

An Analysis of Game-Based Learning for the Design of Digital Science Games

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Abstract

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As science becomes increasingly data-driven, there is a need to prepare the next generation of youth with the wide variety of skills and tools necessary for future scientific careers. In this dissertation, I address the diverse gameplay capabilities present in youth, arguing that educators and designers can and should leverage these in the design of educational science games. I employ both quantitative and qualitative approaches to examine gameplay within the context of the bioinformatics game, *MAX5*. Two initial studies are presented showing that a player's previous experience with a game's genre and the types of messages shared between players during social gameplay are significant predictors for learning outcomes. A qualitative data analysis then identifies themes of gameplay that are compared and contrasted with existing theories to lay the building blocks for a new complex systems model of game-based learning. Components of this model exist within five interlinked layers: the *input*, the *sensory sphere*, the *structural dynamics*, *semiotic translation*, and *memory-action patterns*, all existing within a larger dynamic network of games and players. These research findings

provide a means for game designers to broaden the participation of youth in the sciences by matching player capabilities with appropriate game elements and learning content. This research further highlights the need for more adaptive science games that reflect not only players' varied capabilities, but also the increasingly multidisciplinary and collaborative nature of scientific practice.

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CHAPTER 1. INTRODUCTION

1.1 MOTIVATION

The state of educational game development is one of paradox. While elements of commercial video games have been lauded for their sound learning principles applicable to a broad array of domains including organizations and schools (Gee, 2003), many educational STEM games often feel more like dressed-up skill and drill exercises than the complex or aesthetically immersive gaming worlds that youth are accustomed to playing. An estimated 97% of American teens play video games (Lenhart et al., 2008), and games have shown much promise in their ability to increase learning and motivation from students in a variety of disciplines ranging from computer science to biology (e.g., Mayo, 2007; Prestopnik & Crowston, 2011). Understanding what makes for a successful approach to game-based learning is therefore particularly pertinent as a way to increase participation in science, technology, engineering, and math (STEM) fields in the U.S., which are on the decline, especially for underrepresented minorities and women (Burke & Mattis, 2007). Yet, despite the increased research into serious and educational games, these games have failed to capture the hearts and minds of young learners to the same degree as commercial games (Prensky, 2001). As Moreno-Ger et al. (2008) note regarding educational games, “the designs need to balance pedagogical requirements with an elusive fun-factor,” and it is just this balance of fun with learning concepts that has proved especially challenging for game designers and educators alike. Studies of game-based learning have shown mixed results in regards to learning outcomes (e.g., Ke, 2008; Von Wangenheim & Shull, 2009) and motivation (e.g., Kebritchi et al., 2010), and there has been little consensus on the elements of gameplay that are most effective in producing successful outcomes (Dondlinger, 2007).

While commercial games of all types, genres, and styles exist, which allow players to select the gameplay style that most engages and suits them, a classroom contains a multitude of types of learners with various gameplay experiences that must be accommodated. Game scholars such as Henry Jenkins (2004) have advocated for the importance of accommodating diverse player experiences in learning games “to foster diversification of genres, aesthetics, and audiences, to open gamers to the broadest possible range of experiences.” Educational game developers are then faced with the challenge of designing for a broad array of mechanics and contexts in order to reach players with these different motivations and skills (Prensky, 2001; Salen, 2008). Even when examining one of the most popular genres used in learning games, namely, adventure (e.g., Amory et al., 1999; Dickey, 2006; Torrente et al., 2010), this is only played by approximately 66% of American gaming youth (Lenhart et al., 2008). Yet a one-size-fits-all approach for games in the classroom simply does not account for these highly varied gameplay interests and capabilities. There is a need for further theoretical and practical guidance in translating diverse play experiences into the design of educational games.

In the MacArthur Foundation Series on Digital Media and Learning (Salen, 2008), one of the primary unanswered pathways for the field of educational games was: “what forms of learning do we see emerging from the specific qualities of games (i.e., their status as play experiences, procedural systems, interactive and visual systems, etc.)?” There remains a need to determine how gameplay elements can best match learners' abilities (Salen, 2008; Rapeepisarn et al., 2008). While research has suggested that online learning motivation can vary greatly based on learners' expertise level (e.g., Abramovich et al., 2013) and cultural background (e.g., Andriessen et al., 2006), this same attention has not been applied to educational games. There is an opportunity in games to evaluate learning approaches in a manner that accounts for the rich

interaction environment that a game affords. Digital games contain a host of stimuli and interactions not present in a classroom that make them particularly fitting for understanding diverse methods of learning. The literature supports the many unique attributes of game environments where narrative context, game genre, social and interpersonal interactions, multi-sensory perception, and game objectives have been shown to vary based on player, affecting motivation and in-game performance (e.g., Dickey, 2007; Zagal, Nussbaum, & Rosas, 2000).

The research in the following chapters presents data from a longitudinal co-design process with youth, and a collection of mixed-methods studies conducted in classrooms to examine the effects of game genre, collaborative communication, and in-game information processing modalities on learning and affect. Increasingly, research supports the view that science is far from an emotionless or sterile experience. Rather, it is full of frustrations, hopes, and the excitement of the discovery process (Osbeck et al., 2010). Commercial games leverage player excitement and discovery quite well already. In order to better identify these engaging elements of games and how they connect to learning processes, a qualitative data analysis is used to compare empirical findings against existing theories of intelligence and learning. What emerged from the data was a complex systems approach to understanding game-based learning that operates under different rules and conditions than more traditional classroom learning environments.

Learning technologies are far from immune from cultural and political value systems and biases (Friedman et al., 1996). In this research, my interest is not only to examine the processes of game-based learning, but also to call attention to the possible inequities and mismatched value-systems that can occur within the design of educational games. I also integrate my own reflective critique into this work, as I know that my place as a researcher and scholar is

embedded with its own values and politics. The observations and stories that have emerged from youth in game workshops, design sessions, and interviews have left me hopeful that we can do better, as researchers, educators, and game designers, to allow for a more inclusive learning space. This is far from an admonishment of the many excellent game-based learning projects that have come before mine, but instead, an opportunity for dialogue on how game design decisions made early on can affect the learning and engagement outcomes of students who might already be falling through the cracks of the traditional educational system.

1.2 DEFINITIONS OF TERMS

The following terms make their appearance frequently in this work and warrant fuller definitions in the context of this dissertation.

Digital Games: Defining what constitutes a game has long been contested by scholars (Whitton, 2009). I use a definition from McGonigal (2014) that condenses games into four fundamental aspects: a goal, rules, a feedback system, and voluntary participation. By a digital game, I refer to a game as mediated by a digital device, whether this is a computer, mobile device, or console. My definition aligns with Squire's (2006) identification of digital games as places where cognition is "mediated by players' capacities for action." Therefore, digital games offer a place of exchange between the player's own cognition and the digital environment as a site of enactment.

Learning: While there are many ways that the term 'learning' has been used in previous research, two functional definitions used at different stages of this dissertation are:

- Changes in behavior resulting from experience (Lachman, 1997), as analyzed in Chapters 6 and 7.

- Adaptations in behavior based on responses to environmental stimuli (Lachman, 1997) or regularities of that environment (De Houwer et al., 2013), as analyzed in Chapters 8 and 9.

The first definition is often the default textbook meaning of the term (Lachman, 1997). A definition that is inextricably linked to adaptation within an environment is useful, however, since games are highly immersive designed environments where interaction is key. How the conception of learning evolved over the course of the research process is further discussed in Chapter 5.

Affect: In this research, affect is understood as being inclusive of emotion, feelings, states, and moods, as distinct from cognition (Russ, 1993). Affect is examined both in written assessments using the Positive and Negative Affect Schedule (Watson, Clark, & Tellegen, 1988) as well as through qualitative data analysis.

Capabilities: The term “capabilities” is used quite broadly to refer to “what the individual can or has learned to do” (Brown & McCartney, 2004) as applied to interactions within the game environment. These capabilities might be learned, or have a basis in biology, as exemplified in sensory or movement capabilities.

1.3 THE TRAJECTORY OF RESEARCH QUESTIONS

The research questions in this dissertation developed out of an interest to better connect the existing capabilities of youth in gameplay to STEM concepts and learning experiences. Early on in the co-design and research process, I realized that youth had diverse capabilities and enjoyed varied aspects of gameplay including: exploration, communication, movement, and puzzle solving (Perry et al., 2013). A one-size-fits-all approach to educational game design did not account for the range of capabilities I was observing. Further, instead of being a barrier to STEM

learning, I realized that this diversity was actually a design opportunity, as many of the varied skills seen in gameplay mapped particularly well to the distributed and increasingly multidisciplinary nature of large data collaborations in science (Perry et al., 2014).

The challenge then became how to identify these capabilities operating within a framework of game-based learning in a more targeted manner, and to understand their effects on STEM learning. This interest led to the primary research questions of this dissertation: **What do players bring to digital gameplay that impacts effective game-based learning outcomes for STEM? How do these capabilities relate to the designed attributes of a science game environment?**

This question did not take a straightforward path, as the research processes evolved with multiple qualitative and quantitative approaches and sub-questions used to answer the primary research question more fully. Chapter 6 discusses findings from a quantitative study of genre experience in which data from in-class surveys and an evaluation study are placed in dialogue with qualitative interview findings to answer the question:

***RQ1.** Does previous gameplay experience affect learning outcomes for digital science games?*

Chapter 7 examines the impact of message sharing behaviors on learning outcomes through a quantitative analysis of chat log data placed in dialogue with qualitative findings, to answer the question:

***RQ2.** Do social behaviors affect game-based learning outcomes for digital science games?*

These earlier studies suggested that previous gameplay experiences and message sharing behaviors were in fact facets of a more complex model of game-based learning, the workings of which I had yet to discover. While there has been compelling research suggesting the relevance of intelligence (e.g., Becker, 2005; Jovanovic et al., 2008; McCue, 2005) and learning styles

(e.g., Chong et al., 2005; Hwang et al., 2012; Rapeepisarn et al., 2008) to models of game-based learning, I wished to examine whether the empirical data collected in my research adequately described these theories. In Chapters 8 and 9, I present a qualitative analysis to answer the question:

***RQ3.** Do existing theories of gameplay and learning account for what players bring to digital gameplay as evidenced in the data?*

In Chapters 5, 6, 7, and 9, the findings on contexts of learning, social chat behaviors, previous gameplay experiences, and the model of game-based learning, are brought into dialogue with designed elements of STEM games, in the service of understanding:

***RQ4.** In what ways can players' learning capabilities be supported by design choices in educational science games?*

All of these questions are driven by an aim to understand how game-based learning operates, and further, how designed elements of games can be effectively leveraged for science education. Complex learning mechanisms occur in all manner of games, whether they are labeled as educational or not (Gee, 2010; Prensky, 2003). My hope is that this research challenges game designers and educators to go beyond the use of digital games as thinly veiled versions of the traditional classroom experience and to use digital games for what they are best at: engaging, exciting, and inspiring.

1.4 OUTLINE OF THE DISSERTATION

This dissertation uses both qualitative and quantitative analyses of gameplay with an interest in increasing the participation and engagement of youth in science and computing fields. **Chapter 2** provides an overview of related literature, focusing on relevant work in learning and intelligence, affect in games, player motivation, and studies of STEM games. **Chapter 3** discusses the design

and architecture of the bioinformatics game *MAX5* that I developed and implemented for this research, which serves as a case study for future chapters. Bioinformatics and parallel computing content in the game are described along with mechanisms of gameplay. **Chapter 4** provides an overview of the mixed methods approaches used in this research, introducing a longitudinal co-design process, data collected in classroom studies, and interviews with youth about gameplay. **Chapter 5** explores the evolving understanding of learning as addressed in this work, including a discussion of written assessment measures, as well as a shift to a broader conceptualization of informal learning where context and affect are integral to the learning process.

Chapters 6 and 7 describe studies that use mixed methods approaches to examine how previous gameplay experience and social chat behaviors are associated with learning and affect outcomes. **Chapter 6** discusses the results from a quantitative study of *MAX5* that examines previous gameplay experience as a predictor for learning and affect. Previous experience with the first-person shooter genre is found to be a significant predictor for player learning and change in negative affect, aligning with the predominant genre of the game tested. An analysis of interviews in this chapter further suggests that differences in the symbolic structures of gameplay and bodily reflexes are important considerations for designers. **Chapter 7** investigates social message sharing behaviors between chat participants in the game *MAX5* using a quantitative analysis. The results of the analysis show that types of messages shared are a significant predictor of learning outcomes. A qualitative analysis of the chat messages identifies more dynamic affect patterns relevant for future study. The findings in Chapters 6 and 7 informed the thematic analysis of player gameplay capabilities that serves as the basis for a theoretical model of game-based learning.

Chapter 8 details a thematic analysis conducted across a wide body of data from interviews, surveys, field notes, gameplay observations, and chat logs. Emergent inductive themes are compared and categorized in relation to the theory of Multiple Intelligences (MI) to see whether they stood up against this theoretical scaffold. While the results show overlap between the empirical themes and MI, the interdependency and movement between themes was not well accounted for, highlighting the need for a more dynamic theoretical lens.

In **Chapter 9**, a complex systems approach is used to further interrogate the themes from the thematic analysis and uncover the dynamic properties of game-based learning as they exist within five layers: the *input*, the *sensory sphere*, *structural dynamics*, the process of *semiotic translation*, and *memory-action patterns*. These layers are described further within the information processing and affect exchange network that connects multiple players and multiple games. The theory is then discussed in the context of designed elements of the game *MAX5* and concepts from STEM learning, showing the applicability of the theory to STEM educational design.

In **Chapter 10**, I conclude by summarizing the findings of the studies and the game-based learning model, calling for designers and educators to integrate the varied capabilities of gameplay identified in this dissertation in a manner that helps foster a more inclusive environment for STEM learning, while also reflecting upon the increasingly multidisciplinary nature of data-driven scientific collaborations.

CHAPTER 2. RELATED LITERATURE

This work is informed by research in psychology, gaming, the learning sciences, as well as theories of intelligence and complex systems. The following topics are addressed in this chapter to provide a relevant theoretical and research background: theories of constructivist learning, psychological theories of learning styles and intelligences, research on gameplay styles and preferences, player affect and emotion in games, and research on STEM-related learning games.

2.1 CONSTRUCTIVIST & EXPERIENTIAL LEARNING

Play and experimentation are important activities within constructivist theories as learners create meaning from their experiences (Strommen, 1992; Tam, 2000). Central to constructivist ideas is the concept that children actively construct knowledge and create their ideas as opposed to simply absorbing information (Tam, 2000). Research on video games has shown that games are often inherently proactive and explorative activities that encourage self-reliant learning (Annetta et al., 2007) making gaming environments an ideal setting for constructivist-based learning. Jonassen (1994) describes elements of constructivist learning environments that contain many representations of reality, present the natural complexity of the real world, construct knowledge instead of only reproduce it, support collaborative knowledge building, and provide tasks in context rather than in abstraction. These are all concepts highly relevant to game-based learning. There has been much research on the use of constructivist theory within instructional environments (e.g., Jonassen, 1999; Lebow, 1993; Willis, 1995; Wilson, 1996; Savery & Duffy, 1996), online learning environments (e.g., Mishra, 2002; Huang, 2002; Rovai & Jordan, 2004), and games (e.g., Ahamer, 2004; Dickey, 2007; Kirkley & Kirkley, 2004).

Constructivism is not only relevant for understanding learning processes, but also to the design of instructional environments. Savery and Duffy (1996) offer seven constructivist principles of instructional design to support the learner's ability to develop complex problem solving skills, practice reflexivity, and gain ownership of their knowledge-making ability. Notably absent is the opportunity for the learners themselves to gain ownership and take part in the instructional design process. Willis and Wright's (2000) R2D2 model of design provides some of the earliest and most comprehensive support for integrating participatory design practices into constructivist instructional design through the use of a small group of individuals who represent stakeholders, and the use of a small core team that involves students at various iterative stages of design. Willis and Wright's (2000) work further call for an evolution of instructional design that moves from the "expert-object" framework, in which the expert designer has the primary power in the design process, to a design process that is more recursive, reflective, and participatory.

Several areas of constructivist theories are particularly relevant when considering the design of games: multiple representations of reality (Jonassen, 1994); problem solving to engage students in tackling learning concepts (e.g., Jonassen, 1999; Savery & Duffy 1996); ownership over learning (Honebien, 1996); reflexivity and self-awareness (Honebein, 1996); the social experience of learning (Honebein, 1996), and real world, case-based learning environments (Jonassen, 1994). These values have informed my research throughout the game co-design process.

2.2 PARTICIPATORY DESIGN & CO-DESIGN IN SERIOUS GAMES

Participatory design (PD) has gained use as a design practice, particularly within the human computer interaction (HCI) community (e.g., Druin et al., 1999, Druin et al., 2002; Inkpen, 1999;

Scaife et al., 1997). It has received much less attention among designers of serious games (Khaled & Vasalou, 2014). PD emerged in Scandinavia as part of a movement to democratically empower and integrate the voices of worker communities in design (Muller, 2003). It has since gained traction and use in a variety of contexts with attention towards empowering populations such as the elderly and children (Muller, 2003).

Varying levels of player participation in the serious game design process have been proposed and used. In a muse-based game design methodology, designers look to players as “muses” early on in the game design process (Khaled, 2012). This approach combines practices within the classical tradition of the Western fine arts in which designers look to end users as muses to inspire their creative process, as well as integrating user-centered methodologies including observations, a think-aloud protocol, interviews, and participatory design games (Khaled, 2012). Khaled and Vasalou (2014) discuss the inherent trade-offs and challenges of PD methods in serious game design, as players often do not have domain expertise in the game content. They describe an approach using “boundary objects” including verbal concepts and videos at various stages of design as ways to generate player ideation, sketches, and discussions in workshops (Khaled & Vasalou, 2014).

Beyond using PD to generate game design outcomes, the integration of games as a PD methodology has been used by researchers to generate tools or solutions for a variety of other design outcomes that are not games themselves. Brandt (2006) describes the value and use of exploratory games for PD using four types of games: games to conceptualize designing for use by designers to understand and improve their own design techniques, ‘exchange perspective’ games as inspired by surrealism and often using elements of imagination and chance, ‘negotiation and work-flow’ processes focused on generating a common understanding of work

experiences, and ‘scenario’ oriented design games, in which participants generate scenes or locales relevant to design ideas (Brandt, 2006). Thoughts towards design equality and the generative aspects of the co-design process with youth have been important considerations in my own research process.

2.3 PLAYER PREFERENCES IN GAMES

Research into player preferences has frequently produced typologies and categories aligned with varied sets of motivations and interests. Bartle (1995) offers one of the earliest taxonomies of player types for Multi-User Dungeon games (MUDs), identifying four player typologies for MUDs: *achievers*, interested in point gathering and leveling up; *explorers*, interested in looking for out-of-the-way game features and understanding how things work; *socializers*, interested in the game as a back drop for social relationships and interactions; and *killers*, intent on gaining the adrenaline that comes from destroying other players. Bartle suggests that a stable MUD is one in which all four styles of players are roughly in equilibrium. Yee (2006), in an effort to empirically test Bartle’s player preferences, conducted an online survey of massively multiplayer online role-playing games (MMORPGs) players to determine ten primary components: advancement, mechanics, competition, socializing, relationships, teamwork, discovery, role-playing, and customization. While Bartle (1995) hypothesized that a player’s primary preference suppressed other preferences, Yee (2006) suggests that scoring highly on one component of play does not mean that players necessarily score less highly on another component.

Mixed methods approaches have also been used to understand different gameplay styles. Sherry et al. (2006) utilize a uses and gratifications theoretical approach to analyze reasons why youth are motivated to play video games. Using a multi-method approach they identify six dominant dimensions of uses and gratifications: *arousal*, *challenge*, *competition*, *diversion*,

fantasy, and *social interaction*, finding variance based on grade level, gender, and time spent playing. Chatterjee et al. (2011) use a quasi-experimental approach to investigate the role of collaboration, facilitator intervention, and learning styles on game outcomes by middle school students. They utilize four learning styles (*imaginative*, *analytical*, *precision*, and *dynamic*) from the Children's Learning Styles Inventory, an adaptation of Kolb's (1985) Learning Styles Inventory. Their research suggests that peer collaboration and facilitator support lead to improved learning outcomes.

Nacke et al. (2011) provide a model of seven player archetypes in the *BrainHex* model based on research from neurological findings and previous player models. These categories are: *seekers*, curious about the game world looking for patterns and opportunities to experience wonder; *survivors*, who enjoy the arousal created by experiencing terror in games; *daredevils*, who enjoy risk taking; *masterminds*, who enjoy solving strategies and puzzles; *conquerors*, who enjoy overcoming adversity and enemies; *socializers*, who enjoy interactions with others, and *achievers*, who enjoy completing long-term goal-oriented tasks. Nacke et al. compare these archetypes with psychometric measures such as the Myers-Briggs.

2.4 AFFECT IN GAMES

Games are natural vehicles for facilitating affect given that triumph, delight, and frustration are integral to the game experience (Lazzaro, 2004). Several methods of determining affect, emotion, and engagement in gameplay are commonly used. These include the measurement of physiological signals, the use of self-reported survey data, observations made during gameplay, and text-based analysis of chat logs. Studies that collect physiological measures, such as electroskin conductance (e.g., Ivory & Kalyanaraman, 2007) or electrocardiogram signals (e.g., Ravaja et al., 2006), often combine and compare these measurements with self-reported

assessments of emotional state. Conati (2002) presents an approach using a Dynamic Decision Network and physiological measures to estimate players' emotional states while playing educational games. A growing body of research has also worked to automatically adapt game difficulty and state based on players' physiologically measured emotional states (e.g., Chanel et al., 2011; Liu et al., 2009).

Lazzaro (2004) observed gameplay sessions to determine four areas of fun and to gain insights into associated emotions: *hard fun*, in which frustration at performing an in-game task transforms into a sense of accomplishment once the task has been completed; *easy fun*, which encompasses the "curiosity" filled experience of players as they explore the game outside of direct game goals; *serious fun*, where players experience frustration and relief doing real work or learning; and *people fun*, in which players gain fulfillment through meaningful social interactions with other players. Similarly, Lucero and Arrasvuori's (2010) *Playful Experiences* (PLEX) framework provides a context for understanding player motivations by accounting for twenty-two categories of playful experiences in games. The PLEX framework is a tool for game designers, but also provides insights into motivation in games.

There has been a contradictory body of research around violent video gameplay and aggression. While some researchers have linked violent video gameplay to increased arousal and aggressive feelings in players (e.g., Anderson, 2004; Anderson & Bushman, 2001) and desensitization to violence (e.g., Carnagey, Anderson, & Bushman, 2007; Funk et al., 2004), there has also been research suggesting that aggressive outcomes post-gameplay are minimal compared with other forms of media (e.g. Sherry, 2001) and that previous research has methodological problems leading to inconsistent findings (Griffiths, 1999). Some studies have also found no relationship between violent video gameplay and violent behaviors (e.g. Ferguson

et al., 2008), and research by Peña and Hancock (2006) discovered that the majority of the chat messages within a violent video game were actually positively valenced, contrary to what might be expected. These varied and often conflicting studies suggest that there are complex ways in which games generate affect.

