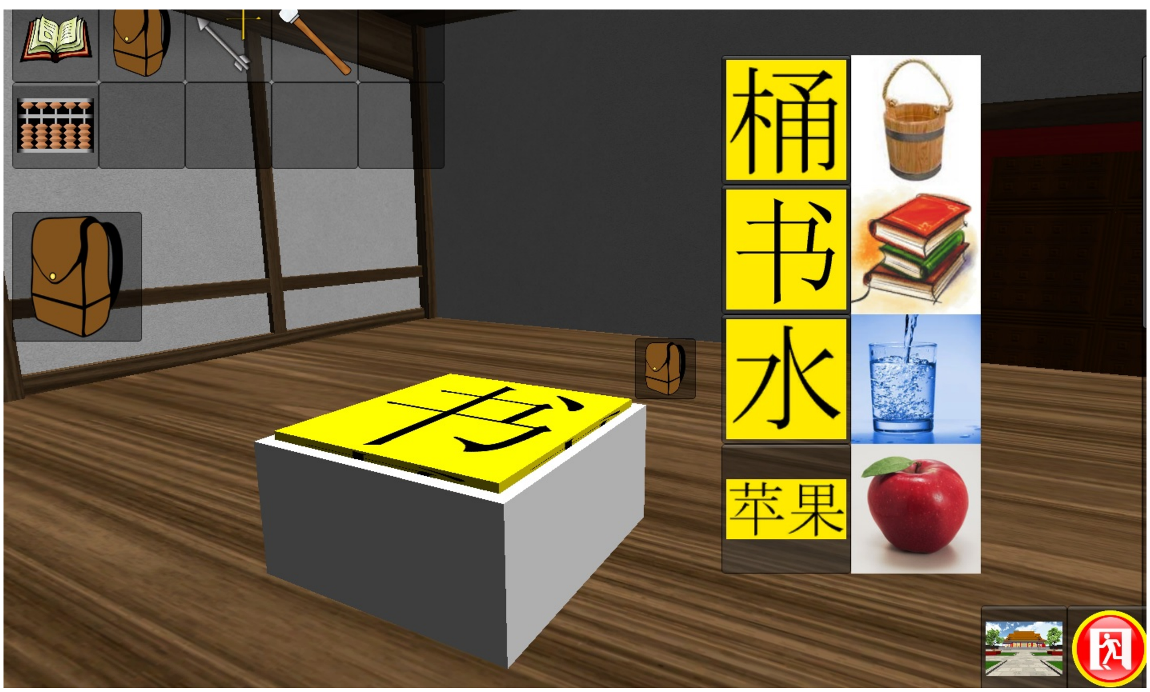


Figure 3.3 Using Library to Complete a Task. The player could bring up the library in order to solve tasks by generating objects.

Figure 3.4 Putting Out a Fire. The player had to have "scanned" a bucket of water, and then generated it via the library to put out the fire.

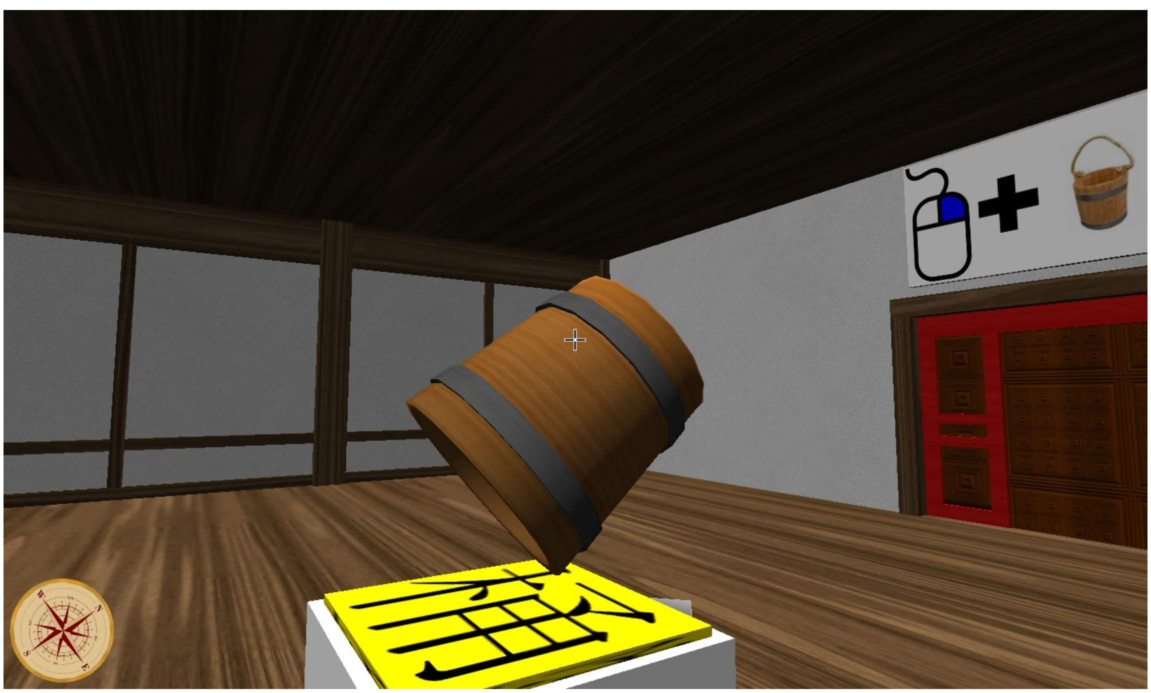


Figure 3.5 Placing a Bucket on Trigger Point. Pedestals with characters on them indicated to the player they must place that object on it in order to advance.

Figure 3.6 Action Scene. At the end of the stage, the knowledge presented must be used in order to battle a boss.

incorporated. Damage inflicted by enemies "confuse" the player by corrupting a few of their acquired words. If a word becomes "corrupted", the picture association of the word is removed from the library, and the word will no longer be usable as a weapon or in puzzles. The player had the option to "uncorrupt" these words at anytime by playing a mini-game.

3.3.3 Mini-games

Throughout the game, players encountered several smaller games, called mini-games, which focused on vocabulary building. These mini-games required the player to complete several 2D based puzzles in order to gain knowledge and received power-ups. Completion of mini-games not only rewarded the player, but also provides clues on how to complete the current level. Mini-games included: memory matching, discovering words within hints through context clues, and dialogue with NPC's as seen in Figure 3.8. One example of a mini-game was a matching game where the player

Figure 3.7 Object Scanning. "Scanning" objects helped develop the player's library, which was then used to solve puzzles.

was required to match Chinese symbols to their corresponding picture representation as seen in Figure 3.9. Through playing this game, the player gained a power-up, and also reinforced their Chinese knowledge. This presented a fun and familiar way to learn basic Chinese vocabulary with repetition. Another mini-game required the user to complete a basic Chinese sentence; players selected symbols and guess their meaning in order to complete the sentence, which was actually a clue to the current level's puzzle. Another mini-game required the player to complete a basic Chinese sentence; players selected symbols and guessed their meaning in order to complete the sentence.

3.3.4 Culture-Based Environment and Plot

Learning the culture of the target language's country is highly beneficial while learning a second language. *Lost in the Middle Kingdom* took place in China, and the game's rich 3D environment utilized traditional and modern day Chinese architecture. This

Figure 3.8 Talking To NPC. The player had to decipher what the non-playable character was saying in order to get a clue about the puzzle in the stage.

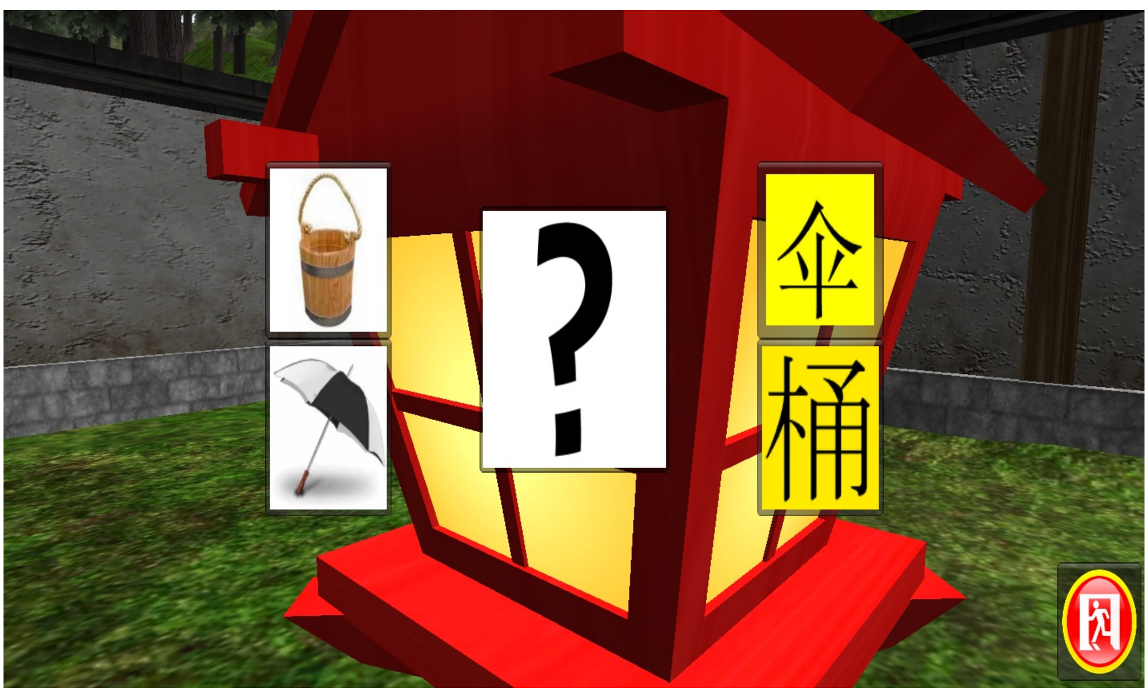


Figure 3.9 Matching Game. Power-ups, such as extra arrows, were awarded to the player after completing mini-games like the matching game.

factor also helped build a unique total immersion game, as well as it helped the player feel as if they were in China.

3.3.5 Level Organization

The player progressed through the game by completing tasks presented in each level. Initially, the player was presented with an over-world with several routes open for exploration, while others are locked until the player has completed a certain amount of tasks. If a task is too difficult, players could take an alternative route or return to the over-world, and try another level. The player had the option to replay a completed level to refresh what they have learned.

3.4 Experimental Results

To test the effectiveness of this game a case study was conducted. A group of thirty high school students were given a demo copy of the game, and were asked to play through at least once a day for two weeks. They were instructed that there would be a small test and a survey after they were done playing. The test consisted of two parts: a visual recognition portion and an aural recognition portion. In the first part of the exam, the user was presented with Chinese characters along with their pinyin that they had encountered in the game. It was their task to choose what the word meant from a group of given words. Likewise, the next section had audio files the person had to listen to, and they had to determine what word it was from a given list. The survey was given to gauge the level of prior Chinese language experience, how often they play video games, and also gather information on what needs to be improved for the next version of the game.