2.5 STEM GAMES

There are an increasing number of games that integrate science, technology, engineering, and math (STEM) concepts. Research has shown the value of engaging players in science games for solving complex scientific problems (e.g., Cooper et al., 2010; Kawrykow et al., 2012). The science game, *Foldit*, offers a way for players to engage in real science and participate in a puzzle that contributes to the development of new strategies and algorithms for protein structure prediction (Cooper et al., 2010). *Phylo*, a citizen science game that crowd-sources the Multiple Sequence Alignment (MSA) problem utilizes NP-hard computational problems embedded in a casual puzzle game framework. This approach was intentionally taken in order to broaden participation, and the game has received over 350,000 solutions from over 12,000 registered users (Kawrykow et al., 2012). Good et al. (2014) describe the game *The Cure* in which players determine molecular signatures for predicting breast cancer prognosis. The tasks are knowledge intensive, and researchers determined there was a significant demographic willing to put in the time and effort to gain the necessary expertise, with helping breast cancer being one of the primary motivations.

Science games have also provided value as learning and instructional environments. Annetta et al. (2009) evaluated a crime scene investigation video game with genetics learning concepts, finding that, while there was no significant difference in learning when compared to a control group, students that played the video game were significantly more engaged in the

genetics content. Miller et al. (2011) developed the digital game *CSI: The Experience – Web Adventures* to expose students to forensics, finding that pre- and post- tests showed knowledge gained and that the game’s usability ratings were a predictor of learning. The game and learning environment *Whyville* offers a learning virtual world where players must work together in the game to fight an epidemic using Center for Disease Control tools (Mayo, 2007). *Immune Attack* is a single-player action video game that offers an immersive experience of the human immune system, allowing players to go throughout the body as they find infections and attack enemy bacteria (Kelly et al., 2007). Science games have also been applied for behavioral change in health. In a video game intervention for young adults and adolescents undergoing cancer therapy, studies on the game *Re-Mission* found that that providing educational content in a video game third-person shooter environment could motivate greater responsibility for healthy actions (Kato & Beale, 2006).

Research has shown the usefulness of games integrating computer science concepts for learning and engagement (e.g., Kitchen et al., 1992; Overmars, 2004; Papastergiou, 2009). Kitchen et al. (1992) note the value of classroom games where students take on the role of processors to illustrate parallel computing concepts. Papastergiou (2009) compares a computer game with a web-based curriculum for learning computer memory concepts, finding that the game group had increased motivation and more effective learning outcomes. *Scratch*, an interactive programming environment created by MIT’s Media Lab, allows players to generate their own games and animations using programming constructions similar to puzzle pieces (Malan & Leitner, 2007). Researchers found that the *Scratch* environment excited students and introduced them to programming logic without the burden of having to learn the syntax of a complex programming language (Malan & Leitner, 2007). While not a game per se, Jacobsen

and Jadud's (2005) research on LEGO *Mindstorms* as a platform for introducing students to parallel programs is notable in combining concepts of concurrency with playful experiences. They suggest that motivation matters in computer science learning, and that by focusing on a fun, authentic, task-based approaches to learning, students are better able to understand parallel programming challenges that might arise in the real world (Jacobsen & Jadud, 2005).

2.6 GAME-BASED INSTRUCTIONAL DESIGN

There have been several notable theories and frameworks for connecting game design elements to instructional content. De Freitas and Oliver (2006) examine how exploratory learning games and simulations can be integrated into a curriculum in a manner that accounts for learning context, learner specification, pedagogic considerations, and the mode of representation. Woods (2004) discusses elements of games that can most appropriately be used for education. Gee (2003) has similarly made recommendations of game elements that should be integrated into educational experiences more frequently as part of learning literacy. These works, while noteworthy in matching learning content to various game elements, do not account for the incredibly diverse gameplay capabilities and experiences of players. While there has been a growing interest in designing adaptive game systems that dynamically change according to player tactics and styles (e.g., Ponsen, 2004; Spronck et al., 2004), further emphasis on adaptive game elements is needed within the space of educational games.

2.7 THEORIES OF LEARNING STYLES & INTELLIGENCES

There has been a large and varied body of work in the field of educational psychology on various learning styles both cognitive and personality based. A conservative estimate places the bulk of the research on learning styles within the past five decades (Cassidy, 2004). This section

provides an overview of several of the major theories on learning styles and intelligence with particular attention to ones that have been used for online learning environments and games.

Kolb's (1984) Experiential Learning Model and Learning Style Inventory (LSI) offers a four stage learning cycle. These four states are: *concrete experience*, in which the learner prefers and takes part in concrete experiences; *abstract conceptualization*, in which the learner participates in more conceptual and analytical thinking processes; *active experimentation*, in which the learner favors trial-and-error in order to gain understanding; and *reflective observation*, in which the learner reflects extensively on the task and possible outcomes before being inclined to action. These stages are seen as a continuous and highly interactive process in which some learners favor various stages over others. Honey and Mumford's learning styles (1992) contain a modified version of Kolb's LSI: *activist*, *reflector*, *theorist*, and *pragmatist*.

The Felder-Silverman learning styles model (1988) was originally developed for engineering students and instructors and has since been modified since initial publication (e.g., Felder & Spurlin, 2005). The more recent version contains learning styles along four dimensions, these are: *sensing* (concrete and practical) or *intuitive* (abstract and theory oriented); *visual* (a preference for visual materials) or *verbal* (a preference for written and spoken explanation); *active* (trying by doing and often group oriented) or *reflective* (learning by thinking); *sequential* (learning through step-by-step processes) or *global* (employing a holistic thinking process). Felder and Spurlin (2005) further note that the optimal teaching strategy balances learning styles in such a way that learner preferences are adequately matched to primary learning styles while learners are also forced to work outside of their comfort area to stretch their skills.

Other researchers have been interested in more explicitly understanding the relationship between learners and their learning environments. The Classroom Environment Scale is a survey

that arose out of research into perceptual environments including hospitals, prisons, universities, and work places (Fisher & Fraser, 1983). Measures are along dimensions that include involvement, participation, teachers, and support. The Individualized Classroom Environment Questionnaire (ICEQ) provides another survey with dimensions related to the learner's environment and categorizes learners along dimensions of personalization and participation (Fraser, 1998).

The concept of human intelligence has provided another way to understand learning capability. Measures of intelligence have undoubtedly been flavored by Alfred Binet's 1905 intelligence test and the Americanized Stanford-Binet test, which was intent on finding a measure of "innate intelligence" (Kamin, 1974). Intelligence as I.Q. has in many ways been reduced to a score that can provide comparisons across populations and age groups on a person's intellectual capacities (Gardner, 2011). The challenge with this concept of intelligence as a single score, and likely why it rankles many modern day educators and learning scientists, is that it is rather reductionist in its interest in how well a person can answer written questions and does not account for the myriad of contexts, cultures, and environments in which learning takes place.

Howard Gardner's *Multiple Intelligences* (MI) introduced a new model of intelligence originating in human biology and based on the "ability to solve problems or fashion products that are of consequence in a particular cultural setting or community" (Gardner, 2006). This focus on the unique attributes of the culture in which intelligence is embedded, and the ability for individuals to have multiple forms of this intelligence stands in stark contrast compared to the uniformity of Binet's intelligence measure. MI theory offered schools, teachers, parents, and organizations a way to make sense of and appreciate the different capacities demonstrated by the chess master, the brilliant musician, the star athlete, and the math prodigy. While visionary,

Gardner's work has also been met with its fair share of criticism, largely around the validity of the methodologies to measure and assess MI. Gardner (2011) himself has noted that while at "one time, I thought it would be possible to create a test for each intelligence ... I now believe that this feat would be extremely difficult to accomplish." Instead more qualitative measures of assessment in MI theory are recommended, including field studies, longitudinal observations, interviews, and questionnaires (Gardner, 2006). These more qualitative methodologies have not always sat well with critics wanting more quantitative ways of assessing MI. Compellingly, digital games do offer a way to record and collect data about learners' interactions with their environment in an unprecedented way.

The term "game intelligence" has been used previously by researchers interested in understanding how performance data from sports games is applicable to learning, creativity, and training. Memmert and Perl (2005) use the term to describe a neural network approach to an analysis of sports game performance data, combining this with qualitative methods to inform an understanding of learning and creativity. Wein (2004) suggests that game intelligence in soccer can explain players' understanding of scenarios on the field and their use of past experiences for decision-making and appropriate action. While there are notable similarities between sports games and digital games in structure and design, the affordances of a digital game make gameplay much more symbolic than non-digital play as players use buttons and devices to interact and translate their experience into the virtual game world.

CHAPTER 3. A BIOINFORMATICS LEARNING GAME

MAX5 is a science learning game built using the Unity3D game engine, a robust development platform that uses .Net class libraries. While Unity3D can be built for operation across numerous platforms (mobile, console, and PC), we built the game for use on PCs, given the ubiquity of PC use in many schools. The code was written in C#, and the game architecture is described in further detail in the following section.

3.1 GAME ARCHITECTURE

Client Side

On the client (game) side RestSharp, a REST and HTTP API client for .NET frameworks, was used to access the server side endpoints. The data was serialized using fastJSON to transform the C# data structures to and from JSON packets that communicated with the server's data endpoints.

Server Side

The server was built using Django, a Python web framework. TastyPie, an extension library, helped serve up the information and allowed us to restrict access to the APIs. All of these libraries are open source.

Data Instrumentation

We instrumented the game to record a variety of information ranging from user IDs, chat messages, player positions, and interactions with in-game tools such as the Basic Local Alignment Search Tool (described further in the next section). The Apache log4net library was used to place data into a more structured format and record data to a file. Python scripts helped

process the data into a more usable form, and these were then imported into the Unity3D Editor by a custom extension. This extension rendered character movements and actions.

3.2 BIOINFORMATICS CONTENT

Bioinformatics is a discipline that uses a computer science approach and software tools in handling the analysis, modeling, and simulations of large biological systems and datasets. Bioinformatics learning concepts within the *MAX5* game include the sequencing of DNA samples and queries performed using an in-game tool that simulates the Basic Local Alignment Search Tool (BLAST) (Altschul et al., 1990). The game also integrates a visualization tool simulating the free bioinformatics software visualization and analysis tool Jalview (Clamp et al., 2004) as a way to visualize multiple nucleotide sequence alignments and to compare similarities and differences.



Figure 3.1: *MAX5* BLAST sequence match. A player compares DNA samples using a simulated Basic Local Alignment Search Tool.

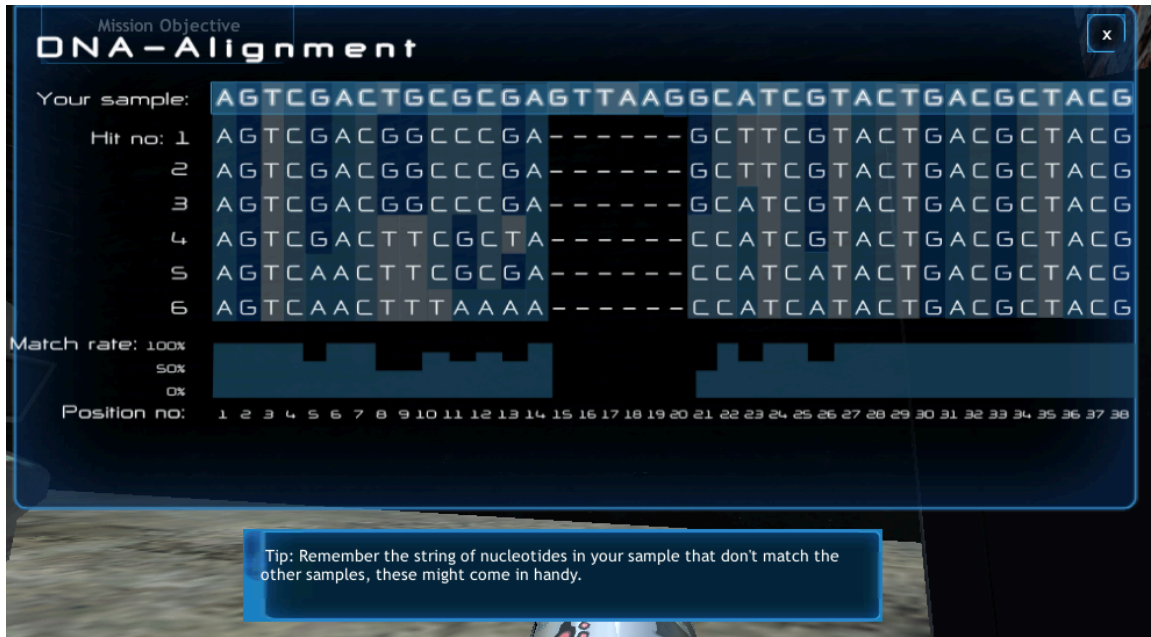


Figure 3.2: *MAX5* visualization. A simulation of a visualization tool for comparing nucleotide sequences.

3.3 PARALLEL COMPUTING CONTENT

The usefulness of parallel techniques in computational biology is increasingly reflected in the vast array of projects and environments using parallel algorithms and computing including the Venus-C infrastructure, the Scientific gateway Based User Support (SCI-BUS), and NSF's XSEDE virtual system for scientists (Merelli et al., 2014). We wanted players to gain experience with software tools needed in the analysis of scientific data while fostering an understanding of the challenges of organizing parallel architectures. Having players engage in a series of game actions focused on learning concepts and tools that were computer science related provided an opportunity to simulate the types of decisions and exchanges that might take place in a collaborative cyberinfrastructure project.

While concurrency is not often taught as an introductory computer science concept, it is valuable as a programming paradigm and offers exposure to real-life computerized systems that do not necessarily behave in a mechanistic or deterministic manner. We felt it important to

include parallel computing concepts within the game as they become increasingly important when working with large scientific data sets and in cyberinfrastructure collaborations. The computer science mini-games within *MAX5* are focused on learning concepts regarding high performance computing. Players make key decisions regarding computing processes and resource-sharing strategies including the efficient use of cycles, and multi-threaded access to shared resources. Kolikant (2004) identifies two primary types of synchronization issues that arise in parallel computing: the critical section problem, in which two or more instructions (threads) attempt to access the same resource and execute concurrently, and the prioritization or order-of execution problem, in which one set of instructions should not execute before another. The mini-game is focused on the critical section problem (Figure 3.3).

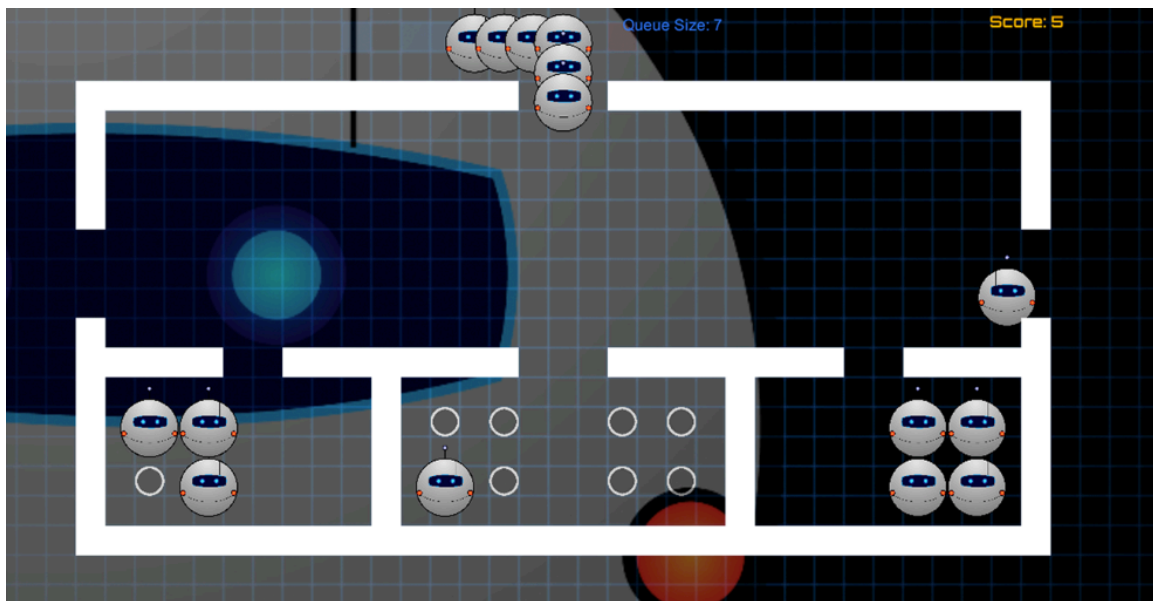


Figure 3.3: A *MAX5* parallel computing mini-game with threads entering a critical section to access a shared resource.

3.4 GAME ENVIRONMENT DESCRIPTION

MAX5 transports players into a fictional world of the future where they face a growing influenza pandemic similar in severity to the 1918 influenza outbreak. Players are provided missions to

explore the game world as members of the Advanced Future Research Lab. One of the primary mechanics in the game is shooting a sphere from a DNA collection tool that traps animal air vapors in a process similar to rapidly collecting DNA from exhaled breath condensate (Figure 3.4 bottom). Efforts were made in the design of the game to make the environment look and feel as immersive as possible and to connect actions to the narrative (Figure 3.4 top).

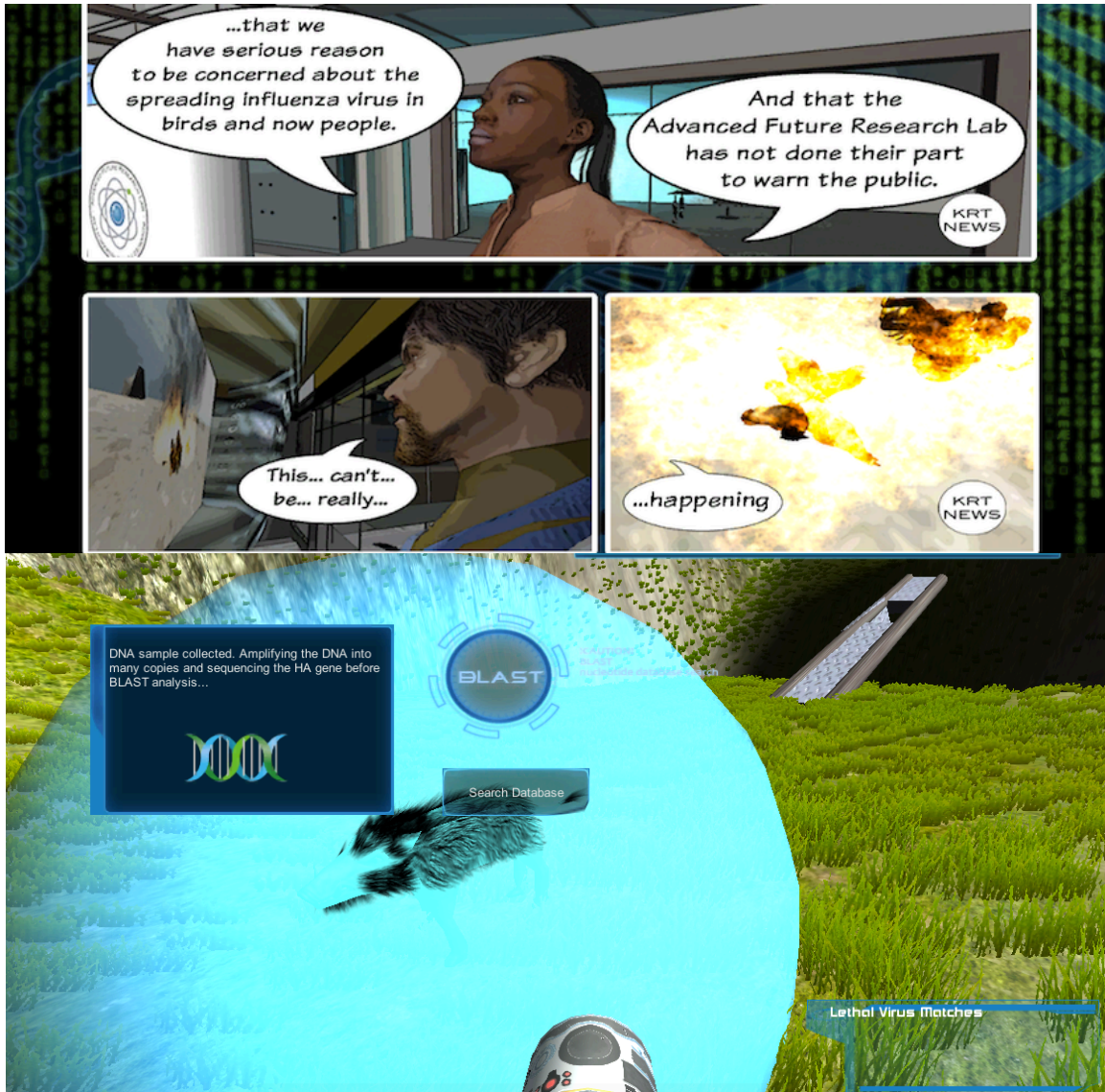


Figure 3.4: Exploring the *MAX5* game world to stop the deadly flu pandemic as introduced in the narrative (top); a player finds and collects a DNA sample from an animal (bottom).

The game is organized into a series of tasks where players are challenged to identify the source of the lethal outbreak by collecting DNA samples, recovering in-game clues, and accessing data resources. Players access levels from a central lab facility (Figure 3.5) and work in teamed pairs, where team members can communicate via a chat interface.