Combining the results from the tests and the survey we were able to extrapolate some interesting data. Most people claimed to have very little knowledge of the Chinese language before playing the game, but scored very well on the test. On

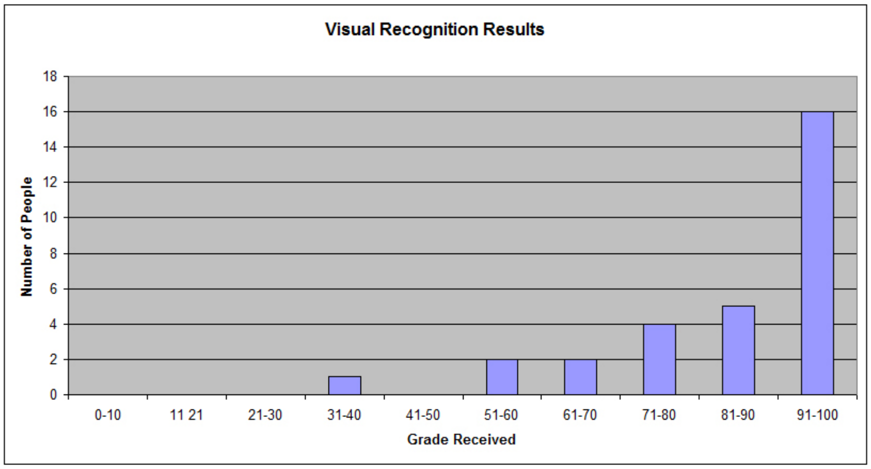


Figure 3.10 Visual Results. These were the test scores from the written section of the exam. After two weeks of playing the game, high school students generally scored well, since they recognized the character's and their meanings.

average, more people did better on the aural portion than the visual as seen in Figures 3.10 and 3.11. This trend indicated that this was similar to learning ones first language — where a person learned how to listen and speak before they learned how to read and write. The visual portion was comparable, but it was not close to the results from the aural portion. From the survey we noted that the people who played more video games did much better than the ones who rarely play video games, and it was observed that these people explored more of the game than their counterparts. Some suggestions for improvement were given, and mostly focused around the game being longer and a better control scheme.

Another study was then conducted in a similar way. However this time the population were eighteen different people from a variety of backgrounds, and also the final version of the game was used. In this case, each person played the game for two hours a day for two weeks. After playing the game they were then given a test similar to an exam in a college level introductory course in Chinese. They were judged in different subjects such as numbers, dates, family members, etc. based on how well they could recognize the character and pinyin representation. Also some parts of the

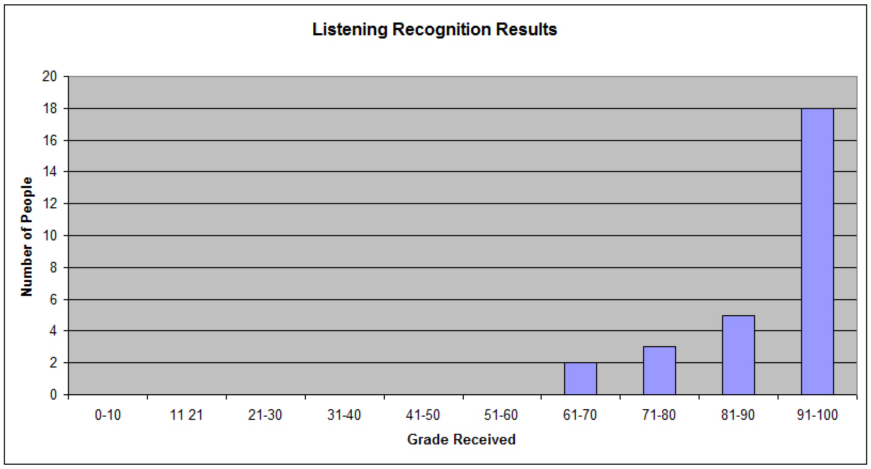
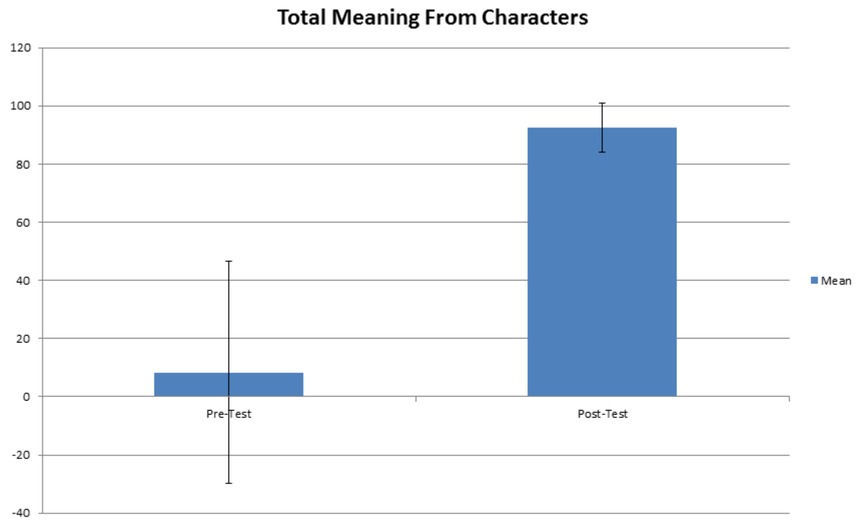


Figure 3.11 Listening Results. The same students did better on the listening portion of the exam. They were given recordings of several words in the game and they had to discern its meaning.

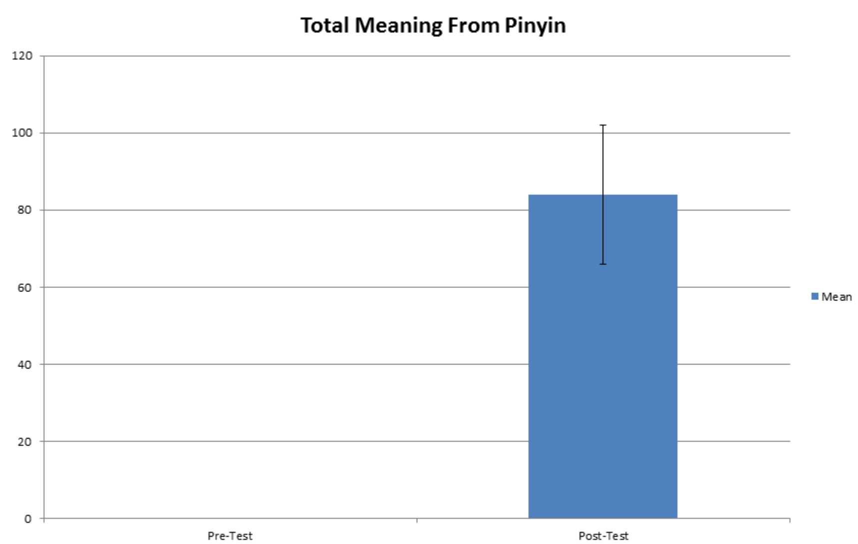
test required the person to translate sentences and also write some of the characters. Along with this test each one of the subjects were given a survey so that we could also gauge their experience.

In most cases there was a significant increase from the pre-tests to the post-tests. Vocabulary recognition going from character to the meaning had the highest results with very little variance as seen in Figure 3.12. We can correlate that since one of the main game mechanics required the player to memorize and recall the meanings of these characters, this is why there was very little variance. Most did well recognizing the pinyin from the characters, but not as well comparatively as seen in Figure 3.13. There was an increase compared to the pre-test, but there existed a wide variance in their answers. One reason for this is because the pinyin was not as prominent as the characters in the game — this even despite the pinyin being directly related to the sound of the words which was featured. These results were contradictory to the results of the other study. We assessed that there may be a disconnect from seeing the pronunciation versus actually hearing the word spoken. This assumption was furthered by the participant's lackluster ability to determine the character from the



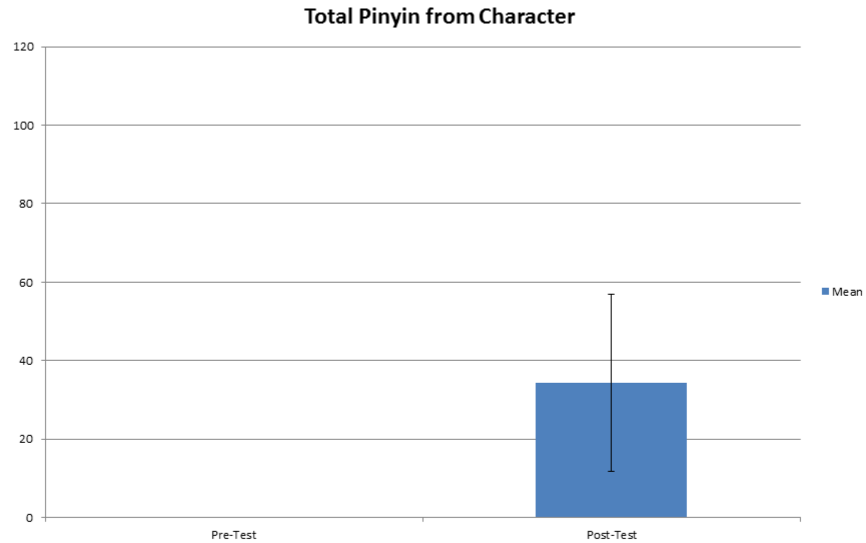
Total Meaning From Characters		
	Mean	Standard Deviation
Pre-Test	8.4	38.22
Post-Test	92.45	8.5

Figure 3.12 Total Meaning From Characters



Total Meaning from Pinyin		
	Mean	Standard Deviation
Pre-Test	0	0
Post-Test	83.9	18

Figure 3.13 Total Meaning From Pinyin



Total Pinyin from Character		
	Mean	Standard Deviation
Pre-Test	0	0
Post-Test	34.35	22.58

Figure 3.14 Total Pinyin from Character

pinyin3.14.

The tests also pointed out a few failing points in the game's ability to teach languages. The game was not able to teach how to write the characters or translate sentence. The game had no mechanics that would train a person in doing any of these abilities, so it is no surprise that there was not change in their abilities.

This effective example demonstrates how a game developed specifically for research in second language acquisition continues to lead credence to the theories it was based. More studies need to further confirm this. Retention, for instance, was never tested, but it is vital in confirming more of these theories. Also a few other populations should be tested so it could solve which demographic these types of games are effective.

Chapter 4

Aphasia Game

Speech therapy and rehabilitation continues to be a well-studied field with many forms of treatments available for different conditions. Unlike other disciplines, where therapies have been adapted into serious games to make the process more enjoyable and accessible, this field lacks the use of these increasingly popular tools. We will show how a game we created called, *Name Game*, is an effective serious game that may aid in the process of speech therapy and rehabilitation for people who have aphasia and/or apraxia of speech an impairment in the planning of articulatory movements.

4.1 Introduction

Within the discipline of speech pathology, there are many forms of communications disorders. One common condition is aphasia, where a person has troubles clearly and consistently communicating what they are trying to convey. This impairment can arise from different causes. Simply, this disorder is when a person has partial or total loss of the ability to use and/or understand speech, and is generally caused by a brain injury like head trauma or a stroke.

Prior research in this field has shown that continued practice or "overlearning" can help cognitive skill acquisition, even after performance has reached a certain level [24]. It has also been shown that repetition of rehabilitative drills is most likely to be important for long-term neural changes [56]. Specifically in speakers with aphasia, the intensity of the treatment has been shown to positively affect the outcomes and maintenance [18]. Another interesting discovery was that rhythm has been shown to increase the fluency in these speakers [10].

Despite being effective, there are problems with how these therapies are administered. One problem is that overlearning must be achieved through repetition, and so this process may become tiresome. Furthermore, the "drilling" exercises requires a trained person to administer them, which may be met with reluctance. In order to overcome these obstacles, we created a game called, *Name Game*. Using a serious game that was created based on the idea of overlearning and rhythm based therapy to create an experience that is motivating, inviting, and effective is the basis of our work. The game awarded the user based on rhythmic accuracy and spoken accuracy. The latter used speech recognition software which has been shown to be a challenge with people possessing this condition [79].

4.2 Related Works

In order to create this game, we examined rhythm games. These games were not strangers to therapeutic research. Many of these games focus' have been oriented around exercise and helping people to become more active and healthy [83] [9]. Along with the physical benefits, there have been others discovered as well which includes increased social interactions, since most of them create an open atmosphere for meeting people [37]. These engaging and welcoming systems have also been shown have improvement to acute cognitive abilities [30]. Despite these findings these games cannot teacher everything as it was shown that people cannot learn musical structure from them [31], or how to dance from them [16]. However, with some other studies showed that rhythm can help with aphasia patients [10] these types of games made the most sense as they model the therapy concisely.

Using computers for the treatment of people who have aphasia is a common and well studied practice [82]. One focus was to help people communicate using a computer [53] [52] [3], or help people with aphasia interact with a computer [29].

Others have sought to create interactions which would invoke empathy for people who have this condition [36]. Some have implemented drilling exercises so people with the condition can practice, thus overlearn [6] [35] [14].

Aphasia games are fairly limited, despite them having been examined in the past [59]. Some works examined the problems with the human computer interactions using speech recognition with people who have this condition [11], but there are very few games that would help rehabilitate. A serious video game made to make the arduous task of drills entertaining is what we created. This system is effective since it used existing therapeutic theories, and aligns itself with a game genre that replicated it. It also gives immediate feedback to the user which compels them to play more, much like other rhythm games.

4.3 The Game

Based on rhythmic therapy, overlearning, and the speech recognition, we decided to create a game with features could embody these concepts. For this reason, we chose to create a rhythm game in the style of *Dance Dance Revolution* or *Guitar Hero*. This game was developed using the Unity game engine coupled together with a speech recognizer called CMU Sphinx. The game consisted of several different modes which allowed for multiple types of customizable games; while also giving clear feedback to the users. From the main menu the user is presented with the options: play, library, and exit as seen in Figure 4.1. While exit is self explanatory, the other modes need a little more explanation.

4.3.1 Library

Before the game began the player could select the library button. This feature was used to acclimate the player with the different words that may be used in the games. Each word is placed in a table where the player can see the name of the word, a

Figure 4.1 Game Menu. The title menu from which the player could choose to play, go over the words in the library, or exit the game.

Figure 4.2 Library Menu. This shows all of the words that can be in the game. It is accompanied with a picture and an option to listen to the word.

pictorial representation of the word that is used in the game, and also a button where the player can hear the word pronounced as seen in Figure 4.2. Once they are done exploring this menu they then can go back to the main menu.

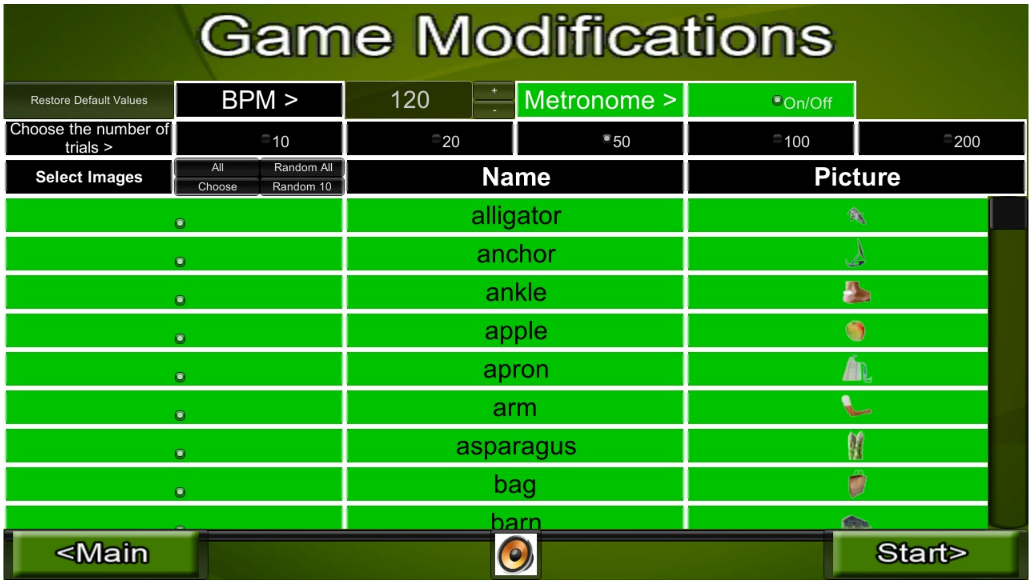


Figure 4.3 Game Options. This menu allowed to player to fully customize the game by changing the speed, turning the metronome on or off, and selecting the words to be tested.

4.3.2 Game Menu

If the user selects the play menu they are presented with several different mini-games such as practice, archery, cup and ball game, horseshoes, and a tutorial video. Once the player had selected the type of game they want to play they are then taken to an options menu to further customize the experience as seen in Figure 4.3. At the top the player could change elements of the game like beats per minute (BPM) to adjust the speed of the game, could turn the metronome on or off, could change the number of words they have to say, and also contained hot buttons for quickly selecting words randomly in the battery. Below that was a full list of all of the words that can be tested. The user could select individually what words they want to potentially be tested in the game. Once the options have been set the player then selects start to begin playing. Also before transitioning from the game menu to whatever game was selected a configuration file was saved with the options they had just set up. This was also loaded every time the player comes back to the menu.

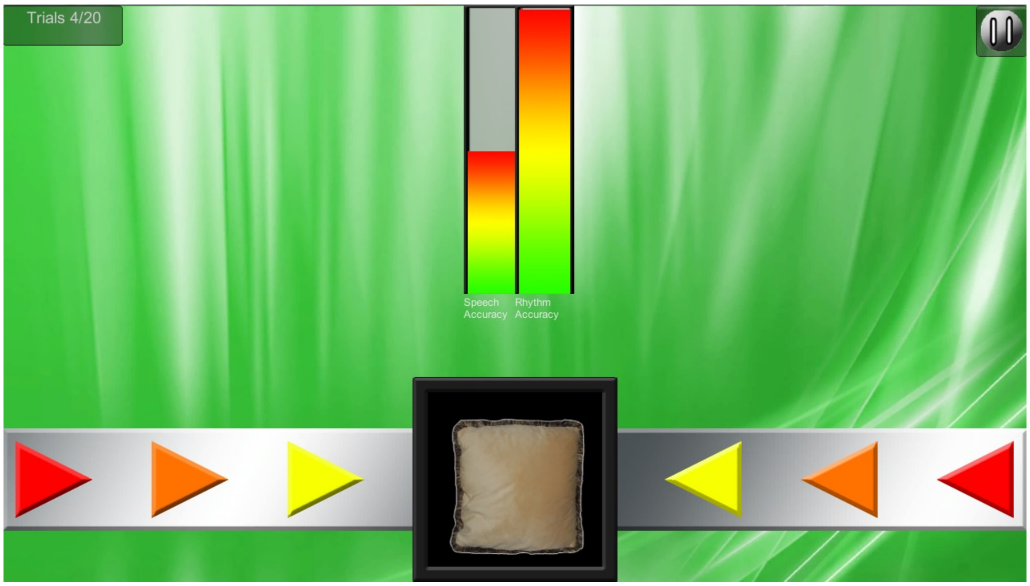


Figure 4.4 Practice Game. In this mini-game the, two bars in the middle showed to the player how well their reaction time was and how well their spoken accuracy was.

4.3.3 Mini-Games

There were different mini-games that the player could select from, but they all work in a very similar way. When the game is started a target word was randomly selected from the battery of words in the options menu. The image of this item was then displayed in the "rhythmic cue bar". This graphical element also displayed at what time to say the word by lighting up arrows based on the metronome tick and also changed the border around the cue box to green. The game recorded from the microphone, then processed the wave, and assigned a score based on the calculated rhythmic and spoken accuracy. This is explained in more detail in a later section. Based on the type of game that was picked the rhythmic and spoken accuracy was displayed in a unique way. The "practice" mini-game was the most minimal in representing graphically how accurately a word was said. In this version there are two bars in the middle that represent the spoken and rhythmic accuracy respectively as seen in Figure 4.4.

The other mini-games borrowed from contests that at their core is some form of target practice. In order to translate how items are launched toward at target, we had

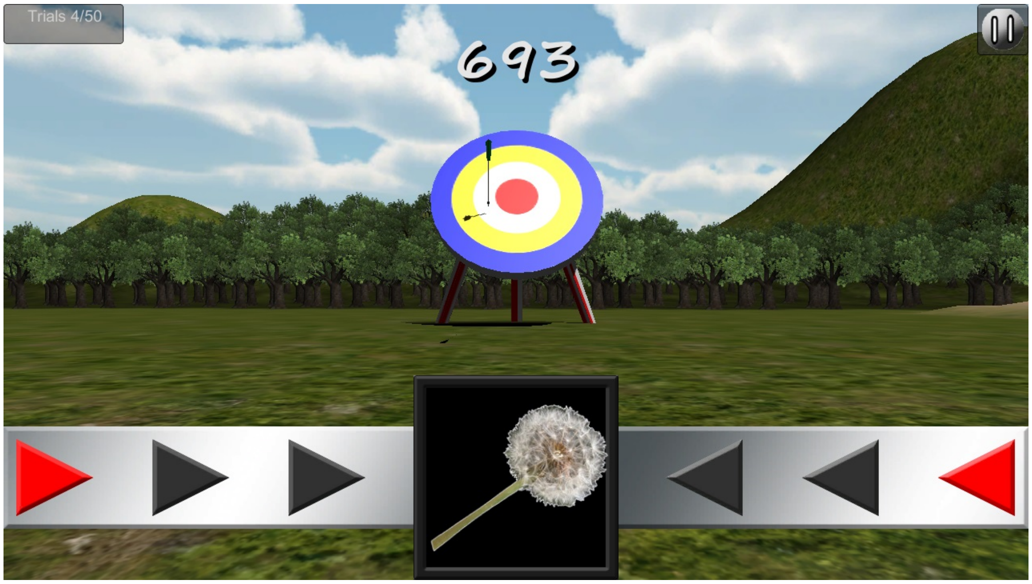


Figure 4.5 Archery Mini-game. In this game, the player launched an arrow at a target. The force behind the arrow was determined by their rhythmic accuracy, and the angle in which the arrow was launched was determined by the spoken accuracy.

the rhythmic accuracy correspond to the force behind the projectile, and the spoken accuracy to represent the angle in which the projectile is launched. For instance in the "archery" mini-game the arrow's speed corresponded to the rhythmic accuracy while where the arrow is pointing corresponded to the spoken accuracy as seen in Figure 4.5. These same concepts also work in the "horseshoes" and "cup game" mini-games as seen in Figures 4.6 and 4.7.