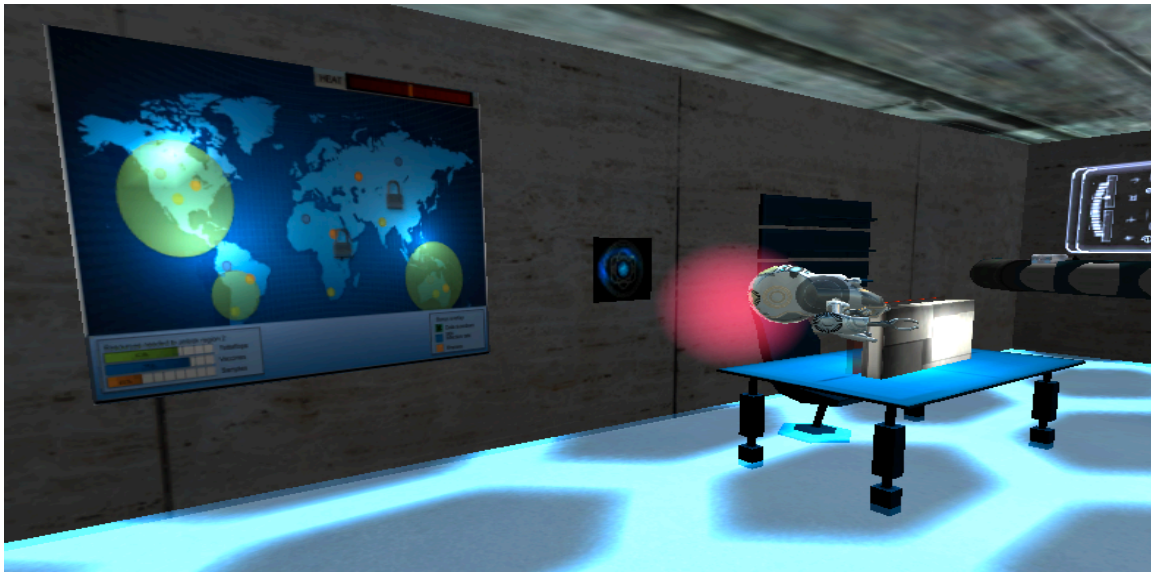


Figure 3.5: The central lab in *MAX5*. The lab serves as an area to access a tutorial and levels.

CHAPTER 4. METHODS

Games make for complex learning environments that benefit from mixed assessments and evaluations including lab studies along with more qualitative work (Foster & Mishra, 2009). To this end, I have used varied research techniques to collect empirical data on the game design process and player experiences including ethnographic observations, co-design sessions, surveys, interviews, observations of gameplay, analyses of in-game data logs, and analyses of chat logs. This chapter provides a description of the various mixed methods approaches used to collect data.

These methods comprise a human centered game design methodology for the design of science games. Human centered (or user centered) design approaches are not new to the game development process. Pagulayan et al. (2003) note the importance of user centered design practices in game development by using various user centered techniques, including usability testing, initial experience playtesting, surveys, and what they call deep gameplay, in which they bring in a group of users repeatedly over the game development life cycle to playtest prototypes and provide qualitative feedback. Human centered design methods have gained greater traction in the development of software resources and tools for science in a variety of domains including astrophysics (e.g., Poon et al., 2008) and gravitational physics (e.g., Prestopnik, 2013). Given the value of human centered design approaches in both games and in the development of scientific tools, it is appropriate that such methods be used for science learning games.

In this research, human centered design practices are utilized in the design and development of the bioinformatics game *MAX5*. This chapter discusses the various methods and data collected in the design and evaluation process. These methods not only provide a model for

game designers, but also have broader implications for the design of a range of educational science media and tools.

4.1 METHODOLOGICAL PLURALISM

The consolidation of various methods coupled with an openness to multiple perspectives may more broadly be grouped under the term *methodological pluralism*, an approach that has gained a growing following in the HCI and informatics communities. In Kaplan's (2001) landmark evaluation of clinical decision support systems, she argues for an expanded use of methodologies and theories for understanding information systems, noting that experimental and clinical trials do not adequately account for the contextual, organizational, and personal influences in understanding information system usage. She further advocates for the use of "theoretically grounded, empirically based approaches" that draw on both qualitative and quantitative methods. The approach of combining qualitative and quantitative methods has also been called a *mixed methods* approach (Johnson & Onwuegbuzie, 2004), or when referring more broadly to the combination of several theoretical and analytic perspectives, a *multiperspectivist* approach (Kellner, 1999).

In bringing together a multiplicity of methods and theoretical perspectives, scholars have pointed to the problematic value systems and power structures that have historically promoted the use of positivist and quantitative methodologies as more objective and scientific than qualitative and theoretical approaches (Orlikowski & Baroudi, 1991). This debate around methodological approaches and the associated value systems is not unique to the HCI and informatics communities and has received attention in varied fields including sociology (e.g., Kellner, 1999), psychology (e.g., Mertens, 1998), and education (e.g., Johnson & Christensen, 2008). Within complex systems research, as relevant to the model presented in Chapter 9, Arrow,

McGrath, and Berdahl (2000) note that quantitative measurements at best provide a snapshot of the system, and that qualitative models are needed to understand and evaluate the dynamical workings and patterns of group systems. They offer several methods for researchers including verbal theory (into which they place their own theoretical work), empirical methods as reflected in case studies, and qualitative work and computational modeling that uses data to predict changes in the system.

The order in which qualitative and quantitative research is conducted and presented is not agnostic to cultural value systems. In many mixed methods research studies it is not unusual to find that the quantitative data is collected and presented first, while the qualitative data is used to contextualize or further validate these findings. In *Game Analytics: Maximizing the Value of Player Data*, Hazan (2013) states, in a chapter on contextualizing data, that quantitative data can “provide a wealth of irrefutable measures” but when “numbers by themselves are not enough, open-ended questions ... can help us gauge how the player is feeling about the experience.” This declaration suggests that qualitative data is primarily helpful for informing quantitative data analysis and not the other way around. In my own research, I have worked to be sensitive to the presentation of mixed methods findings while, at times, wondering whether I have gone far enough in promoting a balanced value system in how I describe both qualitative and quantitative results.

In this dissertation, I draw on critical and reflective research practices (Shacklock & Smyth, 2002), putting my research in context with my own narrative as a software designer and researcher. Critical scholarship can be used to not only inform how data is talked about, but also to align the researcher with a bricoleur who brings together numerous interpretive practices (Denzin, 1994; Denzin & Lincoln, 2011). While the concept of bricolage in research has more

often been applied to various types of qualitative research (Kincheloe, 2001), I will argue that it also has relevance to the presentation of mixed methods results in a way that does not favor one particular type of research over another, producing a more robust and nuanced research story.

A blended research approach is not always a comfortable space for a researcher. As Denzin (2009) grandly suggests, “there is nothing simple about conducting research at the interdisciplinary frontier.” Within my own research practices, I could have opted for a more distant and objective tone, leaving my own voice and experiences muted. I decided against this approach since it would brush aside and neaten what I think are some of the more compelling questions and findings that have arisen as part of the research and design process. It is my hope that this work is helpful to those scholars interested in the use of blended methods and theoretical approaches in games research.

4.2 CO-DESIGN

Many games are designed utilizing user-centered processes (e.g., Ebner & Holzinger, 2007; Pagulayan et al., 2003), yet few educational games are co-designed directly with youth. My interest in having a diverse number of students engage directly as co-designers of *MAX5* draws heavily on theoretical concepts of constructivist learning in which students actively construct knowledge as opposed to simply absorbing it (see section 2.1 for a further discussion). Co-design has been successfully utilized in the design process of educational software using brainstorming, iterative prototyping, and evaluation sessions over an ongoing period (e.g., Penuel et al., 2007; Spikol et al., 2009). I feel that many of the unique aspects of the game originated from the co-design process with high school students.

Data collected included qualitative observations and field notes from a year-and-a-half long co-design process with high school students. In this research I have used pseudonyms and

identifying details have been altered to protect the confidentiality of participants. Seven high school students ages 15-18 (4 female, 3 male) from public schools in the Pacific Northwest United States participated as co-designers of the game in 2012 and 2013. Students came from a diverse range of socio-economic and ethnic backgrounds and from five different Seattle area public schools. Co-design sessions lasted 90 minutes and students participated in ten or more sessions held at a university design lab. High school students met with a team of four to five graduate students and researchers to generate game ideas and mechanics, design levels using Unity3D, and to generate narrative aspects of the game.

We worked to maintain an informal design setting in meetings to position the high school students on equal footing with university students and faculty. Researchers and graduate students went by their first names, dressed casually, and were encouraged to phrase design processes inclusively in terms that reflected a combined effort. By creating a more equal design environment, we hoped to allow the high school students to feel a greater willingness to share their ideas and make mistakes as part of the creative process.

In the co-design sessions, high school students were informed of the core learning goals regarding bioinformatics and computer science concepts and were asked to brainstorm engaging game mechanics and interfaces through the use of white board sketches, note cards, and written work sheets (Figure 4.1). The youth also worked together with researchers to create scene environments and contribute programming scripts using the Unity3D software tool. Iterative prototypes were assessed and evaluated by co-designers and researchers throughout the design lifecycle, reflecting a process similar to that used for the co-design of educational software (e.g., Penuel et al., 2007).

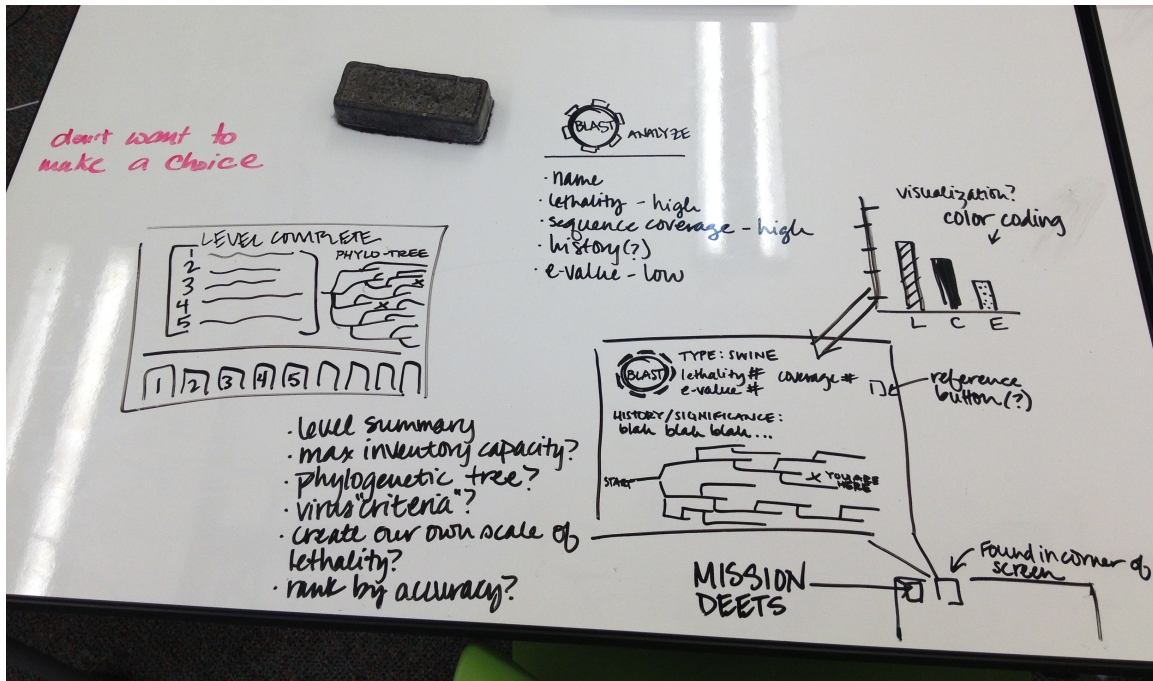


Figure 4.1: A co-designed game information sketch. A youth co-designer draws possible ways to view information about influenza in the game *MAX5*, with a phylogenetic tree and BLAST metadata.

In the design of an educational game where the intended players are also designers, it is likely that many of these co-designers will not have previous knowledge of the game’s educational content, which presents a challenge in getting everyone up to speed. In the design of *MAX5*, learning concepts integrated bioinformatics concepts and computing concepts as discussed in Chapter 3. The high school students we worked with initially knew relatively little about learning concepts in these areas. In each design session, all of the students were provided with a laptop with design software pre-installed. We started sessions by sitting around a shared table and using a projection screen to display the various learning concepts relevant for that day’s design session. We worked to present the learning concepts as part of a dialogue and discussion about the game, rather than presenting ourselves as experts in the field who were teaching them as students. After the high school students had spent time with the learning

concepts they designed information displays, levels, game mechanics, and specific in-game tools around the relevant content. These exercises not only provided useful designs for the game, but also insights into whether and how youth successfully understood the learning concepts.

4.3 INTERVIEWS

Semi-structured interviews were conducted at distinct stages in the game's development. Thirty interviews were conducted in total, split between the game's early stages and the evaluation phase. Students interviewed were ages 14 – 19. All of the interviews were with Seattle area public high school students and were conducted after the students had participated in playing a version of the *MAX5* game. Semi-structured interview questions covered topics related to enjoyment of gameplay, areas of the game that produced excitement or frustration, design idea improvements, questions related to the player's capabilities in accomplishing in-game goals, as well as questions regarding the frequency and type of collaboration with peers in a game.

4.4 CLASSROOM STUDIES

Two phases of gameplay sessions were conducted with public high school students in the Seattle area. In the pilot study, forty-eight high school youth playtested the game for a class period. Students in these pilot study sessions played a beta version of the game and provided written feedback via a survey regarding the aspects they found enjoyable and aspects of the game they would change.

In the second phase, data was collected from one hundred and twenty students in classroom settings. Pre- and post- surveys included learning assessment questions (in the Learning Evaluation chapter) as well as the Positive and Negative Affect Schedule (PANAS), a 20-question mood survey (Watson, Clark, & Tellegen, 1988). While a classroom setting does not

provide the same level of control as a lab environment, we found that taking on this challenge was helpful in discovering how learning games might be used in practice within an actual STEM learning environment. Players were also asked a series of survey questions about gameplay preferences, whether they played socially with others, and the types of game genres they had experience in playing. The analysis of survey questions and chat logs resulting from these classroom studies are discussed in further detail in Chapters 6 and 7.

4.5 IN-GAME DATA

The *MAX5* game was instrumented to record player locations and tasks including the number of times the Basic Local Alignment Search Tool was used (for correct or incorrect outcomes) and STEM learning modules reached throughout the game. Python scripts helped process the data into a more usable form. Player locations and tasks throughout gameplay were imported into the Unity3D Editor and an extension rendered character movements and actions over a map of the level for analysis.

CHAPTER 5. UNDERSTANDING & EVALUATING LEARNING

One of the challenges of any discussion of game-based learning is a clear understanding of what is meant by ‘learning’ in the context of games. Games by their very nature are “learning machines” (Gee, 2010), and scholars have noted that even games focused on seemingly trivial tasks, such as flying a virtual helicopter, are in fact embedded with interactive learning mechanisms, quick decision-making skills, and collaborative areas of problem solving that help players understand complex systems (Prensky, 2003). Evaluations of game-based learning, however, are often focused on explicit concepts learned through pre- and post- tests and assessments external to the game (for a review of relevant evaluation studies see Connolly, Stansfield, & Hainey, 2009). While some scholars have argued for the integration of additional techniques that go beyond survey questions in assessing learning in games (e.g., Chen & Michael, 2005), this has not been the norm.

Some of the studies in this research (Chapters 6 and 7) evaluate learning in the more classical sense, using written responses to questions regarding STEM concepts learned. In later chapters (Chapter 8 and 9), a qualitative analysis takes a broader sweep of information processing experiences within games. Learning in this research, then, generally falls into two categories:

- Quantitative analysis of written pre- and post- responses
- Qualitative analysis of information processing and affect as observed in gameplay and design sessions, and reported in interviews

The use of these two approaches has been intentional. The quantitative evaluation provides due diligence to those interested in identifying explicit STEM concepts learned and applied within a written setting most similar to the traditional classroom approach (learning as

described in definition 1 of section 1.2). As the research questions evolved to gain a more complete picture of the game-based learning experience, so too did the nature of the analysis. The understanding of learning in the later chapters (Chapters 8 and 9) draws more heavily on models of embedded and situated cognition that understand learning as information processing that is inextricably linked with the environmental context (definition 2 of section 1.2). Situating learning as an adaptive process (e.g., Lachman, 1997; De Houwe, 2013) is of particular usefulness for the complex systems approach to game-based learning taken in Chapter 9.

In all of these understandings of learning, affect is integral to the learning experience. Affect is not only inherent in the experience of games (Lazzaro, 2004), but also valuable to informal science learning environments (Feder et al., 2009). Therefore, learning does not occur within a vacuum but, rather, the appeal and relevance of learned content is deeply rooted within the feelings and emotions that the player encounters during gameplay.

5.1 WRITTEN EVALUATIONS

Within the playtesting sessions analyzed in Chapters 6 and 7, players were provided with open-ended learning questions with concepts introduced in the game *MAX5*. Question 1 addressed the players' understanding of the Basic Local Alignment Search Tool (BLAST), question 2 asked about necessary steps for processing the DNA before performing a BLAST search, question 3 asked players' to describe parallel computing processes, question 4 provided a visual representation of Jalview asking players to describe the usefulness of the visualization, and question 5 provided a visual representation of tasks attempting to access a shared resource and asked for important considerations for this process. The same questions were provided in both pre- and post- game surveys. The questions allowed for open-ended responses by the participants. The use of open-ended and less structured questions can be highly valuable in

evaluating a deeper understanding of science learning and reasoning (Lederman et al., 2002).

On the written responses, two independent coders scored each student’s response for full, half, or no credit to produce a combined learning assessment score out of 100 points (1.0 in Table 5.1), and the inter-rater reliability scores for player scores was determined to be acceptable for both the pre- (.705) and post- assessment (.816) using an interclass correlation since data is scalar. The results from both coders were then averaged for the statistical analysis, a technique that has proved useful for the analysis of scalar data from multiple coders in previous research (e.g., Armstrong, 1981).

The median scores for the pre- and post- tests have been provided in Table 5.1 below with the standard deviation reflecting the large spread of scores. Data was non-normal, and a Wilcoxon signed-rank test was performed for the difference between pre- and post- responses (N = 120). A significant difference was found for the post-test as compared to the pre-test evaluation, $z = -4.444, p < .001$.

	Pre-Test	Post-Test
Mean Learning Score (out of 1.0)	.0904 (M)	.1375 (M)
Standard Deviation	.0986 (SD)	.1389(SD)

Table 5.1. Means for learning evaluation questions (N = 120 players) for the game *MAX5*.

The written assessment scores reflect that learning, as evaluated by an improvement in pre- and post- tests, did occur. However, this type of assessment did not adequately describe the game-based learning found in the full breadth of empirical data. In interviews, students were asked to talk through how they understood game mechanics and tools used in the game in order that we might gain additional data to assess the types of mental models they had formed. Previous research has shown the use of interviews to be helpful for understanding science

learning models (e.g., Lederman et al., 2002; Oliver & Hannafin, 2001). There were numerous examples of youth who were able to talk through STEM concepts in the game when asked in interviews that had not provided a response in the written assessment. One such participant, Jeremy, was quite successful at achieving goals in the game itself, completing four out of five levels, yet, actually decreased in his learning score between the pre- and post- written assessments which was a notably perplexing occurrence. However, verbal responses in his interview suggested he likely had a highly adept set of game-based learning capabilities that were not accounted for in his written responses. When we asked him to describe parallel computing, a question on the written assessment he had left blank, he was able to provide a fuller description using game objects, yet this did not translate into his performance on the post-game written assessment. Occurrences like this suggested that the measurement tool does in fact matter, as youth live in a digital age where the style of communication is “multimodal” in nature including not just text and spoken language, but different types of media, images, music, and gestures (Kress & Van Leeuwen, 2001). Games as a medium are unique in providing the affordances for all of these different modes of communication, and yet evaluations have often not kept pace in accounting for these aspects. The qualitative analysis discussed in Chapters 8 and 9 provides what I believe is a much broader understanding of players’ learning experiences.

5.2 CLASSROOM GAMES IN CONTEXT

The place and context in which learning occurs is important when accounting for an ecological framework of informal science learning (Feder et al., 2009). A reflection on the classroom environment as a learning context is therefore critical to a more holistic understanding of game learning processes. In several of the classrooms that participated in the study, the game served as a supplement to existing lesson plans. We recognize that such a partnership where the game

aligns directly with curriculum is rare, and in our discussions with additional teachers, most were more responsive to having the game serve as an end of the year addition to their curriculum after standardized testing, in what one teacher described as an educational “dead period.”

Generally students felt that integrating *MAX5* into classroom activities was a good idea. However, in interviews with students, we received some surprising critiques of previous games brought into the classroom. One girl noted that implementing games in a classroom could be “a good, novel idea, since sometimes class is boring, and sometimes video games are fun”, but that “educational games frequently turn out kind of lame.” Another girl was put off by the last time she had a game in the classroom, a polynomial game, which she described was a “very nerdy game, with polynomials floating around as you connect them.” These comments suggest that if games are to provide a level of engagement over the standard lesson plans and lectures, game designers must place special attention into making games that utilize the same immersive environments and interactions students expect from commercial games. Prensky (2001) readily acknowledges this challenge, noting that most learning games are often “boring” and fail to reach the same level of engagement and “experience-centered ‘fun’” as commercial games. In the design of the game *MAX5*, we were interested in pushing the boundaries of the immersive game elements, putting attention into the graphics and the fullness of the game world, in the hopes of making gameplay more akin to the types of commercial games youth were used to playing.

5.3 DEVICE CONSIDERATIONS

Another important aspect of consideration for designers is the device on which gameplay occurs. One of the bottlenecks we faced in integrating the game into the classroom experience was the limitation of available technologies. One of the biology classrooms we worked with had 16

computers, which were not enough for the approximately thirty students in the classes to play the game simultaneously. Additionally, the computers in the classrooms were often at least five years older than the models available in the school's computer lab, and there was significant lag experienced when playing the game on them. These challenges made it necessary for the teacher to reserve the computer lab several weeks in advance of our study. The device resource limitations we faced highlight the importance of getting to know classroom sites well before a game's deployment, and whenever possible integrating an assessment of site context into the design process.

While *MAX5* was developed for PCs, when observing classrooms, we saw the growing potential of smart phones for a variety of learning uses. In observing students doing a lesson plan in one of our partner biology classrooms, several students were seen huddled over phones at their desks while other students were at computer stations in the classroom. Upon inquiry, the students showed that their mobile devices were being used to access the National Center for Biotechnology Information BLAST website to use the online tool. The teacher noted that it was increasingly common for students to use smart phones in the classroom when performing exercises online, since these were much faster than the computers provided in the classroom, and there were not enough computers for each student. The use of smart phones in classrooms represents a growing trend in the United States, and has been shown to be a positive learning tool (e.g., Williams & Pence, 2011). While PCs are still the more ubiquitous platform in classrooms, I anticipate an increase in development for mobile platforms and personal devices marking a transformation for the use of learning games and interactive technologies in classrooms.

Immersive aspects of the game were also limited by the use of available technologies in the classroom. Several students in their survey listed the use of sound as an engaging attribute of

the *MAX5* game, and educational game researchers have suggested that atmospheric sounds increase the immersive aspects of the game experience (Brown & Cairns, 2004). Yet, the use of sound produced particular challenges within the high school classroom study. We brought headphones into the computer lab for students, however, some students preferred using their own headphones or took them off due to discomfort. Educational game designers are encouraged to explore the feasibility of sounds in educational games and how these might enhance collaboration and learning or detract from the experience if absent. Much further research is needed on how tools used for gameplay affect learning and engagement in classrooms.