4.3.4 Evaluation

One of the biggest features of this game was having near instantaneous feedback which indicated how well the user said a word on time, and how well it was said. In order to accomplish this, the task was broken down into three essential parts: "say it" phase, "heard it" phase, and "understand it" phase. When the game first started, the "say it" phase began by turning on the microphone and continuously recorded. This long recorded chunk was then sliced into a smaller chunks which were processed and then stored in a sound table for further use. These chunks were sliced at a specific

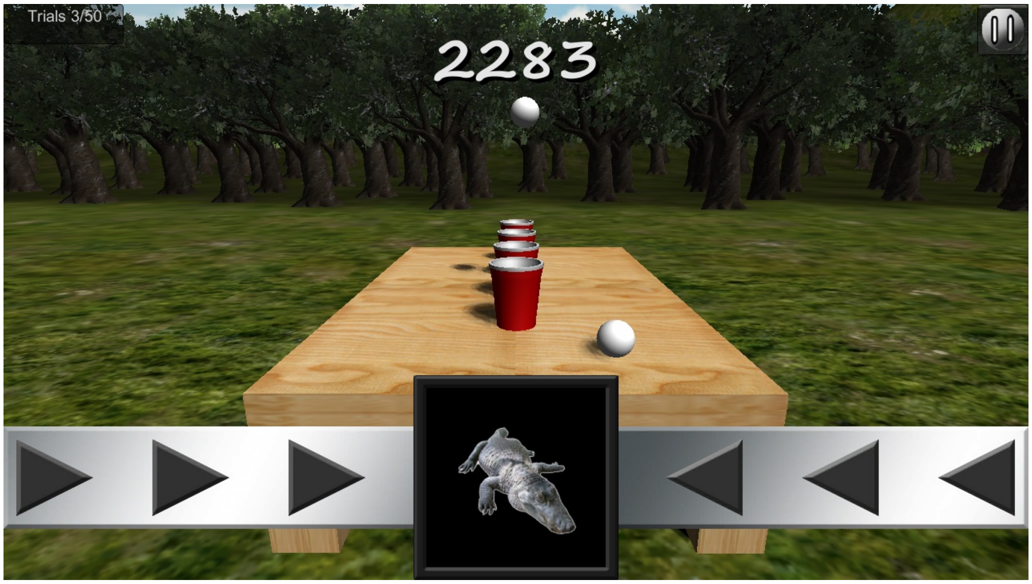


Figure 4.6 Cups Mini-Game. The player threw a ball at a line of cups. Which cup the ball landed into was determined by the speech and rhythmic accuracy.

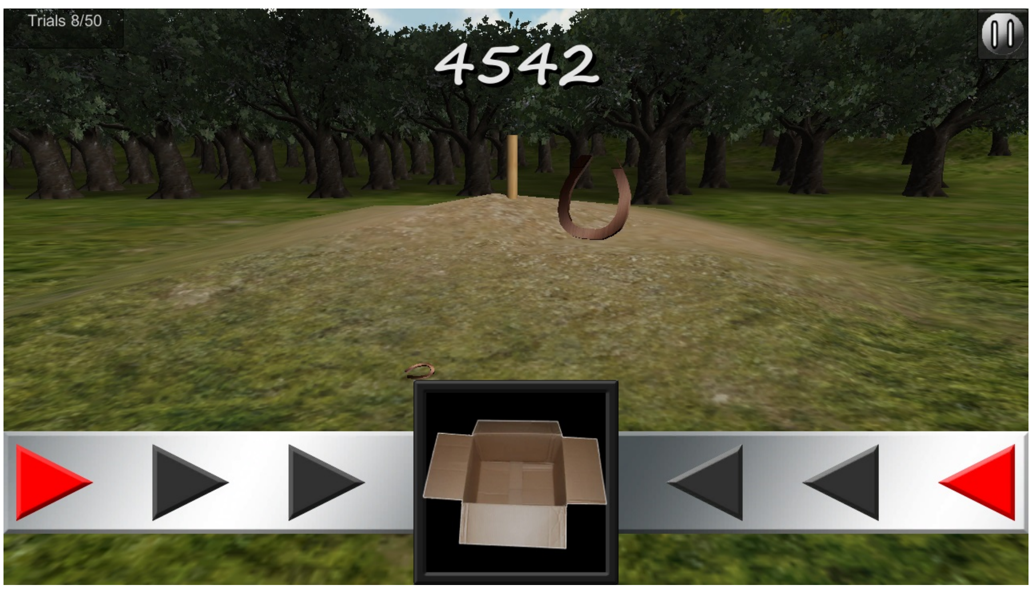


Figure 4.7 Horseshoes Mini-game. This game used the speech and rhythmic accuracy to determine how close the horse shoe came to hitting the stake.

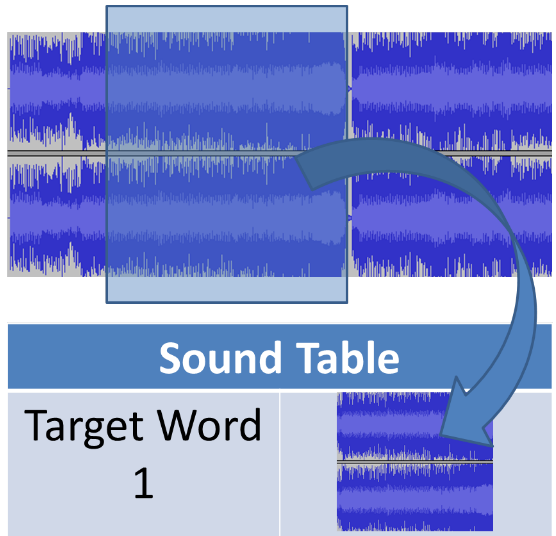


Figure 4.8 Sound Table

time interval which corresponded from the beat before the target beat to the beat after the target beat as seen in Figure 4.8. This allowed a little grace time for the user to say the word and for it to properly evaluate it.

After the chunk is created, it is then evaluated in the "hear it" phase. This judged how rhythmically accurate the word was said in relation to the target beat. To accomplish this, the system scanned through the chunk looking at each raw sample until it reaches a sample that exceeds a given tolerance as seen in Figure 4.9. In this way we assumed that the sample was not background noise but was a deliberate sound. The index of this sample was then converted into a "spoken time", and the difference between the spoken time and the target time is calculated. Rhythmic points were then awarded based on a graduated scale from zero, being they said it directly on time, to some max value, being they missed it completely.

Once the rhythmic accuracy was evaluated the, "understand it" phase begins. In this part, a speech recognition system was used to judge how well the target word was said. The system we used was CMU Sphinx, since it is a well known and powerful tool that gave us both flexibility and utility [1]. We were able to use provided hidden Markov models (HMM's), and created our own specialized library of words that

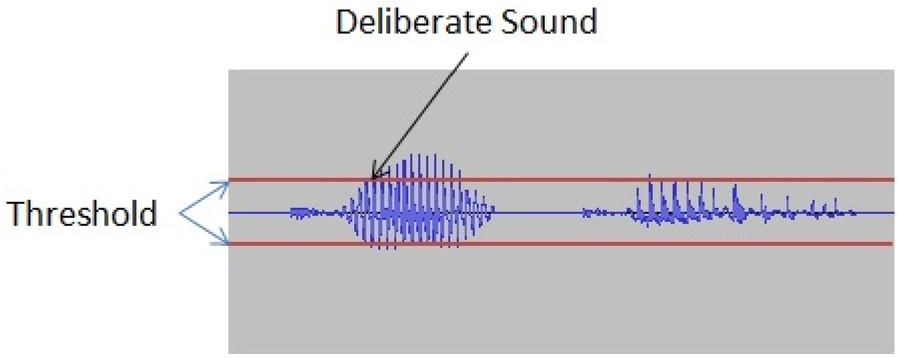


Figure 4.9 Deliberate Sound Detection

could be potentially recognized. With this tool, we took the recorded chunk and then analyzed it, and were given back a list of hypothesized results. The best result was determined by which word had the highest degree of confidence. Using the best result, we then took the word and converted it into its respective phonemes via the library. With those phonemes we then compared them against the phonemes of the target word, which has been seen before in other works [7]. For our purposes we used a Levenshtein distance [49] to make the comparison. This distance measure calculates the number of modifications it would require to change a given word into a target word. If there was no edits between the spoken word and the target word, then the player was awarded 100% of the possible accuracy points. However, if there were edits made then points were deducted, and each edit (insert, remove, replace) were all weighted the same. We used this measure since it is a simple calculation and gave us a good accuracy. Also we used phonemes instead of the actual word since, they are the elemental phonological parts of words and can measure how close the words sounded instead of spelled. This way we would avoid deducting additional points for like sounding phonemes such as the "f" and "ph".

It was found this process generally takes longer than the frame rate of the game. Since we needed to have the game running smoothy in order to preserve rhythmic accuracy we decided to use threading in order to perform this process. Once the

		K	A	A	F	I	Y
	0	1	2	3	4	5	6
P	1	2	3	4	5	6	7
A	2	3	2	3	4	5	6
H	3	4	3	4	5	6	7
P	4	5	4	5	6	7	8
I	5	6	5	6	7	6	7
Y	6	7	6	7	8	7	6

Figure 4.10 Levenshtein Distance Example. This shows the phone comparison between the word coffee versus puppy. It requires six edits overall.