5.4 CONCLUSION

While digital educational games have more frequently used pre- and post- tests and other external instruments to evaluate learning (Connolly et al., 2009), there has been a broader call for a more experiential and less drill-and-retention driven focus on informal learning environments in STEM that account for both affect and context (Feder et al., 2009). This chapter discusses the evolving understanding of learning that occurred in evaluations of the digital game *MAX5*, providing a basis for methods of both written evaluation as well for the qualitative data analysis that occurs in later chapters (8 and 9). Findings discussed in this chapter show a significant post-test difference for the written evaluation showing that improvements in STEM conceptual understanding did take place after playing *MAX5* in classrooms. This evaluation does not tell the complete story, however, and factors such as previous gameplay experience and collaborative sharing are addressed in future chapters to provide further context to the wide dispersion of scores. The shortcomings of written evaluations, as well as the role of affect and the classroom and device context are also discussed, providing a basis for a more integrated contextualized view of the STEM learning experience.

CHAPTER 6. THE ROLE OF GENRE

During a game workshop one afternoon, a high school student looked up at the computer monitor that contained an early version of *MAX5*. She seemed hesitant, “Oh, I don’t play *those* sorts of games,” she said. I asked what she meant, to which she added, “first-person shooters.” I explained that it was not really a first-person shooter in the standard sense, it was a game about science, and the tools were used to collect DNA and stop a deadly virus outbreak. She nodded, saying that she preferred dance games like DDR, referring to *Dance Dance Revolution*, a dance-step arcade game that has gained a resurgence of popularity on the Kinect. I thought a moment and then was silent, drawing a blank on how best to accommodate her experience, thinking, “well, this is definitely not DDR.” This was one of many similar moments that stirred my interest in how players’ previous experience in game genres might impact their performance and engagement with an educational science game. Spence and Feng (2010) have posited that diverse mechanics in genres do in fact impact how games support learning, yet questions remain regarding what these effects are and how they should be measured.

The categorization of video games by genre has become a commonly used industry standard. In Arsenault’s (2009) analysis of genres across numerous game sites, several common categories emerge, including: action, adventure, driving/ racing, fighting, puzzle, simulation, role-playing, sports, strategy, and shooter. Shooter has largely evolved into the dominance of the first-person shooter (Arsenault, 2009). While some have argued that genres do not adequately account for the interactive differences found in gameplay (Apperley, 2006), many aspects of gameplay do vary based upon genre, as some genres require longer term strategy and problem-solving skills, while others might rely more heavily on players’ quick reflexes and visuo-motor coordination (Spence & Feng, 2010). Foster and Mishra (2009) point to the importance of genre

and the fallacy of treating all games as a single entity, further suggesting that different genres provide different pedagogical affordances.

Much existing research takes an approach that favors the majority of players when selecting a genre for educational games. Amory et al's (1998) research represents some of the earlier work connecting digital game genre to game-based learning. In their research they find that adventure and strategy games outperform "shoot-em-up" and simulation games in self-reported measures of enjoyment, leading to their suggestion that 3D-adventure games provide the strongest foundation for the development and integration of teaching resources. Torrente et al. (2010) offer e-Adventure as an automated platform in which users can integrate learning content into a point-and-click adventure game, suggesting that this genre is optimal for learning games due to the value on problem-solving skills and its relatively low development cost. Yet U.S. youth have varied types of gameplay experiences with 72% playing puzzle games, 66% playing adventure games, 49% playing simulation games, and so on down the list (Lenhart, et al., 2008), begging the question: should the designers of educational games simply ignore the percentage of players without experience in a particular genre?

Literature on learning games has suggested that genre likely does have an important effect on learning outcomes. In a review of the outcomes of educational games and simulations, Egenfeldt-Nielsen (2005) suggests that the mixed outcomes of educational games should not be taken as evidence of the overall inefficacy of educational games, but that some outcomes may be due to the differences in the genres studied for the learning games. There has also been research theorizing on ways of appropriately matching learning content to genre, yet this is quite different than matching the player experience to the appropriate genre for learning. Van Eck (2007) suggests that point-and-click adventure games offer opportunities for reflection and problem

solving, making the genre a strong pedagogical fit for a broad number of educational games. Prensky (2001) takes a more measured approach, noting that, while educational game designers may encounter immediate matches between genre and particular learning content, they should engage in a more thorough search process choosing from a diverse number of types of games, speaking with gamers, and playing a variety of games to find the best match for particular learning content.

The tension between what students want to play and what teachers or educators may want them to play is a notable one. In Egenfeldt-Nielsen's (2005) study on the school use of games in Denmark, for example, research showed that teachers preferred the use of strategy and simulation games for learning, while many students preferred action games. Similarly, classroom studies using the history game *Europa Universalis II* observed that players with previous strategy game experience learned the game faster, finding about one-fourth of the class fell into this group, and that this group was predominantly male (Egenfeldt-Nielsen, 2005). I would argue strongly that there is a need to account for the experience of a broader number of youth in gameplay. This work marks the first analysis that I am aware of to examine how previous experience with genre can be a predictor of learning and emotional outcomes in STEM gameplay.

6.1 OVERVIEW & METHODS

This chapter examines the role of genre, seeking to answer the question: *Does previous gameplay experience affect learning outcomes for digital science games?* It draws on data collected in observations and surveys of in-classroom gameplay of *MAX5* by youth ages 14-19 in

a classroom evaluation (N = 112).¹ Data also includes semi-structured interviews with students (N = 30), who were asked about their previous gameplay experiences (see previous section 4.3 for a fuller description of questions asked). Empirical results have been placed in dialogue with relevant cognitive and theoretical perspectives.

6.2 GENRES PLAYED

In the evaluation studies we conducted with youth (ages 14 – 19) in the Seattle area, we asked players to identify the primary genres they played (Figure 6.1).

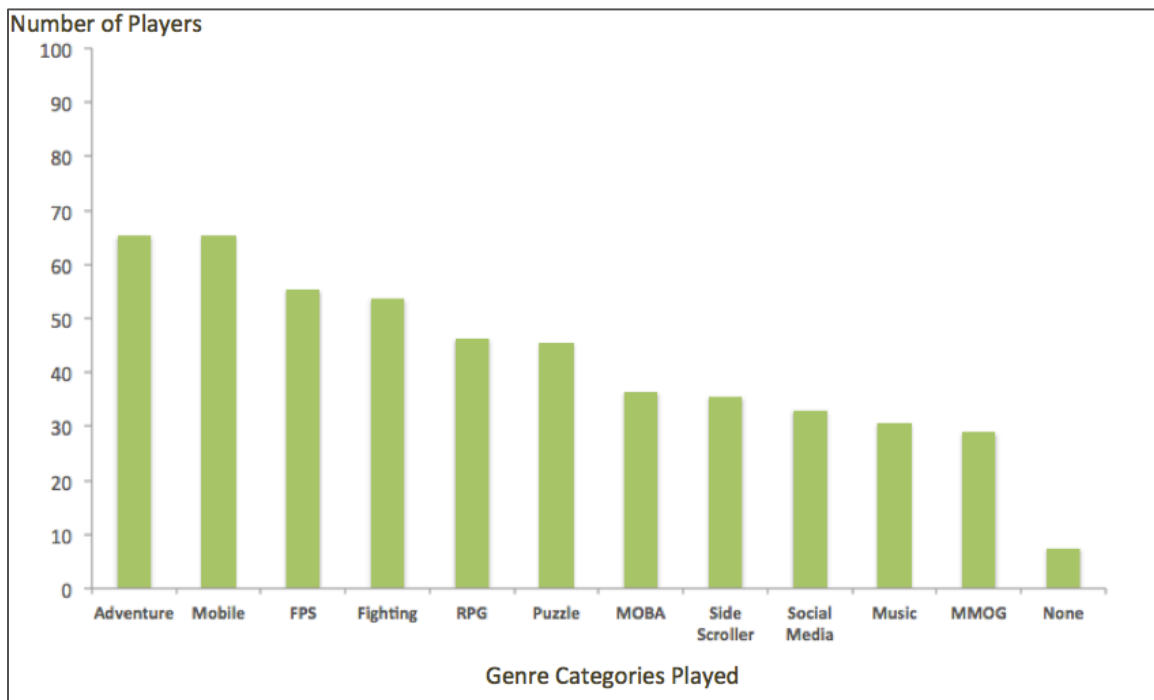


Figure 6.1: Self-reported primary genre(s) of play by participants. More than one genre category could be selected. Note: FPS = first-person shooter; MOBA = multiplayer online battle arena; MMOG = massively multiplayer online game.

Looking at the breakdown of genres at the individual level for a single classroom (Figure 6.2), the diversity becomes apparent, as some of the youth in the class are more high volume

¹ While the study collected data on 120 participants, eight participants with incomplete data needed for the analyses in this chapter were removed (N = 112).

gamers, with experience across most of the genres, while others tended to gravitate towards a few specific types of games. This finding matched research done by Greenberg et al. (2010).

Player ID:	Fighting	Adventure	Sidescrollers	Puzzle	RPGs	MMOs	Music	MOBAs	Other	Total number of categories played:
1	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes	8
3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		8
28	Yes	Yes	Yes	Yes	Yes	Yes		Yes		7
4	Yes	Yes	Yes	Yes	Yes		Yes			6
6	Yes	Yes	Yes	Yes	Yes		Yes			6
16		Yes	Yes	Yes	Yes	Yes			Yes	6
25	Yes	Yes	Yes	Yes	Yes			Yes		6
26	Yes	Yes	Yes		Yes	Yes		Yes		6
8		Yes	Yes	Yes	Yes				Yes	5
11	Yes	Yes	Yes	Yes	Yes					5
13	Yes	Yes	Yes	Yes	Yes					5
17	Yes	Yes	Yes	Yes			Yes			5
2	Yes					Yes	Yes	Yes		4
7		Yes	Yes	Yes			Yes			4
9		Yes	Yes	Yes			Yes			4
18	Yes	Yes	Yes							3
10					Yes	Yes		Yes		3
19	Yes					Yes				2
22	Yes									1
24				Yes						1
5	Yes									1
21										0
15										0
# of people per category	15	15	15	14	12	8	7	6	3	

Figure 6.2: Distribution of primary genres of players in one classroom.

Since *MAX5* was designed with the majority of play mechanics having first-person shooter and adventure game attributes, we hypothesized that players that had primary experience in both adventure and first-person shooter games would be associated with higher learning scores and greater positive affect. The results of this analysis are described in the following section.

6.3 ANALYSIS OF GENRE, LEARNING, & AFFECT

A multiple regression was run to predict the change in learning scores from players' experience with first-person shooter (FPS) and adventure games when controlling for the number of game levels players' completed. These variables significantly predicted the change in learning, $F(3, 108) = 3.676, p = .014, \text{adj. } R^2 = .067$. FPS genre experience adds significantly to the prediction,

$p < .05$. The addition of players' levels completed in the game as a control variable elevated the collinearity diagnostics slightly, with the highest VIF at 1.08 and the lowest tolerance at .925; these are well within the acceptable range for a low degree of multicollinearity (Keith, 2006), and aligns with previous standards used in video game research (e.g., Ferguson & Garza, 2011). The regression equation coefficients and standard errors are contained in Table 6.1 below.

Variables	B	SE	β	<i>p-value</i>
(Constant)	.014	.022		.540
FPS	.046	.022	.199	.039
Adventure	-.034	.023	-.140	.144
Levels Completed	.019	.009	.203	.034

Table 6.1: Multiple regression analysis for genre experience (FPS and Adventure genres) as a predictor of the change in learning when controlling for levels completed (N = 112). Note: B = unstandardized regression coefficient; SE = Standard error of B; β = standardized coefficient.

A multiple regression was run to predict the change in positive PANAS scores from players' experience with first-person shooter and adventure games. While the model was not significant ($p = .064$), the coefficient for adventure game experience was significant as shown in Table 6.2 below.

Variables	B	SE	β	<i>p-value</i>
(Constant)	-1.079	1.314		.413
FPS	.534	1.429	.036	.709
Adventure	-3.557	1.500	-.227	.019

Table 6.2: Multiple regression analysis for genre experience (FPS and Adventure genres) as a predictor of the change in players' positive PANAS score (N = 112).

A multiple regression was run to predict the change in players' negative PANAS scores from players' experience with first-person shooter and adventure games. These variables significantly predicted the change in negative PANAS, $F(2, 109) = 5.591, p = .005, \text{adj. } R^2 = .076$. FPS genre experience was the only variable to add significantly to the prediction, $p = .010$. The regression equation coefficients and standard errors are contained in Table 6.3 below.

Variables	B	SE	β	<i>p-value</i>
(Constant)	5.819	.943		.000
FPS	-2.674	1.026	-.244	.010
Adventure	-1.553	1.077	-.135	.152

Table 6.3: Multiple regression analysis for genre experience (FPS and Adventure genres) as a predictor of the change in players' negative PANAS score (N = 112).

The above analyses shows previous players' experience in particular genres that match the educational game can be a significant predictor of change in learning and the change in affect after gameplay. Given these initial results, much further research is needed with attention to how additional variables might contribute to a more robust prediction of changes in learning and affect pre- and post- gameplay. In the discussion below, I examine the elements of gameplay that could contribute to these differences in genre experience.

6.4 DISCUSSION OF DIFFERENCES IN PLAY

In interviews with youth, several compelling aspects of gameplay emerged in relation to genre, including differences relative to bodily reflexes and an understanding of the designed symbolic aspects of gameplay. Several players with first-person shooter experience noted that while *MAX5* had similar features with other first-person games, the bodily movement and actions were slower than they expected. One youth suggested that the reaction time of the buttons felt different, "I

used to play FPS first person shooter games. It was too slow for me. When I press ‘D’ or ‘A’, the turning was too slow.” There was a consciousness of how the embodied aspects of gameplay *should* feel based on experience with similar games. These responses differed from several players who were not used to first-person gameplay who reflected on their performance and not their expectations of gameplay. One player who was not a FPS player noted, “it took me a while to learn how to aim, I’m not very good at aiming.” This statement and others like it suggest that that embodied action is an important learned aspect of gameplay.

Players also discussed their understanding of the rules and symbolic structures of particular genres. One youth pointed to the differences between gameplay of sports genres and first-person shooters saying, “I’m kind of sports-minded. Sports are kind of my thing. I know what to do. I know what’s going on, I know how to control it.” Yet this same youth reflected that when it came to first-person games like *Halo*, he did not understand what to do or how to interact. Another youth noted difficulty with the sports game genre, saying, “I’m always confused. How do you throw the ball, or pass, or kick, or tackle?” Squire and Jenkins (2002) suggest games are constructed symbolic environments, noting that players “learn to ‘read’ tactical possibilities from the spaces themselves.” Similarly, Friedman (1999) describes the process of uncovering the hidden meanings in games, and Ye (2004) notes that games contain interface metaphors specific to that particular genre. Players must, therefore, uncover these symbolic structures of what to do and how to perform actions within the game world to achieve desired outcomes.

6.5 CONCLUSION

In this research, a study examines the effects of genre on learning and affect for gameplay of a bioinformatics game. We found that previous experience with first-person shooter play is a

significant predictor for a player's change in learning score and change in negative affect for the game *MAX5*. These findings suggest a positive association between FPS genre experience and learning scores, and a negative association between FPS genre and negative affect changes (keeping in mind that FPS genre, in this case, most closely matches the genre style of the educational game). Semi-structured interviews revealed differences in players' understanding of designed symbols of gameplay, and sense of physical presence and timing in games based on genre familiarity. Designers and educators are encouraged to consider ways of integrating multi-genre or adaptable games that are sensitive to players' previous experiences with similar games in an effort to create more inclusive digital learning environments.

CHAPTER 7. INTERPERSONAL GAME-BASED LEARNING

A growing number of serious games have been developed around science and computing concepts, yet far fewer are designed with an explicit understanding of the collaborative socio-emotional aspects of gameplay. Affect has been shown to be an important indicator of interest, engagement, and creativity in tasks (Fabri et al., 2004). Additionally, social technologies that support collaboration and peer connection can play an important role in fostering a positive youth identity (Bers, 2007). There is still further research needed to establish the role of collaboration and affect within the framework of learning games. The research presented in this chapter marks the first study I am aware of to determine significant relationships between the type of text-based message sharing behaviors in a STEM learning game and learning and affect outcomes. The results have implications for designing science games that facilitate engaging and effective learning experiences, as well as more broadly in the design and implementation of collaborative learning environments that account for social learners.

7.1 BACKGROUND ON SOCIAL GAMEPLAY

Literature on social gameplay falls generally into two overlapping areas: research on social interaction as a motivation for gameplay, and patterns and measures of social exchange in games. Several studies have shown socialization as an important motivation for a particular group of players. Yee (2006), in an online survey of MMORPG games, determined that socializers were a primary category of player. Players in this grouping used the game environment for creating strong social interactions and relationships. Similarly, Sherry et al. (2006) utilize a uses and gratifications theoretical approach to describe social interaction as a primary motivation in

gameplay. Nacke et al. (2011) in the BrainHex model identify player archetypes, including *socializers*, who enjoy talking to and helping others and building trust in collaborations.

Studies have also examined patterns in how players interact and create social meaning in games. Ducheneaut et al. (2006) analyze communication in World of Warcraft (WoW), noting that WoW's players utilized chat as a form of performance and for diffuse information access. In research on text chat in BZFlag, an open source capture the flag game, Herring et al. (2009) found that messaging between players occurred at seemingly regular intervals of the same length and that the majority of messages were related to reactions to gameplay. There have additionally been strategies for categorizing affect in text-based communication in games. Peña and Hancock (2006) categorize participant text messages into socio-emotional and task-based messages, finding the majority of the messages in a game with fighting were socio-emotional and, in fact, positively valenced.

7.2 OVERVIEW & RESEARCH QUESTIONS

Research has shown the benefits of collaboration and social exchange for psychological well-being and learning (Laal & Ghodsi, 2012). This section examines the role of text-based communication within the context of a STEM game. The overall research question driving this study is: *do online social message sharing behaviors affect game-based learning outcomes for digital science games?* While previous research has identified more socially driven players in games (e.g., Nacke et al., 2011; Yee, 2006), there is little known about how social players and message sharing patterns shape the game-based learning experience.

In *Research Question 1 (RQ1)* we were interested in understanding whether players' pre-affect scores were predictive of them being a chatter or non-chatter within the game *MAX5*. Previous research has found strong correlations between the Positive and Negative Affect

Schedule (PANAS), a 20-question mood survey (Watson, Clark, & Tellegen, 1988), and the NEO extraversion scale (Burger & Caldwell, 2000). We, therefore, hypothesized that players that scored more positively on the PANAS would exhibit more extraverted tendencies and would be more likely to share chat messages, leading to **RQ1: *Would players' affect scores be a predictor of their willingness to use the in-game chat tool?***

In the *Research Question 2 (RQ2)*, we accounted for previous research on text-based chat that has shown a higher number of socio-emotional than task-oriented game messages within a multi-player commercial game (e.g., Peña & Hancock, 2006). We were, therefore, interested in whether we would find a similar result within a game-based learning environment, asking in **RQ2: *Would more affect chat messages be present than task-related chat messages?***

In *Research Questions 3 and 4 (RQ3 and RQ4)* we were interested in understanding relationships between the types of messages shared and the learning and performance outcomes. Previous research on multimedia learning environments has shown improved learning results linked to positive emotion (Um, Song, & Plass, 2007), and we wanted to expand this understanding to evaluate whether the types of chat messages shared affected learning or game outcomes.

RQ3: *Could significant associations be identified between the type of messages sent using the chat tool (e.g., positive, negative, task-requesting, task-sharing messages) and learning, affect, or game performance outcomes?*

RQ4: *Were task-based or affect messages a predictor for learning scores?*

7.3 STUDY PROCEDURE

Participants were given a survey pre- and post- gameplay for the Positive and Negative Affect Schedule (PANAS), a commonly used twenty question psychological metric of affect (Watson,

Clark, & Tellegen, 1988) that has been used in previous measures of collaborative gameplay experience (e.g., Emmerich & Masuch, 2013).

Players were also given a pre- and post- survey that included five assessment questions based on learning concepts presented in the game on bioinformatics and parallel computing. These questions and their scoring have been previously described in Chapter 3. We conducted semi-structured interviews with ten of the 120 total participants after gameplay. These interviews covered topics related to enjoyment of gameplay, aspects of the game that produced excitement or frustration, ability to accomplish in-game skills, as well as questions regarding frequency and type of gameplay collaboration. Interviews were audio recorded and transcribed and lasted approximately twenty minutes.

7.4 ANALYSIS OF GAME CHAT LOGS

Changes in the both the pre- and post- positive and negative scores (for the PANAS) and in the written learning assessment results were calculated for the analysis. Two trained coders who worked independently analyzed 587 chat messages sent and received using the in-game chat tool. Sixty-two participants out of the 120 total participants used the chat tool. Cases where one person initiated a conversation but did not receive a reply message were removed. Codes were applied for valence (positive, negative, and neutral messages) as well as for messages containing task-based information pertaining to in-game goals and accomplishments. This task-based coding category has similarities with the Bales (1950) interaction process analysis (IPA) classification, which has been successfully used by games researchers (e.g., Pena & Hancock, 2006).

We found it useful in our own classification to further separate task-based information sharing into two subcategories, these were: task-based information sharing messages (e.g., “go to

this location” or “enter this code”) and messages that were requests for task-based information (e.g., “how do I perform this action?” or “help me find ...”). We further refined our classification schema for task-based information sharing to include only actionable messages that could potentially help the chatter’s teammate. This was done to exclude messages that were more generally task-based (e.g., “I just died”) that offered little hope of direct action. Measure of agreement was calculated for valence codes ($kappa = .73$), task-based message sharing codes ($kappa = .81$), and task-based message request codes ($kappa = .72$). Coded messages were only included in the analysis if there was joint agreement reached by both coders.

7.5 RESULTS

***RQ1:** Would players’ affect scores be a predictor of their willingness to use the in-game chat tool?*

A logistic regression was performed to determine the effects of the positive and negative pre- PANAS scores on the likelihood that players would participate in chat. Players who initiated a chat conversation, even if there was no response from their teammate, were included as “chatters” for the purposes of this analysis since we were interested in the likelihood of chatting. The logistic regression model was statistically significant, $X^2(2) = 17.567, p < .0005$. The model explained 18.3% (Nagelkerke R^2) of the variance and correctly classified 63.3% of the cases. Of the two predictive variables, the negative PANAS was the statistically significant one ($p = .002$) (Table 7.1). An increase in players’ negative PANAS scores was therefore associated with an increased likelihood of players using the chat tool.

	B	SE	Wald	df	<i>p-value</i>	Odds Ratio
Pre- Positive PANAS	.008	.026	.088	1	.766	1.008
Pre- Negative PANAS	.195	.062	9.899	1	.002	1.216
Constant	-2.642	.935	7.974	1	.005	.071

Table 7.1: Logistic regression predicting participation in chat based on affect (N = 120).

RQ2: *Would more affect chat messages be present than task-related chat messages?*

Since data was non-normal, a Wilcoxon signed-rank test was used for related samples to compare mean message types for chat participants. We found a statistically significant difference in means for total affect messages and total task-based messages with a higher number of affect messages than task-based, $z = -2.67$, $p = .003$. We did not find any significant difference in means when comparing the subcategories of positive and negative messages and when comparing subcategories of task-based messages shared against task-based messages requested. Descriptive statistics for affect and task-based message groupings along with their subcategories are shown in Table 7.2 below.

	Affect Messages		Task-based Messages	
Mean Number of Messages	2.68 (M)	2.46 (SD)	1.73 (M)	2.32 (SD)

	Positive	Negative	Task-based Shared	Task-based Requested
Mean Num. of Messages	1.35 (M)	1.33 (M)	.84 (M)	.89 (M)
	1.56 (SD)	1.64 (SD)	1.52 (SD)	1.27 (SD)

Table 7.2: Descriptive statistics for affect and task-based message categories.

These findings suggest that players in *MAX5*, similar to research on players in commercial games (e.g., Pena & Hancock, 2006), exhibit a greater number of affect message types than those related to in-game tasks.

RQ3: *Could significant associations be identified between the type of messages sent using the chat tool (e.g., positive, negative, task-requesting, task-sharing messages) and learning, affect, or game performance outcomes?*

To answer *RQ3* we conducted a Spearman’s rank-order correlation to assess relationships between types of messages sent and learning and affect outcomes. We found a low significant positive relationship between players’ total number of task-based messages and changes in learning as well as a low positive relationship between the number of task-based information messages shared and the change in learning (Table 7.3 below). This meant that there was a low but significant association between the task-based messages shared and an increase in players’ change in learning scores.

Message Category	Change Pos. PANAS	Change Neg. PANAS	Change in Learning	Levels Completed
All Messages	.048	.036	-.063	-.020
All Task	.114	-.039	.260*	.034
Task-based Shared	.079	.070	.285*	.033
Task-based Requested	.106	-.008	.199	.038
All Affect	.143	-.031	-.040	.021
Positive	.157	-.019	.135	.198
Negative	.096	.008	-.172	-.138

Table 7.3: Correlations between chat message categories and change in learning, change in negative and positive PANAS scores, and levels completed. * $p < .05$.

RQ4: *Were task-based or affect messages a predictor for learning scores?*

A multiple regression was run to predict the change in learning scores from message types shared in chat. These variables significantly predicted the change in learning, $F(5,56) = 3.078$, $p = .016$, $\text{adj. } R^2 = .146$. Task-based messages shared were a positive predictor of the change in learning scores, whereas negative messages shared were a negative significant predictor of the change in learning scores, $p < .05$. The addition of players' levels completed in the game as a control variable elevated the collinearity diagnostics slightly, with the highest VIF at 1.35 and the lowest tolerance at .74; these are well within the acceptable range for a low degree of multicollinearity (Keith, 2006). The regression equation coefficients and standard errors are contained in Table 7.4 below.

Variables	B	SE	β	<i>p-value</i>
Constant	.019	.029		.518
Positive Messages	-.002	.010	-.021	.871
Negative Messages	-.020	.010	-.283	.043
Task-based Shared	.027	.010	.351	.011
Task-based Requested	.015	.013	.158	.255
Levels Completed	.020	.011	.220	.079

Table 7.4: A multiple regression with message category as a predictor of change in learning controlling for level completion. Note: B = unstandardized regression coefficient; SE = Standard error of the coefficient; β = standardized coefficient.

7.6 DISCUSSION OF MESSAGE SHARING

While previous research had shown a positive correlation between a positive PANAS score and extraversion (Burger & Caldwell, 2000), we found that the negative PANAS score was a significant predictor in participation in chat. These results might initially seem to be conflicting, however, the positive and negative PANAS subscales are distinct constructs (Crawford & Henry,

2004). Therefore, how players score on the negative section of the PANAS is not necessarily an indication of how they might score on the positive. This finding suggests the need for further research into how players' moods previous to gameplay might influence the frequency and type of messages they share in an educational game.

Our findings also show that sharing task-based information is a significant positive predictor for players' change in learning score, and sharing negative messages is a significant negative predictor. It might be expected that these task-based messages were directly related to STEM concepts within the game, given that the assessment questions were about bioinformatics and computing content. In a follow-up analysis of these messages, however, we found that this was not the case and that, in fact, only 19% of the task-based messages had some direct link to STEM concepts (e.g., DNA sequences, the use of BLAST, etc.). The majority of the messages were related to tasks relevant to exploring the game environment including where to go in the game, how to overcome obstacles, and the use of controls. Previous research has noted that one of the biggest challenges in learning games is the ability for players to cognitively link game interactions to domain learning concepts (Conati & Zhao, 2004). The findings in this chapter suggest that active knowledge sharing relevant to gameplay, irrespective of whether these messages are directly related to STEM learning concepts, could still be predictive of STEM learning outcomes.

We were further interested in possible motivations players had for sharing these task-based messages in-game. One particular youth who was one of the highest frequency message sharers noted, "I think nowadays we don't really want to interact with people," and digital games offer "a goal to defeat this thing ... we're teammates, we stick together," showing the importance of coming together around common goals. She also exemplified an ability to reflect on the

thought process of other players, saying she participated in order to “see how the other person thinks” and that this “psychological effect” of interaction was important to her. These comments align with other social players in interviews who reflected on an awareness of their own social and psychological needs as well as those of the other players.

While previous research literature has shown that positive affect can be associated with learning outcomes (e.g., Ashby & Isen, 1999; Konradt, Filip, & Hoffmann, 2003), we did not find significant relationships between text-based positive affect and learning scores, but did find negative affect to be a negative significant predictor for changes in learning scores, a compelling finding. It may be that methods of binning positive and negative do not adequately account for some of the more dynamic patterns we found in the data. In the example below (Figure 7.1), a player asks for task-based information related to the game mission and a highly affective exchange follows this. While there are more negatively coded messages in this example than positive, the overall tone is quite playful and supportive in nature.

<i>Task-based</i>	user_07: I found that most of the viruses are from California, and I think I got all of the animal's DNA
<i>Task-based</i>	user_07: Im in the mountains now, trying to get to the building at the top
	user_07: what did you get
negative	user_08: Like I said, a dead chicken. I'm afraid I'm not terribly great at video games.
negative	user_07: I'm so lost
	user_08: I'm sorry for your loss.
positive	user_07: lol thanks?
positive	user_08: Anytime. Happy my snarky commentary can amuse you in these dark times.
negative	user_08: New low. Almost got killed by a bird.

Figure 7.1: Social support in a coded chat log from *MAX5*.

This exchange mirrors a process that Aragon and Williams refer to in their collaborative creativity model as the *frame* stage (Aragon & Williams, 2011), in which a sense of trust is formed and group members work “to absorb external information, data, ideas, and intellectual nourishment, and at the same time to filter out potentially harmful environment pressures.” The

establishment of trust is also found as important to the socialization process in video games (Nacke, Bateman, & Mandryk, 2011). Such a damping of negative affect with positive affect is a notable pattern that exemplifies trust-building processes in the game, an area deserving of future research.

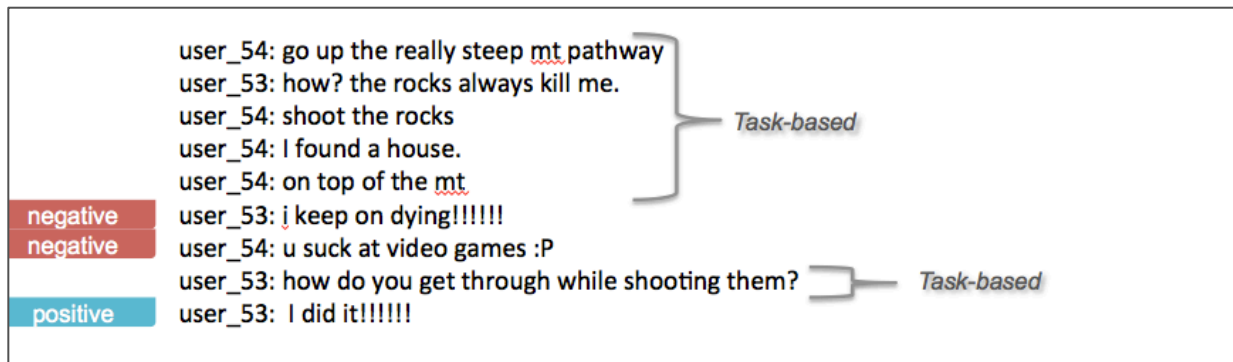


Figure 7.2: An example of *fiero* in a coded chat log from the game *MAX5*.

We also observed transformations from frustration (negative affect) to excitement and release (positive affect) in the chat logs, exemplifying what game scholar Lazzaro (2004) calls *fiero*, or the sense of personal triumph over adversity after struggling to accomplish a goal, a common emotion in games. Comments including “I did it!!!!!!” (Figure 7.2) and “I made it :D” show this sense of excitement. It is possible that future research accounting for these dynamic patterns of social support or *fiero* could be observed in the logs by looking for areas where negative affect transfers to positive after the accomplishment of a game task.

This research could be scaled to larger data sets for game-based chat logs to further show the reliability of these results and to test more granular affect categories (e.g., excitement, frustration, *fiero*, etc.). Automated coding would need to account for slang and highly contextual speech patterns, as in the manual coding process coders were trained for slang and nuanced emoticon usages by the youth, such as “swagge” (meaning “cool”) or “cx” (as a cute smiley

face). Research has suggested that the use of youth slang in multimedia environments can foster a sense of shared familiarity that influences learning (Schneider, Nebel, Pradel, & Rey, 2015). Further research is needed on how the usage of slang terminology and emoticons in games might affect learning and PANAS outcomes. If an automated approach is used, it further needs to account for slang, emoticons, and these more contextually nuanced linguistic features, similar to the classification approach taken by Brooks et al. (2013).

7.7 CONCLUSION

The overall goal of this research is to explore how players' willingness to share chat messages and the type of messages shared can impact affect and learning outcomes in an educational game. While previous research (e.g., Bartle, 1996; Nacke, Bateman, & Mandryk, 2011; Yee, 2006) has identified social players as one particular gamer category, there have not been clear ways of predicting these more social players or how their activities support in-game learning. Our findings suggest that previous mood prior to gameplay, as assessed by the negative PANAS, could be a predictor of whether players use the chat interface. We also found that task-based information sharing was a positive significant predictor for learning outcomes, and negative message sharing was a negative significant predictor for learning outcomes. In a follow-up analysis, less than twenty percent of the task-based messages were directly related to content on the STEM assessment evaluation, suggesting that actively sharing more general information about gameplay might still reflect cognitive processes relevant to learning content within a game.

8. MULTIPLE INTELLIGENCES AS AN ANALYTIC LENS FOR THEMES IN GAME-BASED LEARNING

In the evaluation of learning in the game *MAX5* in previous chapters, I have so far been rather conservative in regards to learning measures, focusing on students' ability to answer written responses on bioinformatics and computing concepts. Such measures of learning concepts external to the game environment, as well as pre- and post- tests, have been commonly used in numerous STEM game-based studies (Connolly et al., 2009). However, in the course of the iterative design and research process, I realized rather early on that my focus on measures of traditional learning felt rather myopic and that I was only scratching the surface of the true diversity of game-based learning experiences occurring.

In the research process, the threshold for defining a game-based learning experience was often a blurry one. While the successful analysis of a DNA sequence fits clearly into a classification of STEM learning, other in-game interactions, such as a player's capability to find her way through digital mountain ranges, the use of tools to escape a fire in a lab, or the discovery and sharing of hidden paths, felt less well defined as *good* in-game learning outcomes. However, it was these types of experiences that were most often reported as exciting and engaging to youth in the surveys and interviews. Similarly, these aspects of the gaming experience map particularly well to recommended areas of informal science learning including "excitement, interest, and motivation to learn about phenomena in the natural and physical world" and capabilities to "manipulate, test, explore, predict, question, observe and make sense of the natural and physical world" (Feder et al., 2009). If the "physical world" as a phrase is replaced with "the game world", this would aptly describe a much wider variety of learning experiences noted in the data. Therefore, by taking a more expanded lens towards learning

experiences in games (definition 2 in section 1.2), I hoped to uncover a model that better fits informal learning outcomes that were more experiential and process oriented.

In the following chapters, an inductive qualitative analysis process is used to investigate: *do existing theories of gameplay and learning account for what players bring to digital gameplay as evidenced in the data?* I was initially inspired by Adam's assertion that the digital age had produced a "digital intelligence" as a new human capability (2004), and I was further curious whether the large segments of time youth spent playing video games in the U.S. (Lenhart et al., 2008) had developed analogous capabilities for learning. In particular, I was also attracted to Gardner's (2006) theory of multiple intelligences (MI), as introduced in Chapter 2 section 2.7, as a theoretical lens to possibly understand the incredible range of gameplay capabilities suggested in the data.

I saw early links between aspects of MI theory and linguistic, kinesthetic, spatial, and logical capabilities of players evidenced in the data. There was also a previous body of empirical evidence linking MI and video games (e.g., Becker, 2005; Jovanovic et al., 2008; McCue, 2005). I was therefore interested in whether and how themes in the data stood up against MI and other relevant learning theories as applied to educational games. In the service of this question, I conducted an applied thematic analysis (Guest et al., 2011) to examine phenomena as observed and measured in *MAX5* as well as in interviews, in chat logs, and in field notes of observations of youth during game design and gameplay.

MI theory has received attention in previous literature for its relevance to the study of games (e.g., Becker, 2005; Gardner & Hatch, 1989) and, in particular, in its application to an understanding of player types within game-based learning (e.g., McCue, 2005; Jovanovic et al., 2008). Becker (2005) suggests that multiple intelligences are inherent in most games and that

certain games favor the use of one of the intelligences over another. Gardner himself has noted the appropriateness of using games along with other interactive materials to assess and observe strengths in intelligences (Gardner & Hatch, 1989). McCue (2005) puts forth the usefulness of MI theory for games more formally, noting that MIs are well suited to be integrated into animation and educational video games, and could provide a “dynamic neural interaction” in which gameplay is tailored to players’ optimal learning style. Similarly, Jovanovic et al. (2008) proposes the usefulness of a player profile classification that uses MI theory to account for users with diverse learning preferences.

While a neuro-biological basis for intelligences is part of Gardner’s original criteria of what qualifies as an intelligence (Davis, 2011), the research is quite clear that given the lack of appropriate psychometric tests or neuro-imaging techniques, data is better collected from direct observation using a variety of methodologies to triangulate MIs (Gardner, 2006). Gardner (2011) further cautions that the separation of the intelligences into concrete entities is misleading, and they should instead be thought of as “scientific constructs” that are useful for addressing practical problems. The following research uses MI theory as a useful scientific construct in this manner, a tool to examine whether and how emergent themes compare to existing concepts of learning and intelligence.

I have taken a constructionist tone in describing the research findings in which I acknowledge my own preconceptions (Charmaz, 2014) and how these shaped my research journey. I will begin by stating quite simply that the analytic process did not end up where I had expected it might. Qualitative research has been aptly compared to the process of a detective looking for causes and effects, who gets rid of hypotheses and explanations through a systematic examination of the data (Johnson, 1997). Similarly, in my own process, despite a rather

convincing pile of clues, I realized rather late in the analysis that the theoretical case was far from being solved. While for many months I continued to see data that aligned into rather neat categories including the exploratory learner, the social learner, the kinesthetic learner, and indeed these categories fit well into existing models of player typologies (e.g., Bartle, 1996; Yee, 2006) and player types (e.g., Jovanovic et al., 2008; McCue, 2005; Rapeepisarn, 2008), I began to develop a sneaking suspicion that these were not the neat buckets they seemed to be. In this chapter, I describe the qualitative inductive process that got me to that point while paying particular attention to the dynamic and interlinked properties of game-based learning themes that did not fit within an existing theory of intelligences.

8.1 RESEARCH QUESTION & METHODS

The primary research question addressed in this chapter is: *what are information processing capabilities that players bring to digital gameplay as evidenced in the data, and do existing theories of gameplay account for these?* In many ways, the earlier research on genre and communication has been a response to this question in a different form by examining the impact of player proficiencies and communication strategies on more formal STEM learning concepts. As the research process progressed, I gained an awareness that these were likely slices of a larger more complex game-based learning process that I had yet to discover. While I was initially interested in whether these ‘things’ qualified as one or more game-based intelligences, I have since taken to examining more generally the capabilities for using information within a game, leaving the qualification of intelligence to another venue.

In the following research, I discuss the use of an applied thematic analysis (ATA) to identify patterns in the data to lead to theory development. While thematic analysis can be integrated as part of other qualitative research traditions such as grounded theory (Ryan &

Bernard, 2003), a growing body of work (e.g., Braun & Clarke, 2006; Guest et al., 2011) has established it as a rigorous qualitative method in its own right. As such, an applied thematic analysis provides a systematic and inductive means to examine patterns in textual data and combines aspects of other qualitative research epistemologies and methods while being more flexible in its approach. Geared towards either theory development or a range of problem solving domains, this type of analysis allows the researcher to find and compare patterns across a wide variety of textual data and may even use quantitative methods of code analysis alongside qualitative techniques (Guest et al., 2011).

Numerous studies of video games have used forms of thematic analysis to generate research findings (e.g., Baranowski et al., 2012; de Gortari et al., 2011; Hussain & Griffiths, 2009; Ke, 2008; Van Deventer & White, 2002). Many of the principles and methods share strong similarities with a constructivist grounded theory approach (e.g., Charmaz, 2014) including the use of iterative coding categories based on inductive readings of the data, the use of memos, and theoretical mapping of codes (Guest et al., 2011). Ultimately, I selected thematic analysis because it is particularly well suited for theoretical development using the analysis of large and diverse textual datasets while allowing greater flexibility when comparing emergent codes against existing theoretical concepts. ATA also allows the researcher to look for patterns across a broad area of textual data including in-depth interviews, field notes, and focus groups (Guest et al., 2011). This aligns with other qualitative research approaches, such as Glaser's grounded theory, that note the importance of using data "whatever the source, whether interview, observations, documents, in whatever combination" (Glaser, 2007).

The data analysis consisted of:

- 30 interviews with youth ages 14 – 19 from Seattle area schools

- Survey questions (N = 51) for an open field response asking players to describe moments they felt good at playing a game and approaches that helped them succeed
- Field notes collected from co-design sessions and gameplay over a 1.5 year period
- Chat logs from the game *MAX5* (587 messages) from 62 participants

It is my belief that having rich and varied data sources allowed for a comparison across data in a manner that provided a more robust conceptual understanding of the emergent themes.

Theoretical sampling

Sampling was conducted in a manner to best follow up on analytic leads throughout the coding life cycle. In practice, this was not always a comfortable process, as I, at times, had to make an analytic shift, exchanging interview questions in favor of new ones or analyzing segments of chat data using newly emerged codes. As new themes and concepts emerged, I could verify these against existing data using the constant comparative method (Boeije, 2002) or, whenever possible, collect further data to reach greater saturation and understanding of the concepts.

Thematic Coding

Coding was done by a single-coder using the *Dedoose* software tool. ATA allows the researcher to take a more targeted approach to coding in which codes may be systematically and rigorously applied in the service of specific research questions and the analytic objective. Of particular usefulness is the concept of a “skeletal conceptual framework” as a possible way of handling previous theory in ATA (Guest et al., 2011). Using this framework, the researcher is aware of a basic theoretical structure similar to an archeological skeleton at the early stages of inductive analysis and this sensitizes the researcher to concepts and allows for more focused inquiry (Morse & Mitcham, 2002).

I was highly inclusive in the labeling process at the earlier stages since I remained unsure of which codes would be most helpful in theory development. As the process continued, I engaged in a more focused coding process in which these initial codes were further refined in the codebook, and I decided which codes should be kept or whether new codes should be generated. This process bears a similarity to the approach of going from initial to more focused codes in constructivist grounded theory (Charmaz, 2014). The codes would often evolve as themes gained further conceptual shape based on the data.

Memo Writing

While codes were applied and refined, I also engaged in a process of memo writing to provide analytic conjectures regarding the structural nature and relationships among the themes. These memos provided insights generated from the codes and source data and allowed me to note differences and similarities across various codes, as well as to begin to interpret higher-level theoretical groupings.

Diagramming

Visual maps were used to show relationships and directionality between the themes. This process of diagramming and mapping concepts has been relevant not just to thematic analysis (Guest et al., 2011), but also to other qualitative analysis approaches as researchers work to better organize and understand their emergent theory (e.g., Charmaz, 2014). Diagramming allowed me to also see what has been aptly called “movement” (Charmaz, 2014) between the various concepts, and to understand how they related within the larger context of player learning experiences.

MI Theory as an Analytic Lens

After more focused codes gained structure in the codebook, these themes were used to interrogate Gardner’s multiple intelligences (MIs) to discover similarities and differences

between the two by asking: *how are learner capabilities organized in game-based learning as compared to Multiple Intelligence theory, and what are the relationships between these capabilities?* The use of existing theory alongside an emergent theory as part of an analytic comparison process has been used in various qualitative approaches including ATA (Guest et al., 2011) and grounded theory (e.g., Corbin & Strauss, 2014). While there are no set guidelines or methods for such a process in ATA, work by Morse and Mitcham (2002) provides a more systematic approach for this form of inductive analysis. This process is discussed further, along with the analytic findings, in the following sections.

8.2 COMPARATIVE ANALYSIS

While previous scholars have claimed MI theory relevant to game player types in learning (e.g., Jovanovic et al., 2008; McCue, 2005), these theories have not included an extensive empirical evaluation of gameplay. I was interested in examining more fully whether and how MI theory compared to inductive themes emergent in the data. Once thematic coding and memo writing had reached a form of conceptual maturity, I utilized MI theory as an analytic lens to group the inductive themes side by side for comparison, in an effort to better understand relationships between them. Morse & Mitcham (2002) discuss the usefulness of using previous theory as a “comparative template” or “scaffold” in qualitative analysis, in which the researcher sees if the emergent theory stands up once the scaffold of analysis of a previous theory is removed. To make this process explicit, I organized the emergent themes from the data into categories based on MI theory, to see if these groupings made sense or whether the data told a different story. This organization is shown in Figure 8.1 below.

Linguistic: An ability to analyze information and create products involving oral and written language such as speeches, books, and memos.

Naturalist: An ability to identify and distinguish among different types of plants, animals, and weather formations that are found in the natural world.

Logical-Mathematical: An ability to develop equations and proofs, make calculations, and solve abstract problems.

Spatial: An ability to recognize and manipulate large-scale and fine-grained spatial images.

Musical: An ability to produce, remember, and make meaning of different patterns of sound.