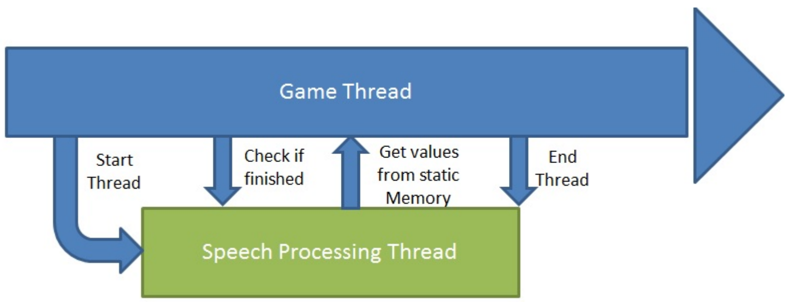


Figure 4.11 Threaded Process. To make sure the game ran smoothly, we offloaded the speech recognition part to a parallel process.

sound chunk was created the speech recognition and the scoring was then offloaded to a parallel process as seen in Figure 4.11. Once that process completed it alerted the game, the game pulled that data in, and applied the spoken accuracy to the game. If this parallel process took too long then it is aborted and a score of zero is given. We do this as partially a safe guard so that all of these process will terminate. Also we assign a zero score as if it takes longer than that set time there is a good chance the system is having trouble recognizing what was said.

4.3.5 Results Screen

Every time the user completes either mode they were shown a results screen, which gave a breakdown of their performance. This displayed both the player's rhythmic

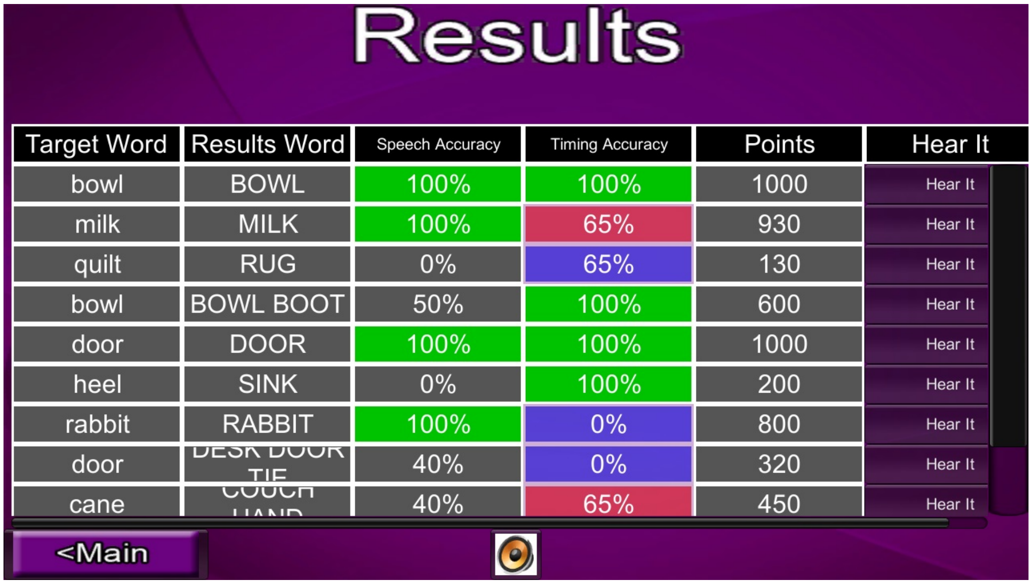


Figure 4.12 Results Screen. This detailed breakdown shows both spoken and rhythmic accuracy.

accuracy and spoken accuracy along with the points assigned for each one of the words as an entry in the table. The spoken and rhythmic accuracies are also color coded in order to make understanding how a person did easier. For instance for spoken accuracy if a person got a perfect score then it was colored green. In rhythmic accuracy if the person was a head of the target beat it was then colored blue. Similarly if they were behind the beat it was colored red. Otherwise if they got it perfectly then it was colored green. Along with those entries, the user had the option to listen to their recorded entry for each word as seen in Figure 4.12. After the results were shown the user was then taken to the main menu and a performance report was generated. This report contained all of the information that was displayed in the results, and more details such as the actual phonemes that the system heard compared to the target words. Also sound samples for each word were also exported. This feature was mostly to be used by a therapist or a clinician to judge their overall performance, and the system's performance.

4.4 Results

In order to test the system we first tested it on people with normal speech to verify everything worked. From there we conducted a pilot study on speakers with mild to moderate aphasia with naming and/or fluency deficits. Their task was to say thirty words depicted using photographs of various objects. A pre-test to post-test measure of naming accuracy was administered. Each test had three groups of ten words: "Control" (ten words unique to pre-test vs. post-test), "Repeated" (ten words that were the same in pre and post), and "In Game" (ten words that were also present in the game). First participants completed the pretest naming task, which did not involve the game and used as a gauge. Next the participants played the game on a laptop for approximately half an hour and were instructed to try out different options with assistance from the researchers provided when necessary. Following playing of the game participants completed the post-test naming task, which again was without the game. Participants then filled out the feedback questionnaire with the assistance of the research when necessary (e.g. due to writing difficulty resulting from language and/or motor deficits).

From our small sample of people, it is easy to see a definite trend upward in both their rhythmic accuracy and the speech accuracy as seen in both Figure 4.13 and Figure 4.14. This is a very good sign.

After the initial study was conducted another was organized. This study had twenty participants with a multitude of aphasia types. Some played the game supervised in a lab while others played at home, and the mean for the total play times for both groups was close to four hours. A way to evaluate their performances was using Western Aphasia Battery Revised Aphasia Quotient (WAB AQ) to conduct pre-tests and post-tests. The other way we evaluated was we used the in-game scores.

In each study there was a change from the pre-tests to the post test. The WAB scores showed a significant increase, and the accuracy increased as well. The reaction

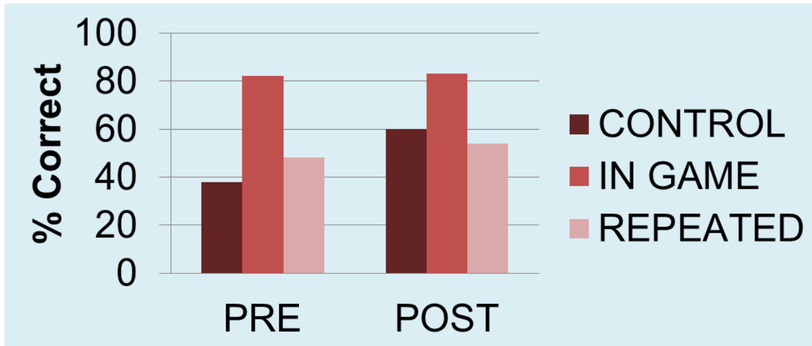


Figure 4.13 Spoken Accuracy Results. The small trial shows how spoken accuracy increased.

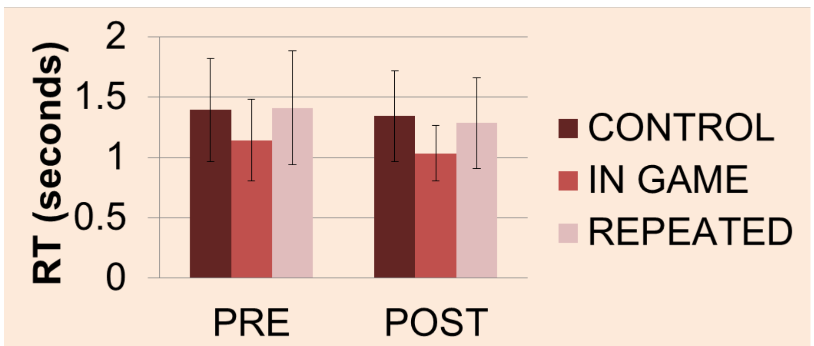


Figure 4.14 Rhythmic Accuracy Results. A trial shows how rhythmic accuracy increased after playing the game.

time had an decrease but only a very small one. While these look good there is a high level of variance in each. One reason for this since the study was broad across many different types of aphasia that it may have caused the large variance. Perhaps there is one type of aphasia that this type of game would work the best.

This was an interesting study as it fell into all three types of gaming research. A game was studied to see what effects the game has. It pioneered new research in game-play as it had to have a near real-time speech recognition system. Finally, the system was created using gaming principles.

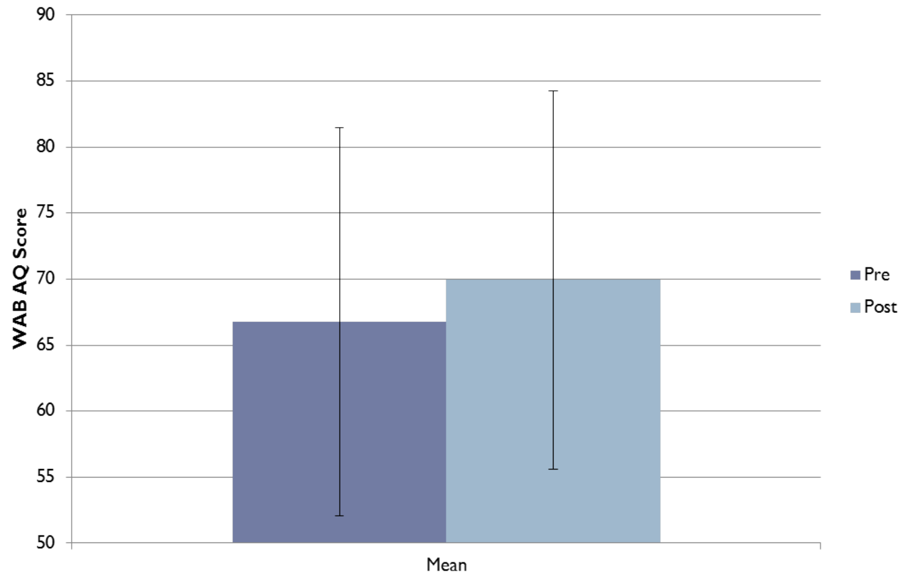


Figure 4.15 WAB AQ Scores. We used the Western Aphasia Battery to test their performance in pre-tests and post-tests. There was a positive trend showing their abilities improved.

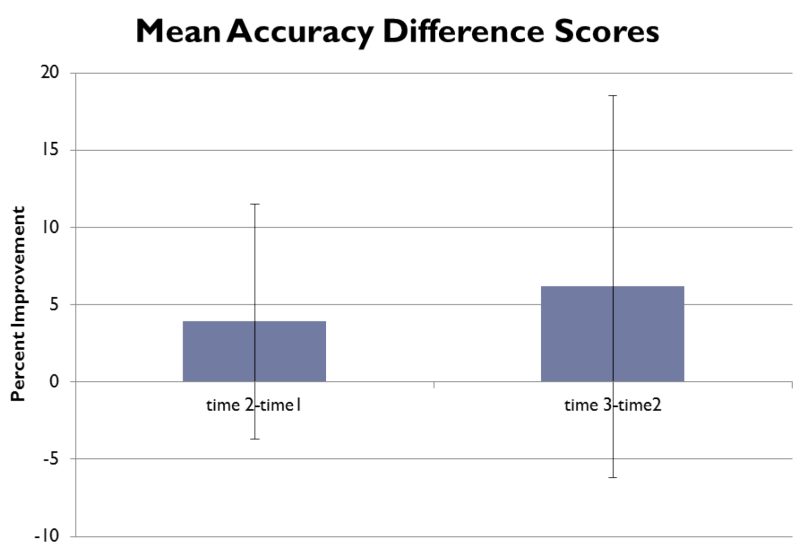


Figure 4.16 Accuracy Difference. The in-game scores showed that their spoken accuracy became better after playing.

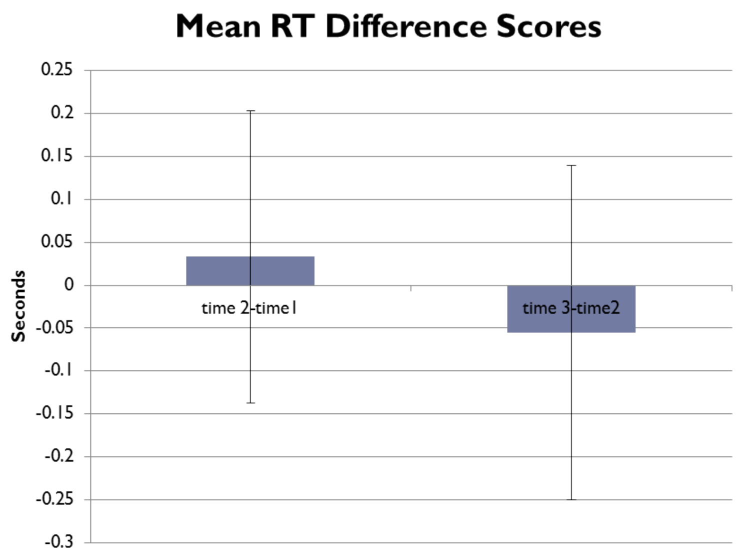


Figure 4.17 Reaction Time Difference. These in-game scores showed that this game did not teach the participants rhythm.

Chapter 5

Genome Explorer

Studying genomes continues to be beneficial for evolutionary discoveries, and prognosticating/diagnosing many genetic disorders and diseases. Most of these studies have used systems that view the DNA in a linear structure, but having this information is only a small part of fully understanding what they can reveal. Visualizing genomes in real time 3D can give researchers more insight, but this is fraught with hardware limitations. Each element contains vast amounts of information that cannot be processed at once. However, by using a game engine and sophisticated video game visualization techniques, we were able to construct a multi-platform real-time 3D genome viewer.

5.1 Introduction

Researchers continue to explore the mysteries of various genomes using diverse tools and techniques. Most of the current software that is used mainly focuses on viewing the primary DNA sequence. However, this is only a small part of the bigger picture. 3D structures of chromosomes have shown to play an important role in gene expression. In recent years, new experimental techniques have yielded higher-level structure data about the genomic and epigenomic characteristics; such as nucleosome position distribution[69], histone methylation[5], transcription factory[77], etc., which could lead to new discoveries. In current software, this 3D information is disjoint from data; causing experimentation to become difficult. Therefore, a system is needed which integrates and visualizes the disparate data to gain comprehensive understanding of genomes. To address this problem, we developed a system to visualize genomes in three dimensions with smooth interactions.

In order for this to be effective, a system must be designed to have a high visualization fidelity, but also allow for fluid interactivity. It should behave similarly to Google Earth where a user can view the planet as a whole, and then zoom down to a very high resolution. However in this case the user should be able to view the entire genome and then zoom down to the atomic scale, but also view is from various angles seamlessly. Creating such a system is not a trivial task. Unlike Google Earth where it is only concerned with one 3D model, this system would handle any number of them. Furthermore, the data that is used to represent this information is very large, so being able to load the entire model into memory is infeasible.

Most modern video games have to visualize a vast amount information at once while also being interactive in real time. In order to make games most developers use game engines, which have been shown to be effective in simulation research [71]. Along with simulations, biology has used games to assist in new discoveries. Games like *Fold It* have been used in the past to help solve difficult questions about protein folding[44]. However, using a game engine and game visualization techniques in this domain has never been attempted. We show through the use of a game engine along with game visualizing techniques were used to create a real time 3D visualization of genomes.

5.2 Related Work

Biological researchers have often used a genome as a scaffold and platform to analyze and disseminate their experimental data. To address this challenge, several types of genome browsers have already been developed by variety of institutions, such as UCSC, Ensemble, and NCBI. These genome browsers not only integrate vast amount of genome information, but also allows users to develop custom tracks to integrate their own data with existing genome information [42]. Such feature-rich genome browsers have become very popular and played essential roles in several important, large-scale genome projects, including Encyclopedia of DNA Elements (ENCODE) [21] and 1000 Genome Project [73]. On the other hand, all these genome browsers were sequence based and visualize genomes in two-dimensional space based on sequence coordinates. This type of visualization was limited in displaying some important epigenomic and structural information generated from recent technologies.

Genome3D was the first model-view framework developed to work with current genome browsers to address these challenges, and to facilitate multi-scale integration and visualization of large genomic and epigenomic data-sets in three dimensions [4]. This model-view framework enabled researchers to infer new knowledge about structure/function of genomes that would have been difficult to accomplish by primary sequence-based browsers. For example, phosphate groups of different base pairs in DNA strand can be either exposed to the outside or sandwiched in between the histone proteins and DNA backbone. This information has important functional implications as exposed phosphate groups can be easily accessible by DNA binding proteins [26]. While new sequencing technologies allowed researchers to map individual nucleosomes across the whole genome [68], it was a significant challenge for current genome browsers to capture such important epigenomic information. Visualizing and inferring such information from 3D genome model may provide additional evidence about potential functional versus non-functional SNP's in non-coding regions. However this system proved to be limited. It could not handle loading large amounts of information in, nor could the user explore the complete 3D model in real time. It was developed in C++ with some antiquated libraries which made it available for only one platform, and near impossible to port to others.

We solve these problems by using a game engine and sophisticated visualization techniques. Game engines are designed to aid in the process of creating games and

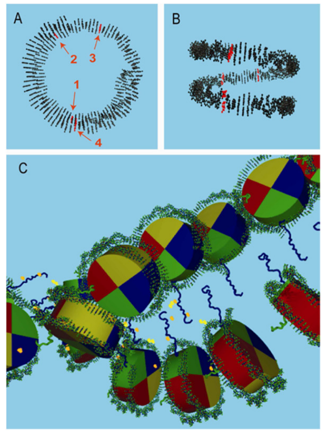


Figure 5.1 Genome3D. A pre-rendered example of the older software to render genomes in 3D.

generally provide interactions and complex rendering techniques as standard features. Also since games are a large industry and need to be highly marketable, most modern engines have multi-platform support, which allows programs developed with one to be ported to a number devices. Furthermore game engines have been used for large simulation research and have been proven to work well in many different disciplines [84]. For these reasons, we found it most appropriate to use a game engine to solve this problem.

5.3 The System

The greatest dilemma facing this type of system was how to manage the large amount of information and having interactivity in real time. Since modern games engines provide this as a standard feature, this was a good starting point. The engine we used was called Unity, and has become widely used by independent developers and researchers. While the built in interaction libraries were standard in an engine, the greatest problem is still visualizing this vast amount of data. A large portion of our focus was mostly concerned with features in relation to rendering the scene. One of these is the level of detail (LOD) system, which is traditionally used to cut down the amount of processing power needed to generate the elements in the scene. Different parts of the scene were presented at different LOD's generally based on a criteria like distance from the camera to that section. An object further away from the scene's camera was rendered at a lower resolution or a lower LOD without much notice by the viewer. By doing this the system was not required to process as much information and can focus on rendering objects closer to the camera at a higher detail. To best solve the problem of rendering the genome we used a special data structures commonly used in games, and then further processed multiple data sources in different LOD's.

5.3.1 The Octree

Many modern games have vast, open worlds, which need to be carefully processed in order to keep the action fluid. To reduce the amount of data processed at a given time, most of these applications use a data structure called an octree. This structure subdivides 3D space into eight sections which represent nodes in the tree. These subsections can be further subdivided making more nodes in the tree. Each node also has an associated level of detail, which is generally determined by the spatial distance from the virtual camera and each node as seen in Figure 5.2. When a node is very far away it is assumed that it and its children can be displayed a lower LOD. However, when the camera is closer to a node, then each of it and each of its children need to be fully processed and displayed.

Most of the time static octrees were used with a set number of subdivisions that was optimized for a given model. However, with a system where the 3D models were generated, such as ours, and with the far large amounts of data that that needed to be processed, we could not afford to waste any space. This is why instead of using a static octree we incorporated a dynamic version[34]. This variation of the data structure automatically subdivided into eight parts when the data contained in said node exceeded a given tolerance. In this way, we avoided having an unnecessarily big

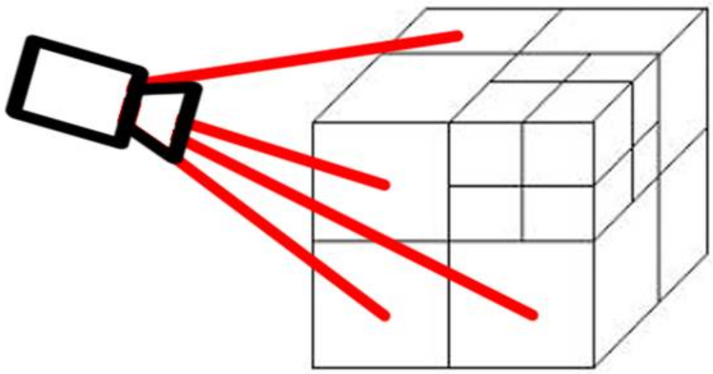


Figure 5.2 Octree Example. The distance from the camera was used to determine at which level of detail the elements in that node was rendered.

tree(s) in memory. Also since we were dealing with a large object it makes sense to stay away from loose octrees [76].

Preserving the structure of the information was key, so finding a way to split up the ordered information was an unique challenge while using this structure. In most cases, the mesh for the objects in the scene were provided, and each polygon in the mesh was placed in a node in the tree corresponding to its spatial location. However in this case, the mesh is generated given a series of files that contain an ordered set of control points on the curve. For this reason instead of dissecting the problem by polygons, we do so by the control points given by the files. Whenever the curve intersects an octree node boundary, a new control point on the curve is constructed and placed into both nodes. While this increases memory usage minimally, it preserves the content.

5.3.2 Further Levels of Detail

Along with the octree, the information given was grouped into three different levels: fiber, nucleosome, and atomic. The fiber level represents the lowest level of detail where each chromosome's 30nm fiber is displayed as seen in Figure 5.3 and Figure

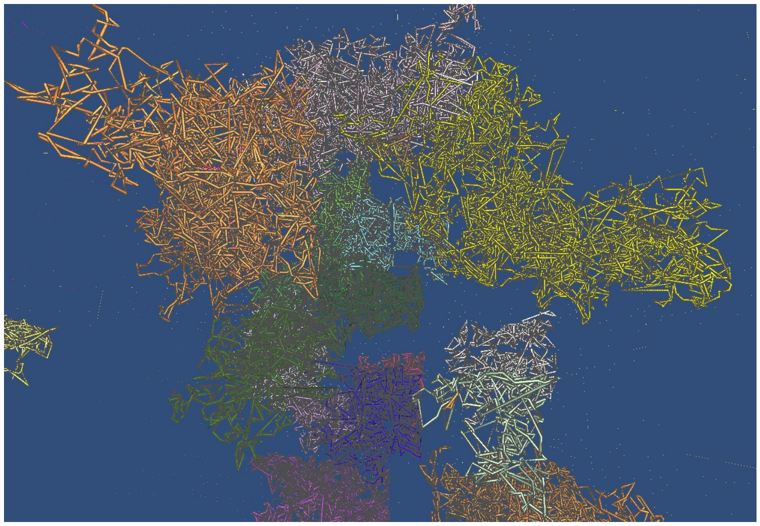


Figure 5.3 30nm Fiber Level Zoomed Out. This was the structure of the each of the chromosomes in the human genome.