Bodily-Kinesthetic: An ability to use one's own body to create products or solve problems

Interpersonal: An ability to recognize and understand other people's moods, desires, motivations, and intentions

Input Semiotics: An ability to translate symbols on input devices into movement and interactions in-game.

Domain Language: The use of words or phrases specific to a particular domain or game context.

Environment Semiotics: An ability to understand encodings of symbolic structures within the physical game environment and translate these into meanings and actions.

Event-Outcome Strategies: A logical organization of component parts or steps of various events as relevant to game outcomes.

Visual-Spatial Patterns: Visual patterns presenting information to assist the player in responding quickly to in-game stimuli.

Immersive Sounds*: The use of sounds to create immersive experiences and to generate affect.

Perceptual Sound Cues*: The use of sounds to augment and process visual stimuli in-game.

Automated Reflexes: Quick automated movements and responses to game action.

Embodied Perspective: Sense of physical self and identity based on perspective in-game (e.g., 1st, 2nd, 3rd person).

Task-Relevant Support On Demand: Providing information or help to others for in-game tasks when requested.

Task-Relevant Support As Needed: Providing information or action based help to others for in-game tasks as needed or just-in-time.

Social Support: An ability to recognize and regulate moods in other players based on social or affect cues.

Intrapersonal: An ability to recognize and understand his or her own moods, desires, motivations, and intentions

Exploratory Affect: An ability to find game elements, interactions, or environments that affect and help regulate a player's affect.

Figure 8.1. MIs definitions from Davis et al., 2011 (left column) grouped alongside emergent thematic codes in the data (right column). Themes have been organized in such a way as to group them near MIs sharing conceptual similarities. *Note: These two themes did not receive enough saturation in the data to reach full conceptual construction, however, they are worthy of noting.

In the following sections, I discuss the details of the analysis in order to make visible the process by which MI theory was compared against the emergent themes found in the data to stir comparisons and add depth of understanding.

Semiotic Processing

Emergent in the data are three themes relevant to a grouping by MI theory's *linguistic intelligence*, these are: *input semiotics*, *environment semiotics*, and the use of *domain language*. *Input semiotics* reflect a player's capability for symbolic input into the game system for interaction and movement in that environment. In the game *MAX5*, this theme was most readily represented by players' ability to identify and enter appropriate keyboard keys, allowing them to move and interact with content in the game world. As examples, *W-A-S-D* moved a player through the virtual environment of *MAX5*, whereas the *F-key* would initiate the action to sequence DNA. Players with a high capability for semiotic input communication using the gamepad or keyboard could be quite self-aware of these abilities. As one youth noted in an interview, "I became stronger by learning the control of various characters and specialized in one. I learned the moves, combos, etc. and I was filthy." Players also reflected how their understanding of previous game semiotic inputs impacted their capability at using the ones in *MAX5*. As one player, a fourteen year-old female youth who was a frequent player of online PC strategy games including *Age of Mythology*, noted, using the space bar for "jump" felt odd

because the button was different than those used in her previous gameplay experiences. The attention to the meaning and ordering of the input symbols in games shares similarities with what Gee (2008) calls the “design grammar” of a semiotic domain in which patterns are combined for more complex meanings.

These symbolic input actions share similarities with one of the core purposes of linguistic intelligence, namely, its ability to persuade others to act (Gardner, 2011). In the use of game learning, however, the symbolic structure of the language is not used for rhetorical persuasion, but rather to ask the game system to perform an action. As such, the language is much more rigid. Whereas one could imagine any infinite number of words and phrases that might allow a child to request a cookie (e.g., “please get me a cookie,” and “mmm those cookies look good”), there might be only one or a limited few symbolic combinations of buttons or input interactions that produce the desired outcome in a game. Further, the genre of game and device type (e.g., console, mobile, keyboard, Kinect sensors, etc.) figures prominently into whether the player has experience and knowledge of the specific grammar of these input semiotics. Therefore, it is not surprising that a youth that predominantly plays games using the Kinect or on a mobile device with more natural gestures has difficulty using the keyboard keys in *MAX5* to move.

Also of note is that this theme did not occur in isolation, but contains elements of *automated reflexes* as players use high precision movements and interactions to place their fingers on the buttons. The *input semiotics*, therefore, address whether the player has knowledge of the symbolic structure, and the player’s *automated reflexes* account for the ability to put these inputs into action on a game device.

While these input mechanisms have often been overlooked as merely affordances rather than complex languages in their own right, I argue that they are an important consideration for

designers of educational games, as they are often players' first encounter with the game environment and can immediately establish either confidence or discomfort with that learning environment. In Norris and Soloway's (2004) study of a math game using a Gameboy, four out of the thirty-nine youth in the study sample needed additional instruction on "how to turn on the Gameboy, where the various buttons are located, and so on." This challenge becomes all the more compounded the more complex the inputs and structure of the game. Taking the popular commercial game *Halo 2* as an example, there is not one, but three possible button combinations that allow a player to double-melee attack (e.g., B-X-B-, or B-Y-B, or B-L-B that can be combined with X or Y to finish), and these must be performed at the appropriate time within the correct game context. I have often marveled at the speed and knowledge of youth highly conversant in these semiotic inputs in games, as they display a memory for all manner of movement and interaction combinations with great rapidity.

The data also reflected many youth who felt unsure of button combinations and engaged in what they referred to as "button mashing" showing that despite the frequency of gameplay by U.S. youth, not all input capabilities are equal. This offers an opportunity to tailor input mechanisms to youth strengths through games with adaptable inputs rather than simply dismissing these youth as outliers. In one example of this, a player who had much difficulty using buttons and coordinating movements of her character in video games was a top fast-pitch softball player whose sense of coordination felt good when playing softball. This disparity between physical movements in the digital and physical environment suggested that she would be far more adept at less symbolic input capabilities and more direct movements such as those offered by using the Kinect or other motion sensors for input. There has been some attempt in

educational STEM games to provide various physical inputs as exemplified in research on *Foldit* using the Kinect (Hsiao, 2014).

Environmental semiotics emerged as a theme accounting for encodings of symbolic structures within the physical game environment and, further, how these represented potential actions in the game. An example of such environmental semiotics might be an open door within a game that represents the potentiality for entering and exploring that area. These visual symbols map to a large degree to one of Gardner's later intelligences, the *naturalist* intelligence, defined as "an ability to identify and distinguish among different types of plants, animals, and weather formations that are found in the natural world" (Davis et al., 2011). While this intelligence in MI theory may have its origins in the natural world, this process has continued into areas such as identifying advertising brands or identifying car engines (Gardner, 2011). I have placed this theme between both linguistic and naturalist intelligence in my grouping (as shown in Figure 8.1) because it represents not only the recognition of these symbolic structures in the game environment, but a communication channel, clarifying for the player what actions could be taken within the game environment.

The data in the thematic analysis shows that players less conversant or familiar with these particular semiotic environment encodings could find play quite challenging, whereas ones familiar with the environment's symbolic conventions were better equipped to complete levels in *MAX5*. One player who did not have much gaming experience reflected, it "took a long time to realize I had a lifeline. I didn't realize what the bar on the upper (corner) was. Once I figured that out though it was easier to conserve life," showing how this representation was learned through gameplay. Another player, when asked about his ease at level completion for one level within *MAX5*, described how he noticed footholds in the building to reach a lab and that this gameplay

was quite intuitive to him given the many games he had played with similar mechanics. Gee (2008) discusses a similar type of encoded relationship in descriptions of how players' potential actions can be inferred by the objects in the game environment. The encoding for actions in the game may vary along degrees of implicit or explicit. A low health bar may mean that the player needs to perform any variety of actions to increase health, whereas a bouncing health box may mean more explicitly "jump onto this particular object to collect health here." The understanding of these *environment semiotics* exist within a feedback loop with the *input semiotics*, therefore, as players act upon the game environment using learned inputs, they are also unlocking the knowledge of the symbolic structures and potentiality of the environment.

The theme of *domain language* accounts for shared terminology and vocabulary for players to coordinate game actions as well as a means to create community identity and cohesiveness. In our early stages of design, one of our high-school co-designers brought up the importance of a common language in the game, noting her highly developed game vocabulary from playing *Lord of the Rings Online*. Similarly, the usefulness of creating a shared terminology for workers within a scientific collaboration across multiple groups is increasingly important to articulate and share information across teams (Börner et al., 2010). In playing *MAX5*, how players described various game objects or interactions at times developed in organic ways that mapped well to actual scientific domain language. Youth frequently referred to the action of performing a BLAST search as "blasted" in interviews and in game chat logs, creating a verb out of the use of the Basic Local Alignment Search Tool to compare sequences. While this colloquial usage of the term was not in the game itself, it has likewise been used in the bioinformatics literature (e.g., Conesa, 2005; Telles et al., 2001), suggesting that how players co-opt game language can map in appropriate ways to domain language co-opted within scientific fields. The

use of *domain language* also connects readily with the themes of both *task-related* and *social support* as these terms were used frequently within instructions between players working together. Shared terminology was also used more subtly in a manner that created a sense of a community united around a common game goal. These connections again highlight the dependencies between themes that are not explicitly reflected in MI theory.

Logical Ordering & Visual-Spatial Processing

Emergent themes that were grouped alongside *logical-mathematical* intelligence in MI theory are *event-outcome strategies* and *visual-spatial patterns*. *Event-outcome strategies* as a theme represented player descriptions of logical steps of various events they performed in order to achieve game outcomes. These strategies shared similarities with MI theory's *logical-mathematical intelligence* described as "an ability to develop equations and proofs, make calculations, and solve abstract problems" (Davis et al., 2011). In interviews with youth and in game chat logs, this type of logic was often expressed as a well-ordered series of steps to perform a given action. A popular numeric game puzzle *2048* was frequently mentioned in interviews in a manner that reflected this ordered logic as youth reflected on steps in calculating and breaking down the various subcomponents of the game. Within the game *MAX5* players shared strategies formed in this type of logic with phrases such "first I tried" with the related outcome, "then I" did this, and so on, in a sequence of events until the outcome was reached. The chunking of these components showed information organization through a step-by-step progression towards a goal.

This type of logical pattern organization differed markedly from the *spatial-visual patterns* players described as they were responding to stimuli in a game. One youth explicitly noted the difference between these ways of processing information during gameplay saying that

during the game *2048*, “I have to calculate a lot of things. Whereas in Black Ops I’m just visualizing a lot of scenarios.” Several high-frequency gamers noted these types of visual patterns that would form while making decisions about actions to take. A youth reflecting on playing the *Legend of Zelda*, said, “I knew how to react to situations coming at me at this one point. If something came right at me ... (I) knew what to do in an instant. Patterns, it’s kind of a visual pattern ... an enemy has an attack pattern and only has that type of attack pattern.” These types of visual patterns correspond with Gardner’s description (2011) of the blindfolded chess player who must be able to visualize the absent board, describing visual patterns that were processed.

These distinctions between the more *event-outcome* oriented logical ordering of games and the flashes of *visual-spatial patterns* players experienced connects in compelling ways to previous research on chunking mechanisms of cognitive processes. Gobet et al. (2001) delineate two distinct forms of cognitive processes, one that is more goal oriented and one that is more perceptual in nature in which chunking information is used to processes, store, and retrieve patterns to make decisions that inform action. In the goal oriented model, chunking of information occurs in the service of various sub-goals, and decisions are based on a search of possible operators and object states (Rosenbloom et al., 1987). This process differs notably from the perceptual chunking in the Chunk Hierarchy and Retrieval Structures model (Gobet et al., 2001) in which visual, or other perceptual stimuli, are processed within short term memory, and then stored in long term memory using a learning discrimination network of patterns along various nodes (e.g., each node of patterns in the game of chess might contain a visual diagram of the order of pieces on the board). The CHREST model bears a striking similarity to representations of visual patterns described in player interviews in the data on gameplay. Among

coded data with the visual-spatial pattern theme, two additional dimensions emerged for consideration: the immediacy of use of the pattern as well as the complexity of the patterns, namely, the manner in which visual patterns were stored for multiple scenarios and over multiple characters and interactions in the game.

This theme of *visual-spatial patterns* was grouped also alongside MI theory's *spatial intelligence* in the analysis, sharing similarities with a player's ability "to perceive the visual world accurately, to perform transformations and modifications upon one's initial perceptions, and to be able to re-create aspects of one's visual experience, even in the absence of relevant physical stimuli." This theme is also highly interlinked with themes of *input semiotics* and *environment semiotics*, as players often described a process going from visual pattern flashes based on a reading of the game environment to actions in quick succession using inputs. These interlinked themes again show interdependent concepts, whereas MI theory is rarely clear on how intelligences might map to each other based on context.

Embodied Presence and Response

Themes coded in the data that corresponded most readily to MI theory's *bodily-kinesthetic intelligence* include the use of *automated reflexes* to respond to stimuli, and *embodied perspective* in providing a lens for problem solving and action. Gardner (2011) notes the role of Bartlett's "well-honed sense of timing" in bodily-kinesthetic intelligence, similar to the use of automated reflexes within a game. Interview responses and observations of gameplay suggested that fast-twitch responses were integral to interactions in many games, becoming more automated as a learned response to stimuli in games the longer they were played.

The *embodied perspective* is a theme that emerged in the analysis as relevant not only to players' sense of physical presence and embodied identity in the game, but also, more

fundamentally, as an ability to process information within the physical environment of the game. While the role of viewpoint and perspective is not explicitly mentioned in MI theory's bodily-kinesthetic intelligence, Gardner (2011) does suggest that the use of the body plays an integral part of the human sense of self and identity. The data revealed how a sense of familiarity with a particular gameplay perspective, whether first-person or third-person, provided a sense of self within the game that affected interactions. As one youth noted, while *MAX5* was "really Minecrafty", referring to the popular sandbox game that uses a similar first-person perspective, "I think it would be nicer to have a different angle where you can see the person because it's just one view. It's just weird because I like to see my person. I like to see them running; it's more realistic to me." Attention by designers towards the role of these various perspectives is needed in learning games, as research suggests that switching perspectives can be jarring in games (Salamin, Thalmann, & Vexo, 2006) and can further affect task outcomes (El-Nasr, & Yan, 2006). Similar to the role of *input semiotics*, a player's capability to interact from a certain perspective likely affects many of the other analytic themes as well, as it immediately frames a sense of confidence or discomfort in how a player processes information in the game.

Awareness of Self & Others

Themes that emerged from the data show evidence of both *task-relevant support* that is provided both *on-demand* and *as needed* in which players provided support relevant to accomplish in-game tasks. There is also evidence of *social support sharing* in which players recognized and helped other players in a manner to regulate moods and affect states. These themes relate to the *interpersonal intelligence* of MI theory in the ability to detect others' intentions and desires, even when hidden, and the ability to act upon this knowledge (Gardner, 2011). Particularly pertinent to game-based learning are when and how support is given. Gee (2005) notes that game systems

are quite good at providing information “just-in-time” when the player can use it most and “on demand”, when the player wants it. Similarly, there has been much literature on methods of “just in time” teaching methods in STEM education (e.g., Novak et al., 1998; Marrs & Novak, 2004). However, less explored is an understanding of support timing mechanisms in informal peer learning environments such as games, providing an opportunity for future research.

In interviews and chat logs there were some players who were particularly attuned to recognition of when and what type of support other players needed. This is no easy matter, as intervention in another player’s activities can be disruptive, as part of the pleasure of learning in games is the working through the problems and gaining mastery (Gee, 2005). Imagine a player has been working for many minutes figuring out how to move a boulder in a game and just as she has figured out the necessary action to take another player comes along and performs the action for her – the potential for disruptive support becomes apparent.

The timing of support is integral to the fundamental enjoyment of game tasks. One youth who was a frequent player of dungeon strategy games noted how she would use the health bar status and location of other players in-game to determine whether and when a player needed help saying, “oh I really know this person and it looks like they need help, so why don’t I go help them.” Players with a strong capability of providing just-in-time support become well-versed in the particular semiotics of the game environment (e.g., health bars or types of puzzles or challenges in the game environment) as well as gaining a perceptiveness of other players’ experiences and skill levels in order to provide just the right amount of support at just the right time.

Examples of *social support* were rarely on demand in this manner. Players instead provided emoticons and phrases to support teammates in *MAX5* in response to cues within the

text. Therefore, a player struggling to complete a task in-game might receive encouragement, even if the other player was not able to provide direct task-base support in the action. This type of affect was often mirrored back in a supportive way (e.g., the player that responded “me toooooo” to another player saying “I keep dying”). Much further research is needed on the affects of this just-in-time support on affect and learning as well as ways of scaffolding just-in-time peer support into games.

The theme of *exploratory affect* offers some insight into players’ regulation of their own feelings and emotional states. Some players displayed a capability to find and explore areas of the game environment that produced certain affect states, whether this was the joy experienced at sliding down mountains or the excitement generated at discovering an unintended passageway. One youth who spent much of his time jumping from building to building instead of engaging in the game mission noted, “it was fun, when I was jumping over buildings, I felt like superman.” Whereas in MI theory, navigation capability has been grouped more generally alongside aspects of *spatial intelligence*, in the empirical data, exploratory navigation in the data is more aligned more with *intrapersonal intelligence* in its ability to access “one’s range of affects, or emotions” (Gardner, 2011).

MAX5 players’ self-reported behavioral types were categorized within survey responses as “exploratory” or “navigationally confused” based on a text analysis of their response, and these were mapped to their locations of the second level of *MAX5*. Exploratory players were more prone to taking wide circular arcs through the game environment, whereas navigationally confused players were more prone to traverse the same area repeatedly (Figure 8.2 below).

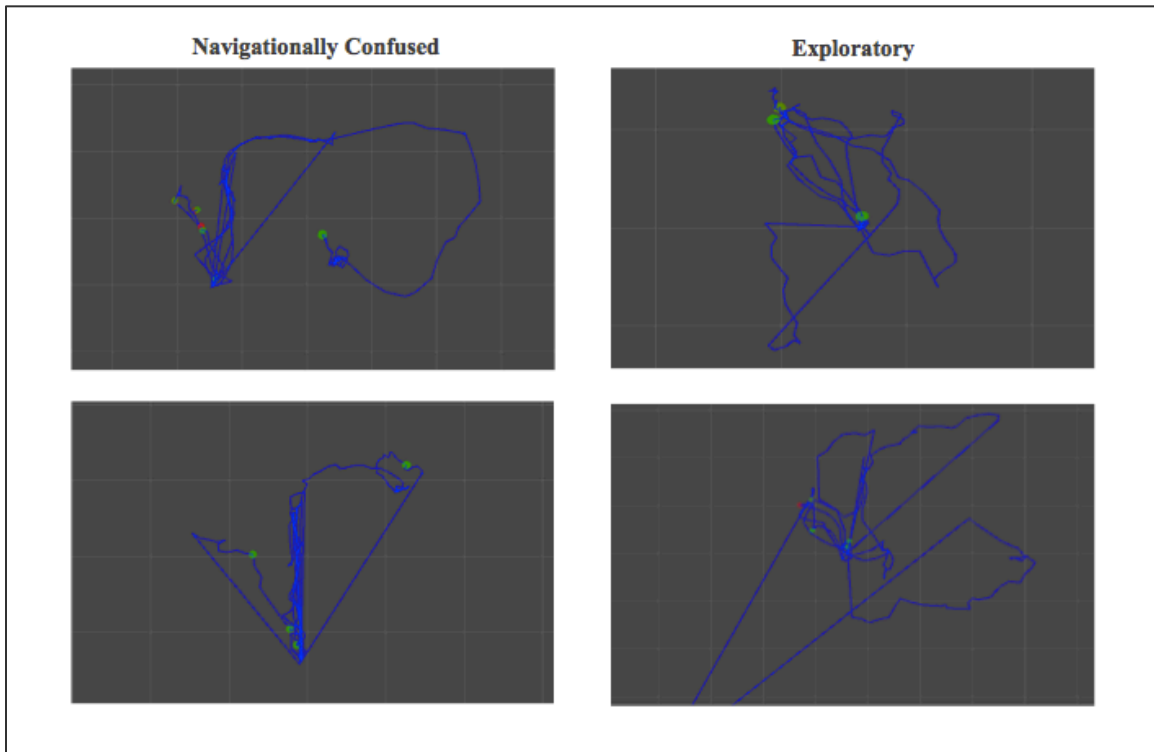


Figure 8.2: Mapped locations for exploration and confusion. Examples of players reporting navigational confusion (Column 1) and exploratory enjoyment (Column 2) within a level in *MAX5*.

There was no direct association found between greater self-reported positive affect and players that were categorized as exploratory. However, this data does suggest that there are identifiable patterns for exploratory players that can distinguish them from players that are merely confused and much further research in this area is needed.

Use of Sound

Two themes related to sound emerged from the analysis that could be grouped more generally alongside MI theory's *musical intelligence* in the "ability to produce, remember, and make meaning of different patterns of sound." These themes did not receive the same level of saturation in the data as the other themes and therefore did not reach a fuller conceptual construction. Given that most video games depend on visual sensory representations, it is not surprising that data on the use of sound patterns was relatively sparse. However, there was

intriguing evidence of players using sounds as *perceptual cues* to augment visual stimuli in the game. A fifteen-year-old youth who was a heavy gamer, playing numerous genres 16-19 hours a week, described in detail how she used sounds in games to identify proximity to game objects that were not in her line of vision, noting that “sounds help me ... because sometimes the (game objects) are pretty small.” There was also evidence in the data of players using sounds to enter more fully into the game world. Numerous players requested the use of a greater number of environment sounds in *MAX5* to help create a more immersive experience. While some commercial games exist that are more auditory based such as *Guitar Hero* and *Wii music*, there are few learning games that exist in this domain outside of therapy training games (e.g., Boulay et al., 2011). Further research on the use of sounds for this type of information processing and retrieval is needed.

8.3 DISCUSSION OF THEMATIC MAPPING

While the comparative lens of MI theory reflects many similarities between overarching concepts present in MI and the themes that emerged in the inductive analysis, it was in mapping these themes that MI theory as a scaffold first began to crumble. Gardner (2011) has long maintained that MIs are rarely expressed as a single dominant intelligence as might be seen in the music prodigy or the star athlete. However, MI as a theory offers few clues as to how these intelligences are interlinked, and intelligences are often listed as categories that show little directionality or movement between them. In mapping concepts from the thematic analysis, however, it was the dynamic relationships between the themes that emerged as critical to an understanding of game-based learning.