5.4. At this level the data is assumed to be given as a series of files each of which are in XML format. They each represented a separate chromosome and its positional information is given by an entry that contained in its base pair number and a Cartesian position. The system scaned the directory that is given by the user, and then loaded and displayed each one. Each file is first loaded into memory and this was placed into an octree. As the data is loaded, a separate octree is constructed from information in each file. This was chosen so that the information from one chromosome to another would not be mixed up.

Diving deeper the nucleosome stage holds the next level of detail. In this level, nucleosome base-pair positions and the DNA that wrapped around and linked to them are displayed as seen in Figure 5.6. Instead of loading all the chromosomes like the previous level, this only displayed one chromosome at a time. The files for these are different from the previous section as well as they were much more detailed. Once again, for each chromosome there was an XML file that contains the information about how it is structured. However, these files not only have the base pair number and positional information, but also the size and orientation of each

Figure 5.4 30nm Fiber Level Zoomed In. Finer detail is displayed in this zoomed in version of the fiber level.

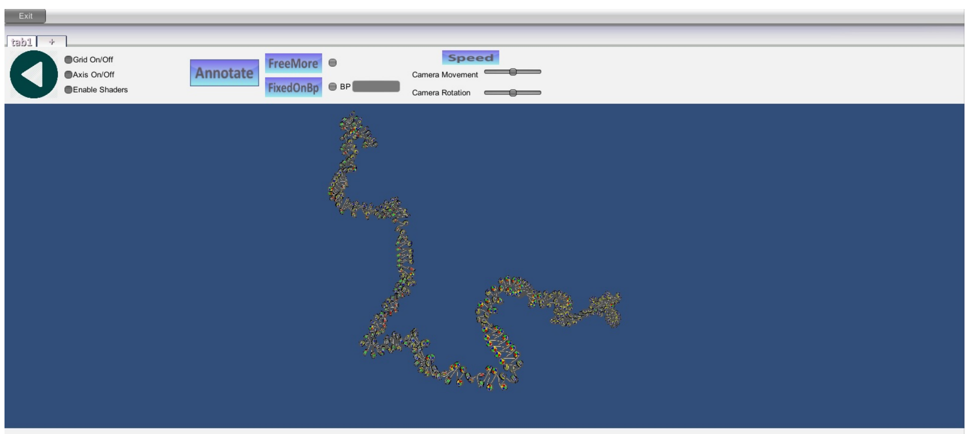


Figure 5.5 Nucleosome View for Chromosome 1 Zoomed Out. This shows a distant view of chromosome one at the nucleosome level.

histone. Also since most researchers are not interested in loading and viewing the entire chromosome, we implemented an option to reduce the the viewing size to a user specified range as seen in Figures 5.5 and 5.6. In most cases the linking DNA was procedurally generated, but the system also takes into account when that linker data is known. That information, in these special cases, is loaded and displayed.

Finally, the highest level of detail is at the atomic scale. Similar to the nucleosome level, the user chose a range from a start base pair to an ending base pair, and the

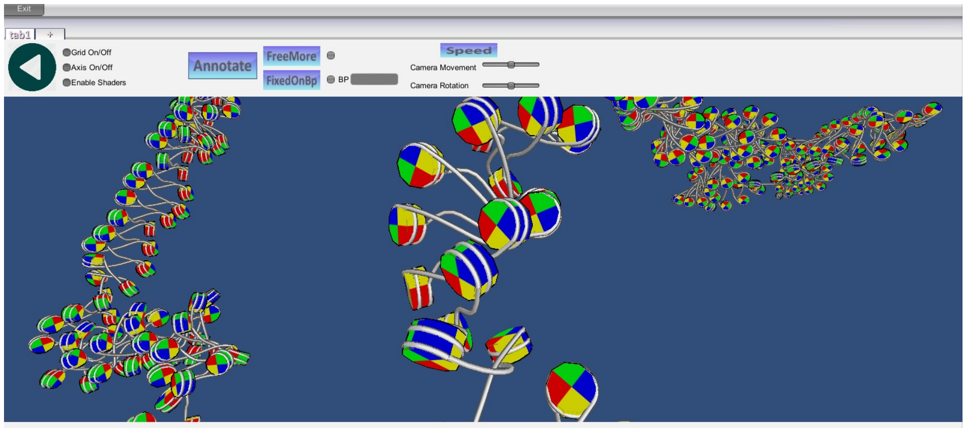


Figure 5.6 Nucleosome View for Chromosome 1 Zoomed In. A little closer, this is the more detailed view of chromosome one at the nucleosome level.

system would display that atomic structure as seen in Figures 5.7 and 5.8. However, this level became tricky as two sets of information has to be merged into one display. Taking the information provided at the nucleosome level that provides positional information, and then combining that with a new file that contains the DNA sequence had to be done carefully to preserve fidelity. To do this we had to first use the base pair number given in the nucleosome file, the system would scan through the sequence file and then begin gathering that information. From there, the system read the sequence from the start to the next base pair, and using that information it then places each atomic model in order. This is done until the final given base pair was reached.

5.3.3 Other Benefits

Besides the robust interactivity and the superior display managers that a game engine provided there were other benefits for using it. For a game to be successful it must be accessible to multiple platforms, and for this reason most game engines can deploy to a wide range of platforms. The system we created has been deployed to Windows, Mac, and some mobile devices which included tablets as seen in Figures 5.9, 5.10 and 5.11. Each version had some minor changes but overall the system still worked the same. The way we are able to make this possible for mobile devices is we limited

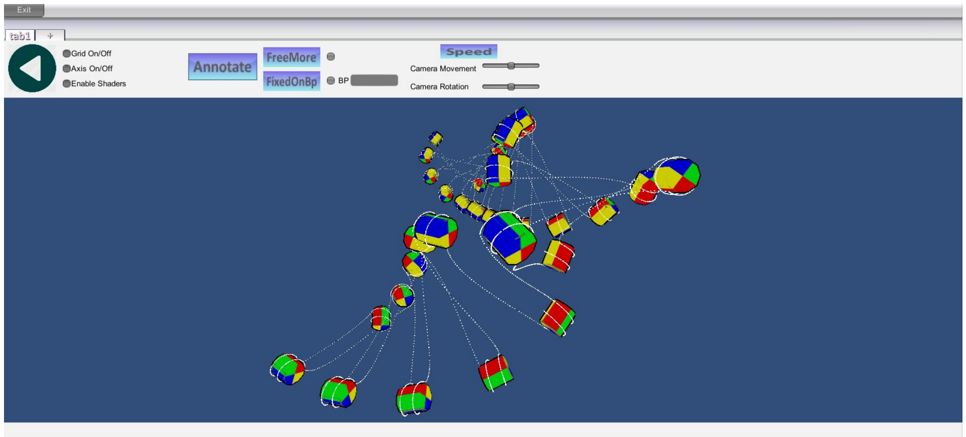


Figure 5.7 Atomic View for Chromosome 1 from BP 10,300 to 16,300 Zoomed Out. This was a far away view of the atomic level of chromosome one from base pair 10,300 to 16,300.

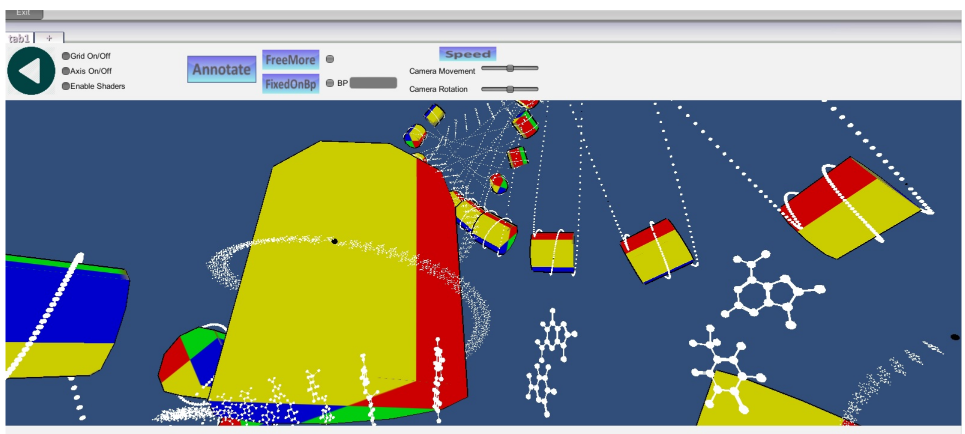


Figure 5.8 Atomic View for Chromosome 1 from BP 10,300 to 16,300 Zoomed In. A little closer, this view shows each of the atoms of chromosome one that were near the camera.

the rendering capabilities, and also read the files from a centralized server instead of from its hard drive. Making this multi-platform was a great benefit as this can now be in the hands of more people.

5.4 Results

In order to test the performance and functionality of this application, we compared it to the only other 3D genome viewer[4]. Every test ran on an average power machine,

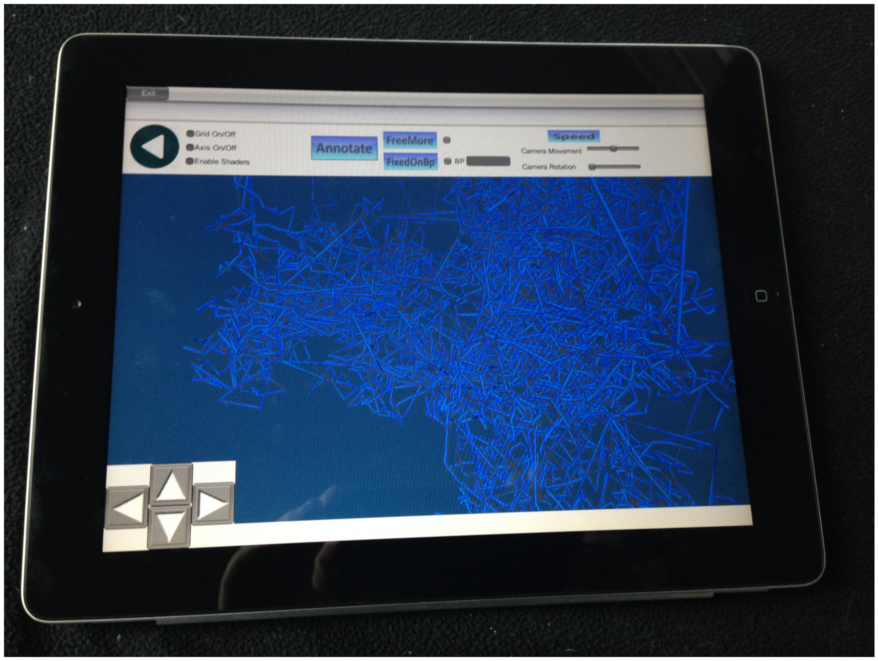


Figure 5.9 Fiber View on iPad

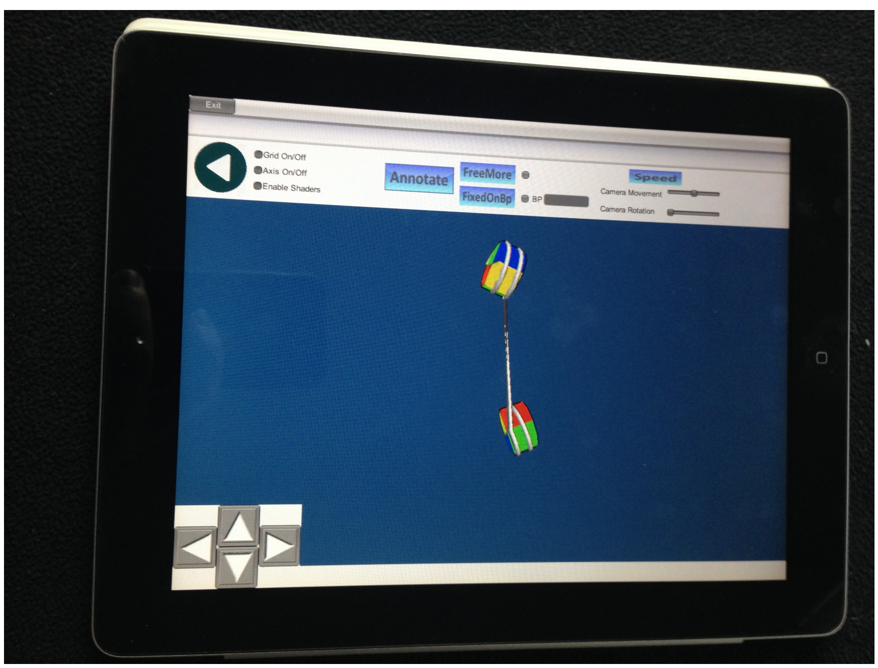


Figure 5.10 Nucleo View on iPad

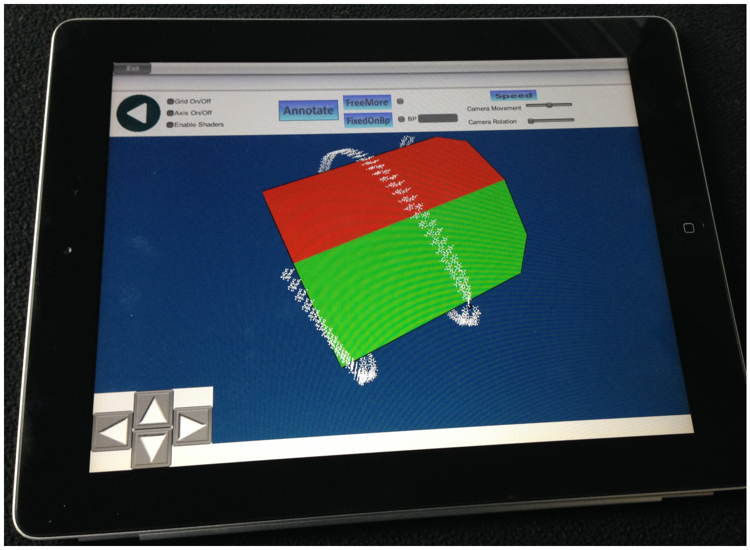


Figure 5.11 Atomic View on iPad

which had four GB of RAM, an Intel Xeon CPU at 3.07 GHz, and running 64-bit Windows 7 Professional. Here are the tests and our results.

The primary focus was to push each of the applications' rendering capacity, since that is a good measure of its functional performance. To accomplish, we loaded a set amount of data and then sequentially more data for each individual test, while also keeping track of the running frames per second (FPS). Each of these smaller tests were also ran for each separated LOD: fiber, nucleosome, and atomic levels. The first set of tests were at the fiber level. The results, as seen in Figre 5.12, were surprising. The original genome viewer out performed the new one with only one chromosome file loaded, but after that the old viewer would crash once more were added in. This is why no other data was available for the original genome viewer. We believe the reasons for the crash was due to the original system not being designed to render more than one chromosome at a time.

Next a similar test was conducted for the nucleosome level. However, this test was not about the number of files the system was able to load, since only one chromosome's nucleosome information could be loaded in at a time at this stage for both

Program	1 Chromosome	5 Chromosomes	10 Chromosomes	20 Chromosomes
Original Genome Viewer's FPS range	60-120	n/a	n/a	n/a
Game Engine Genome Viewer's FPS range	60	60	60	60

Figure 5.12 Fiber Level Results. The results of the new Genome Viewer out preformed the original Genome3D, because it was able to load more information.

Program	25 Nucleosomes	100 Nucleosomes	10,000 Nucleosomes	100,000 Nucleosomes
Original Genome Viewer's FPS range	60-120	n/a	n/a	n/a
Game Engine Genome Viewer's FPS range	60	60	20-60	15-60

Figure 5.13 Nucleo Level Results. These results show that the new Genome Viewer could load more histones than the original Genome3D.

applications. In order to gain accurate insight of this level's performance, the test focused around the number of histones that could be loaded and rendered at a time. The results in Figure 5.13 show a parallel result from the last test. When only a few nucleosomes are loaded the original genome viewer performs faster, but once more data was added the older system simply could not handle that amount of data. However, there was a noticeable decrease in performance in the new version once the number of histones loaded exceeded 10,000.

Finally, the last set of tests were ran in a similar vein as the others. Much like the nucleosome scale, the purpose was to test and evaluate each program's performance when a certain amount of atoms were loaded and rendered. The results, as seen in Figure 5.14, show a more comparable trend. Both systems simply rendered the given

Program	25 Atoms	100 Atoms	250 Atoms	500 Atoms
Original Genome Viewer’s FPS range	60-120	60-120*	60-120*	60-120*
Game Engine Genome Viewer’s FPS range	60	60	60	60

* The original system would only load 25 atoms

Figure 5.14 Atomic Level Results. Genome3D’s capabilities look better at first, but it was only able to load twenty-five atoms at a time, and so the Genome Viewer is better by default.

data without any further LOD data analysis, and it first appears that the original genome viewer out performs the game engine version. However, the original system only seems to allow twenty-five atoms to be rendered at once, so its hard to make a comparison after the initial twenty-five.

From these tests, it is obvious to see that using the game engine with sophisticated rendering techniques commonly used in games resulted in a performance superior to its predecessor. The key to the performance enhancement was breaking apart and grouping the large amount of data in a better way, which was facilitated by using an octree for spatial information. In this way, more data was loaded and displayed at any given time, and yielded such drastic results compared to the previous incarnation.

5.5 Conclusions

In this paper we presented the problem of visualizing genomes in 3D, and the potential benefits that this could provide. We solve this problem by applying techniques and tools that are commonly used in video games, which included using a game engine, partitioning the data with an octree, and grouping the files to perform multi-tier level of detail analysis (LOD). The use of a game engine provided the user interfaces and fast rendering systems, and also allowed for fast multi- platform support. Organizing the data with an octree reduced stress on the system while still providing visual fidelity. Finally, recognizing the data was given in three different formats provided another level of detail which we incorporated, such that the system did not need to load all the information at once. Finally, we showed that using this application compared to the older non-game application out performs it at nearly every level, since it was able to load more data and visualize even more elements. With our application we have provided researchers with a tool that could be used for more genomic work.

Chapter 6

Conclusions and Discussion of Future Work

In this work, we explored games as being a tool for research in different disciplines. After discussing what games are and how they have been used in research, we then explored three works of our own which helped further the concept of using games for research. The first game was used to aid language acquisition. It was created with modern language acquisition concepts at its core to drive the game-play. It was shown that it could be an effective way to learn vocabulary. However there is still work that needs to be done. Features like new mini-games that help with grammar is needed to round out understanding how to read and write the language. In the same vein, mini-games that use speech recognition would help in the player's speaking abilities and listening comprehension.

The next game was used to aid speech rehabilitation. This game was created by examining common therapies used in treating aphasia. After constructing new styles of game-play, we then tested this rhythm game, showed its effectiveness. The game works, but there is still more ground to cover. For instance, discovering which type of aphasia this works the best for. It's possible that this game works well for some but maybe not others, and this could be a source of new discovery in this research. Also right now it only will grade one word at a time, so a next step is testing entire phrases and sentences. This will require a retooling of the interface, and possibly some new research in gaming.

Finally the last system was not a game, but a visualization tool which used gaming principles. We showed how solving the problem of visualizing this large data sets were possible by using concepts that were common in most large games. Also we showed how using a game engine to create this was better since it became easily multi-platformed, easy to set up user interfaces and controls, and also optimized graphically.

Each one of these games fell into the concept of conducting research which uses games. The first two games used games in order to test different theories in their given fields. They also established new styles of game-play, in these cases they also fell into research for games. Working in both areas was shown to be mutually beneficial. The final system was not a game, but it used the concepts of games as the foundation of its back-end. Again this is another way games can be used for research as solutions to other problems can borrow common gaming practices.

Now that we have shown in a few examples how research using games is beneficial, we would like to give a suggested methodology for conducting this style of work.

1. Understand the problem and their theoretical solutions
2. Find or create a game who's mechanics closely align with the process of the solutions
3. Validate the game through tests

The first item seems obvious for any form of research. It is important to know where the cutting edge of these problems lie, so that the system that is being created does not use outdated practices. Now once potential solutions are found is when this purely speculative step occurs. While it may be just be speculation right now, our few examples seems to lead credence to this idea. If one subscribes that games are a communicative form, as we mentioned in the introduction and also is furthered by the classic work of Caillois, Bogost, and Flanagan, then aligning the play with the concepts of the solution(s) should yield an effective result. We believe if a game designer mindlessly tacks on extra game-play, or creates a system that does not agree with its intended purpose, then the message becomes confusing and ultimately ineffective. Furthermore when implementing these concepts the difficulty will always remain in the detail. Trying to reach the cutting edge can potentially expose new concepts and breed more innovation. Finally once the game is created or found, then studies must be conducted to validate the claim.

More studies will have to be run in order to see if this methodology has some truth, but for now this will remain speculative. This is another instance of how the concept of using games for research is very new. It also shows that this field is ready for new discoveries. Games are much more than entertaining; they can be a powerful tool for research.

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