Examples of interdependencies between the themes abounded as illustrated in several players that I initially categorized as exploratory. Upon further analysis of the data, more

complex and dynamic relationships were present in their behaviors. In several cases, *exploratory* players in *MAX5* used a complex symbolic knowledge of the game's *environment semiotics* to discover new areas to explore by, first, noting the signs that had been built into the game (e.g., paths along the mission or DNA clues), and then using this knowledge to break with the designed game conventions in clever ways (e.g., breaking outside lab walls or using tools for new purposes). These explorations generated a notable shift not only in players' own affect and mood, as observed in excited facial expressions and chat analysis, but also allowed these players to stir and excite the affect of friends and teammates by sharing their discoveries as a form of *social support*. The links between themes could also change based on player and context, as when players who received *task-relevant support* from teammates seemed unable to leverage this knowledge given challenges using *automated reflexes* or a proper reading of the *semiotic environment* within the game. Examples of these types of interdependent connections were numerous, and the themes began to emerge as far less discrete and far more complex than I had ever originally expected.

The connections between the concepts started to look less like bounded categories and more like networked nodes that would connect (or disconnect) dependent on the context of the game-based learning task. In a series of "aha" moments, I felt what Charmaz (2014) has referred to as the "pivotal insight or realization of analytic connections" that "can happen any time during the research process." There was a stir of excitement at the realization that I was on to something that could perhaps have a much stronger impact on the design of future learning games. I also felt equal parts dread at the prospect that I would have to rethink and reconstruct the entire theory that had been forming after many months of work. Further, I realized that countless more hours would be spent going back to the data to see again what was there.

Once the dust settled, I have been ever thankful for the process described by Corbin and Strauss (2011) in which the researcher must let go of her or his emerging theory, no matter how difficult, if it does not adequately describe processes seen in the data. What ultimately emerged is, I believe, much truer to the capabilities players bring to the game-based learning experience. Going back to the data, I used a constant comparative approach similar to Boeije's (2002) in which I made comparisons across single categories of data (e.g., all interviews) and between groupings of data of various types (e.g., between field notes from design, chat logs, and interviews). I began to see the themes as part of an ever reordering and interlinked set of highly dynamic capabilities with interactions that were not reflected in the more static categories offered by MI theory. These capabilities and their interactions within the game environment are discussed further in Chapter 9.

8.4 CONCLUSION

This chapter presents a cross comparison of MI theory with themes that emerged from a qualitative inductive research process conducted over a large corpus of textual data consisting of interviews, surveys, gameplay observations, field notes from co-design sessions, and game chat logs from the STEM game, *MAX5*. This analysis reveals notable conceptual mappings that arose from a comparison of concepts from the inductive thematic analysis and MI theory, helping to refine these thematic concepts while providing a useful lens for examining the possible existence of player learning typologies. The analytic process of comparison led to the discovery that the themes were more linked and interdependent than the capabilities presented in MI. While Gardner notes that the intelligences in MI are used in overlapping capabilities dependent on the domain (Gardner, 2011), the manner of overlap is quite opaque within MI theory, and these underlying connections are left unstated.

In the themes emergent from the data on game-based learning, it is in fact the dynamic connections between concepts that are instrumental to an understanding of how information processes occurred. *Automated reflexes* were at times highly dependent on players' use of *input semiotics* and *visual-spatial patterns*, and, similarly, players' capabilities to understand *environment semiotics* affected their ability to provide *task-relevant support* to other players in a peer-learning environment. This comparative analysis showed the importance of directionality and feedback loops between the themes in a manner not explicitly seen in MI. The directionality of themes could also dynamically reorder based on gameplay contexts. Given these findings, I realized that a different theoretical lens was needed to further develop a theory of game-based learning and that MI as a theoretical scaffold did not stand under the weight of themes that were far more interdependent and dynamic than a categorization by player type or intelligence allowed.

CHAPTER 9. A COMPLEX SYSTEMS APPROACH TO GAME-BASED LEARNING

The thematic analysis showed game-based learning concepts that were dynamic and interdependent in ways that were largely unaccounted for in MI theory and previous typologies of players based on intelligence or learning style (e.g., Jovanovic et al., 2008; McCue, 2005; Rapeepisarn, 2008). In the following sections, a complex systems approach is used to identify five layers emergent from the coded themes to better understand features of game-based learning, these are: the *input*, *semiotic translation*, the *sensory sphere*, *structural dynamics*, and *memory-action patterns*, all existing within a larger system of *network exchange*. These layers are discussed in relation to features of complex systems, and as relevant, research in psychology, cognitive science, gaming and media studies. These layers are then connected to areas of STEM learning and careers to gain a better understanding of their potential applicability to educational game design.

A systems perspective is not new to an understanding of media or communications. Previous work has suggested that a complex systems perspective is useful for understanding the dynamic learning mechanisms of video games (e.g., Rosas et al., 2003), yet does not account for how that system operates. Holland (2006) offers several characteristics of complex adaptive systems (CAS) including parallelism, conditional action, modularity, and adaptation that he claims are relevant to numerous domains, including games. While not explicitly referenced in Holland's original model, I would add to these concepts, *emergence*, in which behaviors at one level or state of the system lead to emergent patterns at another level or state of the system (Holland, 2000; Smith, 2005). These characteristics provide an entry point for discussing the

characteristics of complex adaptive systems in more general terms. Holland's (2012) more recent work on uncovering the mechanisms of signal/boundary systems, in which adaptive agents within the network accept or ignore signals, provides a more targeted way of understanding the system's functionality. These signal/boundary systems further consist of "building blocks" described as pieces of the network that interact in dynamic ways and that can be reused across many contexts of the larger system (Holland, 2012). In the following sections, I argue for the applicability and appropriateness of a complex systems perspective in organizing the previous thematic concepts and propose the building blocks of information processes within game-based learning. The descriptions of these system layers do not represent in themselves a fully formed CAS theoretical model for game-based learning, as that is beyond the scope of the dissertation and would likely require many more years to achieve. The following sections do, however, offer a first look at the proposed building blocks of this larger game-based learning system emergent from the empirical data. It is my hope that these building blocks are then taken up by researchers, educators, and game designers to further test, refine, and develop in the context of their own data.

9.1 BACKGROUND

A study of game-based learning lends itself well to a systems framework as games are, by their very nature, designed systems with boundaries, inputs, outputs, and goals. Holland (2006), in a comparison of complex adaptive systems in control theory, economics, biological cells, and games, argues for the importance of sorting out these various parts and defining the component agents and their interactions. It is my interest to provide a more complete understanding of these component parts and interactions relevant for game-based learning. These various components of a complex system are continually evolving and changing based on their interactions with each

other and their surroundings (Holland, 1992). In this sense, the properties of the system are not fixed and are continually emergent. This maps well to the history of digital games, which has been one of change, evolution, and flux. Arcade games with relatively simple mechanics and joystick controls have now evolved to become a ubiquitous part of the home and personal space on a range of devices, including PCs, consoles, and mobile devices. There are now millions of titles offering innumerable types of gameplay experiences. Perhaps some of the most rapid changes in recent years have been in interaction paradigms for games with devices such as the Kinect motion sensor, mobile sensors and cameras, and the use of virtual and augmented reality devices, changing the way players engage and sense in the game world. Therefore, the properties of the system have emerged and adapted in co-evolution with the technological and creative outputs of their time. Game-based learning capabilities will continue to adapt and evolve to meet the needs of ever changing technologies and communities.

9.2 A NETWORKED MODEL OF GAME-BASED LEARNING

It is helpful to note that, while the proposed model begins with the individual player and a single game as the boundary of description, this is largely an artificial construct selected to highlight the composite parts of the system in a more straightforward manner. Five of these layers (the *input*, *semiotic translation*, the *sensory sphere*, *structural dynamics*, and *memory-action patterns*) are discussed within a framework of exchange between an individual player and a single game while the reality is much more dynamic. The player and game sit within a much larger network (of *network exchange*) that consists of information and affect transferred and stored between other players, other games, and external media artifacts (blogs, chat rooms, videos, etc.), as shown in Figure 9.1 (top) below. Therefore, the layers may be thought of as repeating across the many

nodes with looping signals in a growing network as players interact with an ever-increasing number of games and other players.

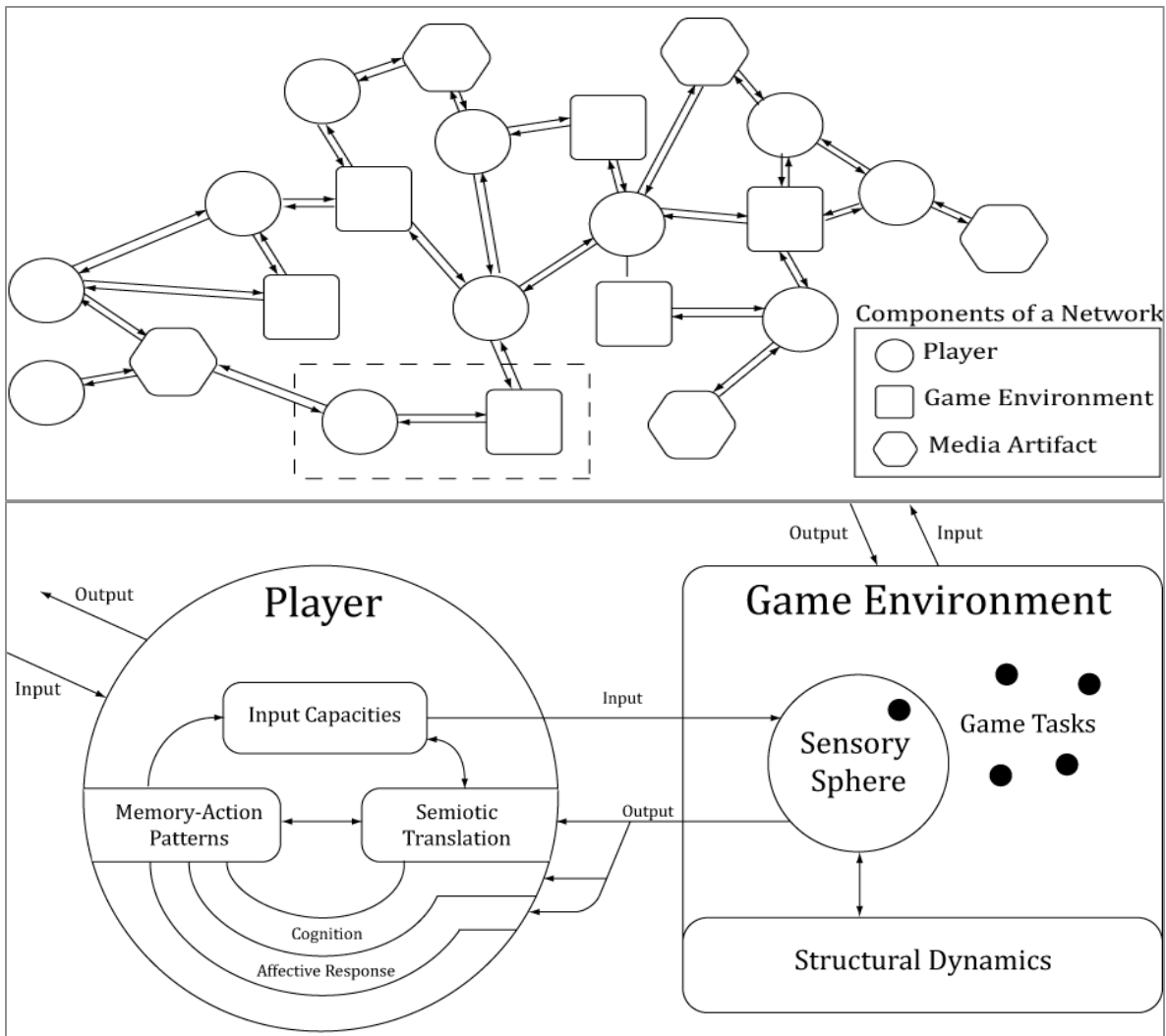


Figure 9.1: A diagram of the complex system components of game-based learning. The exchange network, consisting of players, games, and media artifacts relevant to gameplay is shown (top). The diagram (bottom) shows the layers existing between the player and the game environment.

This notion of an expanded information processing network across people and artifacts shares notable similarities with distributed cognition’s focus on cognitive events that are not limited to the skull of the individual but that exist within a distributed networks of people and the material environment (Hutchins, 2000). Complex systems theory was chosen as the lens for the

theoretical approach given the strong similarities between the interconnected and dynamic properties seen in the gameplay data and the existing body of work that has identified structural dynamics of the system related by signals, boundaries, and feedback loops (e.g., Arrow, 2000; Holland, 2000; Holland, 2012).

The concept of a complex system as a network with various interconnected nodes draws on models of neural networks in which signals are passed back and forth among the component parts (Cilliers, et al. 1999; Holland, 2000). In a similar manner, the interconnectedness of these various nodes shifts and adapts dynamically over the lifetime of a particular network, as they connect or fall away based on collaborations with other players, the starting and stopping of gameplay, and contexts of use (e.g., one network pattern might form for gameplay at school, and another pattern for gameplay with online friends at home). In this way, the exchange network mimics properties of neurons passing information signals along given pathways. The nodes, in this case, represent what Holland (2012) refers to as “agents” or “bounded subsystems capable of interior processing” within the network.

The game system is not a closed system and signals across the game-based learning network can occur that affect the intensity and signal direction of other properties of the system. As an example, information shared in a chat tool in the game between players (e.g., “have you checked out the microscope?”) may cause the player receiving these messages to be more attentive to game objects that look like microscopes, thereby directing her or his sense towards that particular feature in the game, further activating additional feedback loops that work to decode information around objects with properties similar to microscopes.

9.3 INPUTS

The *input* layer provides a means for the game player to control the avatar and/or objects in the game-based learning environment, further acting as a bridge between the player and the game world. Evidence of this layer came from the theme of input semiotics previously discussed. These input states are represented in several areas; these are: gaze, gesture, touch, speech, and biosignal. While touch was the primary category observed in data on *MAX5*, given the game’s reliance on keyboard input, gesture also emerged as relevant from interviews and design sessions while additional categories emerged from the related literature. Each of these types of input allow players to input signals into the game learning system as they move their avatar or transfer attention, interact with other players or characters, and manipulate objects in the game environment. The component elements of the input layer are shown in Figure 9.2 below and discussed in further depth in the following sections.

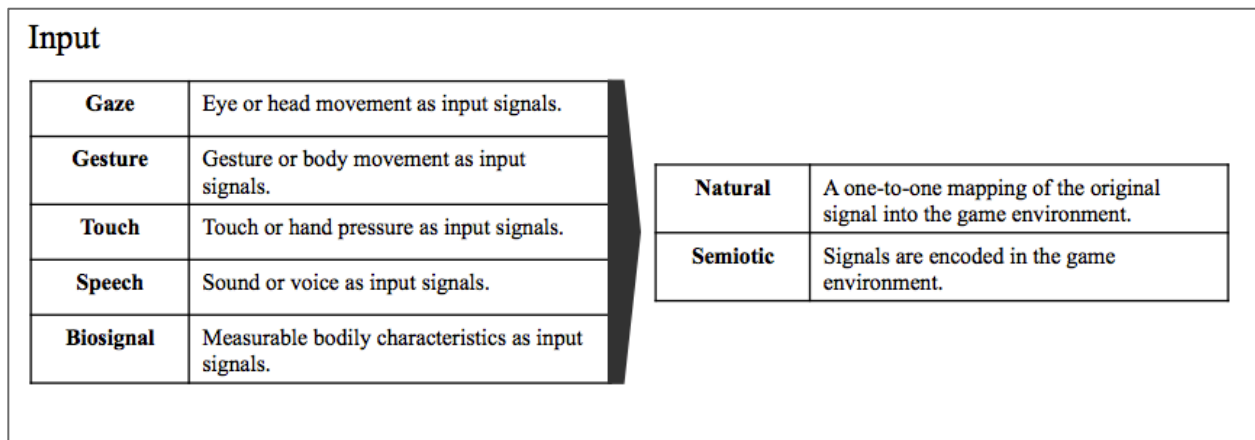


Figure 9.2: The input layer of game-based learning as players input signals to interact within the game environment.

These input signals share similarities with Holland’s (2006) more general conception of signal inputs that are converted into an agent’s states and external actions in complex systems. Input capacities affect players’ interactions with game-based content, and these can in turn

further affect mood, confidence, and learning capacity. If one imagines trying to perform a math problem at a white board where instead of using one's hand to write directly to solve the problem, there is only a marker tied to the end of a four-foot-long stick, the challenge of mismatched input to a player's capacity becomes immediately apparent.

In digital game-based learning environments, these input signals activate all player interactions within the game system. These mechanisms lie along a spectrum from *natural*, in which sensory physical or biological interactions within the external environment are mimicked in a one-to-one relationship in the game environment, to *semiotic*, in which player sensory interactions are symbolically represented and translated into interactions within the game. One of the most common inputs is *semiotic-touch*, in which touch-based interactions symbolically represented by keys and buttons are translated into interactions and movements in the game-environment. In this manner, the keys on a PC become symbolic representations translated by a player's touch into signals within the game for moving an avatar forward, backward, or to the sides. Inputs that fall further along the *natural-touch* scale are represented in mobile or tablet games where players' interactions with the touch-screen generate signals that are translated into similar interactions within the game environment. Therefore, a player's finger swiping of a ball shown on the screen results in the ball's movement in the same direction within the game.

Gestural input capacities offer a means for player gestures to be represented as signals for interactions within the game environment. An example of a more *natural-gestural* input would be the Kinect game *Dance Dance Revolution* in which player movements and gestures in the external environment are translated by the Kinect sensors into highly similar gestures in the game environment. Few games employ fully *natural-gestural* input interactions as these gestural signals are often converted into more highly symbolic outputs and vice versa, resulting in a

semiotic-gestural input signal. In a version of the protein folding science game *FoldIt* developed for the Kinect (Hsiao et al., 2014), players manipulate the protein molecule using their hand positions to map to positions on the proteins. Additional conversions of the signals are done in this gesture-controlled version of *FoldIt* to account for possible occlusion as players use both hands. Therefore, these are not one-to-one signal translations, rather, they sit between natural and semiotic along the spectrum.

While less common than gesture or touch-based interactions, *speech*, *gaze*, and *biosignal* inputs can provide additional types of signals to game-based learning environments. *Natural-speech* may include the player producing a sound vocally or rhythmically as an input that is then reproduced in the game environment, whereas *semiotic-speech* includes a symbolic translation of player sounds to actions in the game, as with voice controlled character movements (e.g., Luisi, 2007). *Semiotic-gaze* signals include eye movements that are translated into forms of movements or interactions in the game environment (e.g., Smith, 2006). *Natural-gaze* inputs allow players to use eye-movement, gaze, or head movement to move the visual perspective of the player in the game accordingly (e.g., Yim et al, 2008). *Semiotic-biosignal* inputs include the use of EMG signals, heart-rate signals, and brain waves (e.g., Nacke, et al., 2011), converting these signals into symbolic interactions in the game (as an example, alpha waves might be translated into moving an object up in-game). As technologies for these biosignal inputs improve, they have much potential within learning games as reaching optimal levels of biosignal control over prolonged periods has been shown helpful for attention and learning tasks (Linden et al., 1996). These category types for inputs in game-based learning are not discrete, as many input signals might lie somewhere along the semiotic and natural spectrum or might include more than one type in combination to represent more complex inputs (e.g., *semiotic-gestural* + *natural-speech*).

Within the empirical findings, several youth showed a particularly strong capacity in *semiotic-touch* controls in the game *MAX5*, noting how their understanding of previous game controls impacted their capacity at using the ones in the learning game. As noted in the previous chapter's discussion of the semiotic input theme emergent in the analysis, these input capacities amount to more than simply just affordances for game-based interaction but represent complex learned systems that should be treated accordingly. The capability to translate these signals is discussed further in the Semiotic Translation section of this chapter. The data suggested that learning transfer within the same or similar inputs may be relatively common (e.g., *semiotic-touch* within PC keyboard play and gamepad console play), whereas transfer between two different categories of inputs is more challenging, as youth that excel with *natural-gestural* interactions in a Kinect sports game might struggle with *semiotic-touch* interactions in a complex PC game relying on keyboard input.

9.4 THE SENSORY SPHERE

The input layer allows players to send signals to manipulate the *sensory sphere*, the sensory extension of the player into the game environment. The conceptual basis of this layer arose out of further construction of the *embodied perspective* theme discussed in the previous chapter with an interest in how players receive and interact with sensory information in an educational game environment. This concept of a sensory frame of perception shares similar attributes to the concept of *mis-en-scene* used in film studies (e.g., Gibbs, 2002), yet in game-based learning it extends beyond the player's visual lens or framing to additionally include visual, auditory, and haptic interactions within the player's sensory bounds of the game world and the player's perspective (Figure 9.3). In this way, the *sensory sphere* is a dynamic extension of the player's perceptual self, similar to Holland's (2012) identification of detectors that pick up the

environment changes of situated agents within a CAS. As the player shifts attention, action, and movement to various aspects of the game environment the sensory sphere also shifts the player’s sensory perception. This aspect of perceptual attentiveness also shares commonalities with selective visual attention (Koch & Ullman, 1987) although the *sensory sphere* includes additional auditory and haptic stimuli as well, extending beyond visual perception.

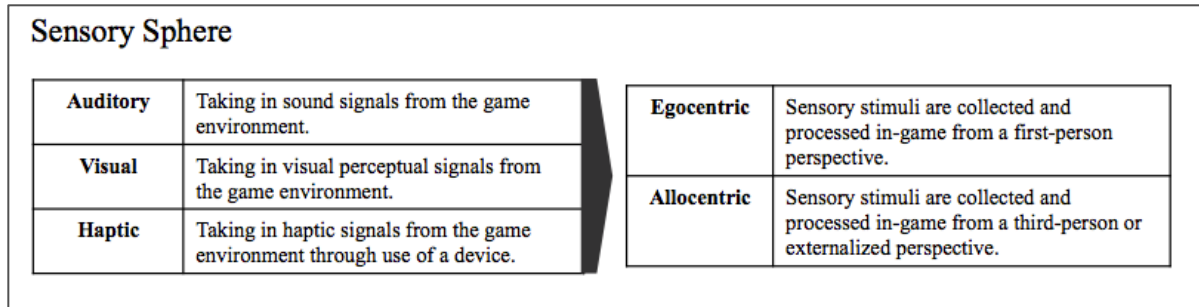


Figure 9.3: The sensory sphere collects and focuses stimuli from the game environment.

Within games with avatars, as a player moves an avatar throughout the game, the *sensory sphere* moves with this avatar to pick up new sensory signals from the game world. In games where the player stays within a single frame for an entire level, this *sensory sphere* shifts at the micro-level as attention and interaction-focus moves to components of that particular frame. Therefore, in the puzzle game *Tetris*, as pieces fall from the top of the frame towards the bottom, the player’s attention and the *sensory sphere* move from the top to the bottom of the screen. This attention to select stimuli as they enter player’s focus becomes critical as the player works to filter and translate the sensory signals to determine actions. The sensory sphere exists along a spectrum of perspectives that may be either *egocentric* or *allocentric* in nature. An *egocentric* perspective is matched more closely to the player’s viewpoint, while an *allocentric* perspective is more object-centric. Previous research has shown these two perspectives affect gameplay abilities (Bae et al., 2012; Spence & Feng, 2010).

In the *sensory sphere*, the conception of an *egocentric* or *allocentric* perspective extends beyond visual stimuli to include auditory and interaction perspectives as well. The use of player perspective arose in the inductive thematic analysis discussed in Chapter 8. Foreground sounds that are made louder based on the player’s position provide an *egocentric* auditory perspective. Similarly, gameplay conventions that require the player to be within a certain range of an object to interact with it provide a more *egocentric* interaction perspective. These particular perspectives provide a focused lens for the sensory sphere as it collects perceptual signals and as the player shifts attention and movement dynamically within the game. The process of *semiotic translation*, as described in later sections, offers a means by which this signal is filtered and information is processed based on the player’s symbolic understanding of the game environment.

9.5 STRUCTURAL DYNAMICS

The degree to which the *sensory sphere* collects information in the game environment is limited in part by the *structural dynamics* of the game. These structural dynamics may be *locational*, based on where a player can move or focus attention within the game environment, *temporal*, in which interactions are enforced by time constraints in the game, and *interactional*, referring to the limitations on the type of interactions a player is able to perform in the game environment. These dynamics are shown further in Figure 9.4 below.

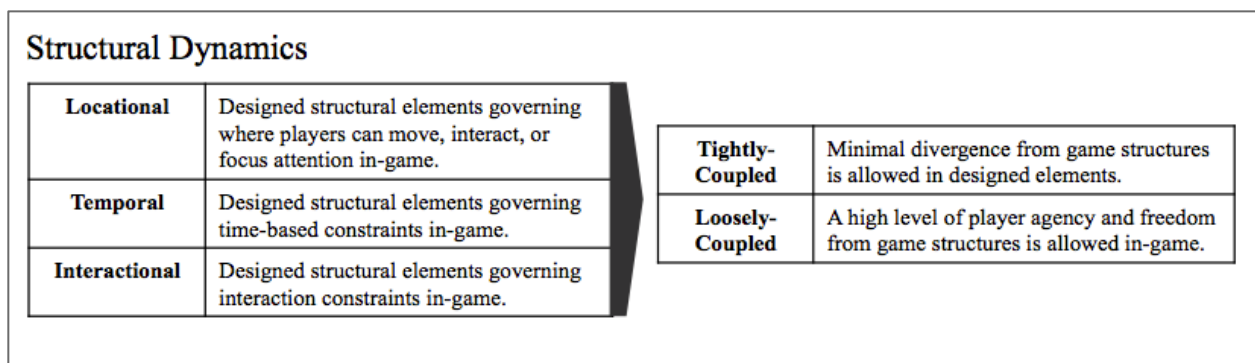


Figure 9.4: The structural dynamics determine the player’s sense of agency in the game.

The layer arose out of consideration of several subthemes in the thematic analysis such as time necessary to interpret visual-spatial patterns in fast-twitch mechanisms as well as exploratory player behavior where players acted outside of the game's prescribed path.

Structural dynamics bear a similarity to the concept of “rules” that govern whether signals can be processed in complex adaptive systems (Holland, 2006) as well as the structural features identified in small group complex systems by Arrow et al. (2000). These structural dynamics are organized as either *tightly-coupled* or *loosely-coupled*, referring to the amount of design constraints placed on the players' set of potential actions in the game environment. More *tightly-coupled* structural dynamics reflect game tasks closely spaced with minimal divergence, whereas *loosely-coupled* structural dynamics reflect game tasks loosely tied to specific actions with high exploratory affordances. This definition draws on Weick's (1976) description of loosely-coupled elements as containing parts that are responsive to each other but still preserving their own identity as exemplified by weakly tied mutual events between them. In the game environment, structural dynamics assist in moving the player along a prescribed design path to accomplish game goals.

While game designers can work to guide and tether the player's path through the game, researchers have noted that, ultimately, this decision of whether to accept this expected pathway is left up to the players (Squire & Jenkins, 2002). While playing *MAX5*, players tested boundaries of the structured game environment as they encountered new game elements resulting in feedback loops and fluctuations between the intended structure and how players actually used the environment. Players also uncovered elements of unintended design within the game such as walls they could jump over or new paths they could take, adapting the game in a manner similar to what has been referred to as “emergent” gameplay (e.g., Dormans, 2008).

Temporal structural dynamics govern how long a player will have to accomplish an interaction within the game before time runs out. In interviews with youth, several reflected an awareness of how having to perform actions within a prescribed time limit affected their sense of urgency in the game environment. Games designed to allow players thirty seconds to perform a task, as opposed to thirty minutes, would be considered to have a more *tightly-coupled* structure. References to temporal dynamics are found in other complex systems approaches such as Arrow et al's (2000) model.

Locational structural dynamics determine the capacity of players to explore locations within the game environment. Exploratory behavior has been identified as a primary motivation for playing games (Yee, 2006) and, as observed in *MAX5* and discussed in the preceding chapter, was often related to players seeking a heightened experience of affect. Some games would seem a natural fit for navigational exploration. Open world multi-player games where players have the freedom to explore a large geographic territory with an avatar are exploratory by design. Within puzzle games or games without an avatar, these locational structural dynamics might include areas that a player can view. In the protein folding game *Foldit*, players may rotate and turn the protein to view connections to the molecule (Cooper, 2010), amounting to locational structural dynamics that are more tightly-coupled because the player is bounded by constraints to the distance and angle the protein can be rotated. These differences in movement structures bear similarities to Squire and Jenkins' (2002) conception of *hard rails*, for games in which player movements are more tightly structured, and *soft rails*, where player movements are more multidirectional and multi-linear.

Interactional structural dynamics represent the number of game elements players can interact with in the game as well as the types of interactions that may occur. In the game *MAX5*,

players frequently tested the boundaries of the designed interactions. One example is seen in several players who decided to jump on a chicken in the game and ride it around instead of collecting DNA from it, an option initially unbeknownst to us as the game's designers. A more tightly structured puzzle game such as *Tetris* might seem less prone to exploratory interactional behavior. Yet, even in *Tetris*, examples of exploratory behavior at a more micro-scale have been observed; research has shown that the number of extraneous rotations and backtracking, both actions outside of the shortest path to accomplish the game goal, actually increases as the player's skill increases (Maglio & Kirsh, 1996). These results suggest that exploratory behaviors that run contrary to the intended structure of the game provide a means for the player to both make sense of the game environment and to achieve and discover desirable affective experiences. There is a dynamic tension and fluctuating state between the game's designed temporal, locational, and interactional pathways and a player's desired actions and experiences.

9.6 SEMIOTIC TRANSLATION

Semiotic translation is the process by which players convert noisy signals collected by the *sensory sphere* and translate these into meaningful and actionable information based on their symbolic properties. This is one of the primary filters by which signals are either accepted or are ignored. This layer emerged conceptually from the themes of *semiotic input* and *environment* in the thematic analysis. Semiotic translation in game-based learning occurs as either *input-oriented* translation, translating representations for input capacities including buttons and keyboard keys, *contextual* translation, translating representational information that provides contextual knowledge for gameplay (such as GUIs that provide information about a game object or character), and *environmental* translation, translating representations of potential actions that can be taken in the game environment.

Input-oriented semiotic translation includes the ability to decode and use buttons or computer keys that most commonly use assigned symbolic representations, including lettering, shape, or position on the keyboard or gamepad (e.g., the space bar allows the player to jump). While this concept is connected to the previously discussed input layer, the former represents the signals for enactment and interaction within the game environment, whereas input-oriented semiotic translation is the process by which the player makes sense of the encoded structure that can be used to represent these signals.

Contextual signs within the game environment provide contextual information that may be useful without providing a path to direct action in the game. This concept makes use of Lee's (2011) framework for contextual information in digital collections which identifies contextual elements including states, related agents, actions, and relationships with other objects. An example of a contextual sign is found in auditory encodings of music associated with particular enemies or characters. Collins (2007) provides examples of this type of semiotic representations in the music in the game *Zelda* where all enemies share a similar score. This music cues the player to the enemy's presence, however, it does not provide a clear link as to what action the player should take.

Environmental signs are directly linked to actions within the game and denote what actions are possible. Gee (2008) discusses this type of encoded relationship in games when describing how a player's ability to crouch and hide in the game is inferred by an environment that containing a high amount of shadows or objects a player could conceivably crouch beside. These properties of semiotic encoding are presented in Figure 9.5 below.

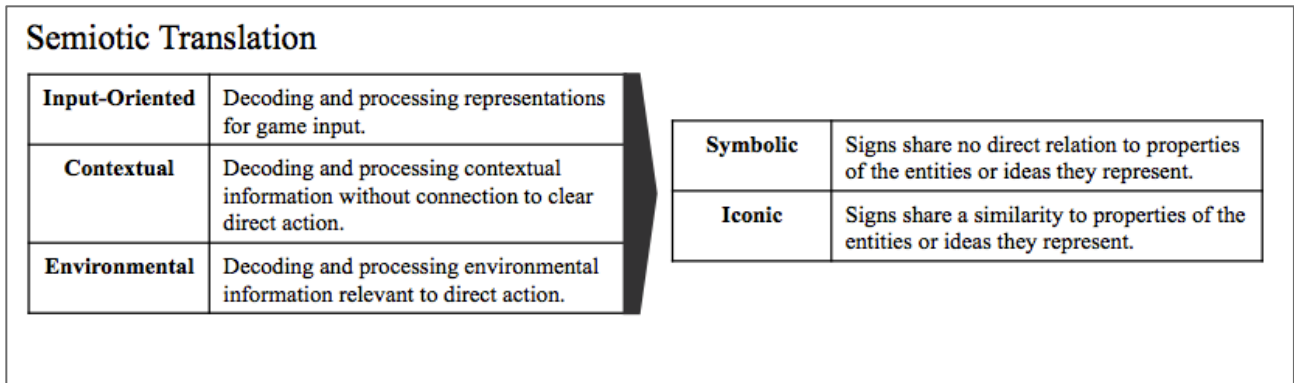


Figure 9.5: Semiotic translation describes the process by which signs are processed, decoded, and made sense of by the player.

Peirce’s (1991) work in semiotics provides a basis for further categorizing these types of signs for the layer of semiotic translation. Semiotic game elements sit along the spectrum of *iconic*, in which signs share similarities with the objects they describe, and *symbolic*, in which the signs represent objects or ideas without sharing direct properties with them. The production of these signs further exists within an affective context in which certain aesthetics or narrative elements act as memory cues that help players call attention to important semiotic encodings as well as retain these in their memory. Therefore, ominous music might be associated with a particular character (*symbolic-contextual*) while also eliciting a particular emotional response from the player. Players use this process of *semiotic translation* to either cycle back in quick feedback loops to the *input layer* and *sensory sphere* to collect more information in the game environment or to compare these filtered signals against *memory-action patterns* as discussed in the next section.

9.7 MEMORY-ACTION PATTERNS

Once the player has translated the game’s semiotic environment into more meaningful signals, the outputs are compared to stored memories of previous patterns of in-game behavior to allow the player to make a decision on the appropriate actions to take. These decision-making processes are represented in *memory-action patterns* (MAPs) in which semiotic filtered signals, as well as direct data from the sensory sphere, are compared against these previous patterns of gameplay. These patterns share similarities with the tags and motifs that Holland (2012) describes in CAS. The development of this layer is based on the themes of event-outcome strategies and visual-spatial patterns as previously discussed in the thematic analysis and the layer components are shown in Figure 9.6 below.

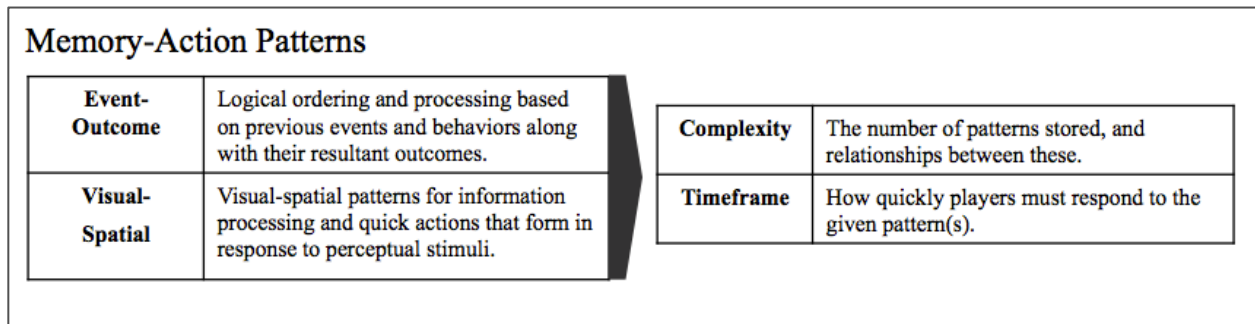


Figure 9.6: Memory-Action Patterns (MAPs) that players use when comparing new information against stored patterns to pursue a course of action in-game.

This process of connecting sensory perception to patterns of action also bears similarities to Pentland’s (2000) description of perceptual intelligence in which a person’s perceptual apparatus classifies situations using learned-responses to determine the most appropriate biological behavior. In the case of game-based learning systems, the player is classifying signals both directly from the *sensory sphere* and as filtered through *semiotic translation* into patterns and comparing these patterns to stored patterns from previous levels and previous games.

Cognition and affective responses flow back and forth from *semiotic translation* and the MAPs as the player filters behavioral patterns. Affective responses act to highlight particular areas of attention for the player. Salovey and Mayer (1990) describe how emotion can act as an interruption for complex systems, calling attention to more pressing needs. In this case, however, the interruptive affect response is actually embedded as part of game-based learning processes. Therefore, when suspenseful music is played whenever an enemy is present in a game scene, the player's affective response to this music becomes a cue (even if not consciously) to compare interactions with that one enemy against similar patterns of interactions that have occurred with other enemies. If the player has never played an educational game, or any digital game for that matter, these patterns are compared against stored experiences that occurred in non-game circumstances (e.g., perhaps the music reminds the player of a scene in a suspenseful movie) although these do not provide as strong a signal or as strong a match for action responses.

MAPs vary greatly in both complexity and in the timeframe in which the information is processed and used to perform actions. They may be categorized more generally as either *event-outcome* or *visual-spatial* when referring to the types of comparisons players make as they store and process patterns of behavior within their memory. *Visual-spatial* refers to patterns of visual processing often connected with motor-responses to stimuli that become more automatic than conscious, sharing similarities with motor-skills within procedural memory (e.g., Schacter & Tulving, 1994). *Event-outcome* MAPs are formed through grouping actions and events to resultant outcomes over time. These memory patterns share similarities with episodic memory, which facilitates recollection of personal experiences and the relationship of these experiences to each other over time (Schacter & Tulving, 1994).

A network model of memory, with each memory type stored along a single interconnected node of the network, provides a helpful understanding of how memories are clustered. A relatively simple game that relies solely on fast-twitch muscle memory has fewer nodes along the spectrum, whereas a highly complex strategy game where players must compare multiple types of actions (e.g., player character attributes, outcomes of numerous events, and locational directions, etc.) contains multiple webs of interconnected nodes. Therefore, within game-based learning, the number of memory patterns that the player makes use of determines the number of nodes of the network. This network model draws on previous work by Tourangeau (2000), who describes how remembered events are stored within a single node as activation fans along these nodes when trying to recall an event.

The number of nodes along the MAPs and the manner in which these nodes combine is also dependent on the player's task. A youth describing her experience playing *2048*, in which the objective is to slide numbers along a digital tile board until reaching 2048, described an event-outcome approach where she would stack the higher numbers on top to view and compare them. This technique provided a relatively straightforward MAP in which she established and stored a single pattern of behavior. Processes described by players of more complex strategy games suggest the use of more multi-nodal and interlinked memory patterns where they must plan over a longer term by comparing data on numerous types of armies and resources, remembering previous actions and previous outcomes for enemy strengths and rankings while engaging in game battles. The MAP responses allow players to select the optimal action based on the stored memory patterns of previous behaviors. Once this action has been selected it is relayed back to the input layer as a signal and the entire cycle repeats itself again in rapid feedback loops.

9.8 THE LAYERS IN CONTEXT OF MAX5

While the layers of the complex systems model for game-based learning have the potential to be more broadly applicable to an understanding of educational games, the development of the model has always fundamentally been in the service of STEM learning. The next sections bring the lens back onto STEM games to show how each of the proposed layers map onto the game *MAX5*.

In *MAX5*, players use *input* signals that are *touch-based* and *semiotic*, in this case keyboard keys and mouse clicks, to represent players' movement and interactions within the game environment. In order to collect DNA samples in the game, the player must be able to successfully move towards animals using the W-A-S-D keys and, similarly, use the mouse to click on tasks to view nucleotide sequences. The keyboard keys offer physical interactions that then must be converted into highly symbolic understandings within the game world. The use of the mouse to select a microscope sample is an example of an interaction that is further towards the *natural* side of the spectrum as this more realistically mimics actual touch-based interactions in the external world. These signals are quickly interpreted in the process of *semiotic translation* as the player works to make sense of the symbols and translate them into meaningful action. In observations of players familiar with first-person style computer games, the symbolic conventions used for moving in the environment were familiar and often became highly fluid within minutes of gameplay, whereas players unfamiliar with the semiotic input conventions (e.g., mobile touch gamers) had more labor-intensive interactions.

The *sensory sphere*, as represented in *MAX5*, allows players to collect perceptual data from the game world consisting of *visual* and *auditory* stimuli. The perspective of this sensory collection mechanism is more *egocentric* as a first-person view is employed in which the player

sees through the eyes of the game avatar. This sensory sphere becomes the embodied experience of the player, and numerous players who were used to third-person perspective where they could see the avatar in gameplay expressed discomfort at this aspect of gameplay. As players move the sensory sphere throughout the game, they are guided both by cues within the game environment and by limitations and rules, or the *structural dynamics*, designed into the game that encourage them along certain game mission paths. *Locational* structural dynamics in *MAX5* work to guide players towards certain places in the game to collect DNA samples or to solve puzzles in labs. Therefore, if players step too far off an intended paths into surrounding terrain or water they would “die” and restart the level, or they face a wall to encourage them along the game goal path. Players of *MAX5* were observed learning, testing, and at times breaking these locational structural dynamics as they explored game paths and interactions that were new or unintended by the game’s designers. *Structural dynamics* in the game are, therefore, more *loosely-coupled*, as there is much that is left exploratory about when and where players can accomplish game tasks.

Symbolic meaning is unlocked in *MAX5* and processed in relation to experiences with previous games played. *Semiotic translation* in *MAX5* occurs in numerous areas within the environment. One particular type of puzzle uses a convention popularized in many commercial first-person shooter games including the *Halo* series and *BioShock*: the use of hidden door passcodes to unlock secret areas. In *MAX5*, players are prompted to find the passcode for a locked door leading to a mission critical lab room. The code is hidden in a visual comparison of a nucleotide sequence that does not correspond to the other sequences (e.g., CCTGGA). Engineering hidden messages within DNA in a similar manner has received attention within the nascent field of genomic encryption (e.g., Jiao & Goutte, 2008). The game narrative suggests that this segment represented a code that can then be used to access a secret lab chamber. Players

familiar with first-person shooter play are likely to have encountered this type of door passcode puzzle in other games and therefore are better adapted to semiotic translation in the game. This convention also gains localized symbolic meaning as players learn that these door passcodes are encrypted within the nucleotide sequence data, a convention particular to the context of *MAX5*. The many symbolic knowledge structures and resultant game outcomes are then stored by the player for future cognitive reference for ensuing tasks within the game. These *Memory-Action Patterns* (MAPs) within *MAX5* are largely *outcome-event* based as evidenced in interviews and in chat logs where players provided highly ordered ways that they take action, subscribe meaning to events, and achieve outcomes in the game.

9.9 THE LAYERS IN CONTEXT OF STEM GAMES

The critical opportunity for educational game designers is a deep integration of desired STEM learning concepts to the game-based learning complex system layers. Examples of this type of integration are described in further detail in the following section. While previous research has suggested that pedagogical concepts appropriately map to certain genres, such as the integration of problem-based learning content to adventure games (e.g., Torrente, 2010), these broader links do not account for the unique capabilities that youth bring to gameplay as offered in the complex system layers described previously in this chapter.

Attention to the *input* layer offers compelling ways to integrate input controls directly into learning areas relevant to STEM careers. Research on lab technicians has shown that they display sensory-motor skills in which they ‘have a feel’ for instruments and materials in a manner that becomes learned and intuitive. Barley (1996) describes how cell culture specialists develop an intuition for this sensory-motor action in a manner that is critical to their workflow where too light or heavy of a touch could impact the survival of cell cultures, making gestural

input a particularly relevant area to explore in this field. Similarly, scientists, doctors, and technicians are increasingly working with distributed equipment and robotics that require a complex and highly physical understanding of buttons and touch inputs in areas such as remote surgery (Shirzadi et al., 2012) and telescope control in astrophysics (e.g., Davignon et al., 2004). In these areas, the learned manipulation of tools using symbolic GUIs is critical to the scientific and medical processes. While biosignal inputs are still relatively new in commercial games, these inputs offer much potential for assisting in learning in fields where emotional attention is important to outcomes including surgery and emergency response. Much further thought and research into how input mechanisms already popular in many commercial games can effectively map to STEM learning pathways is needed. Educational game designers could, further, integrate inputs most relevant to domain specific STEM learning contexts into games while matching these to player capabilities.

In other scientific fields, the use of the *semiotic translation* layer in game-based learning is highly relevant. The identification of symbolic color changes of organic samples is used to quickly detect toxic materials within chemistry (e.g., Zhou et al., 2008). In seismic monitoring of earthquakes (e.g., McNurr, 2000), symbolic mappings of the environment are already a common part of collecting data. Fields such as geo-visual analytics use spatial decisions to support rapid short-term decision-making (e.g., Andrienko et al., 2007), which have overlap with the use of *memory-action patterns* described in the previous sections. All of these areas present intriguing possibilities for integrating STEM concepts more deeply into the game-based learning layers described in this chapter.

CHAPTER 10. CONCLUSIONS

While digital games are played by the vast majority of U.S. youth (Lenhart et al., 2008), they have not reached their potential as educational tools with mixed and conflicting learning and motivational outcomes (e.g., Kebritchi, et al., 2010; Von Wangenheim & Shull, 2009). This disparity is due in part to a fundamental mismatch: while commercial games offer millions of titles and mechanics that youth have stretched their capabilities in playing and learning, many educational games have largely taken a ‘one-size-fits-all’ approach in which designed features are good enough if they appeal to the majority of a classroom. This attitude is seen starkly in game genre selection in which recommended educational genres, such as adventure games, are largely based on educator and designer preference (e.g., Amory, 1999; Dickey, 2006; Torrente et al., 2010) and are only played by 66% of youth (Lenhart et al., 2008). In my research, I advocate for the other 30 – 40% of youth and their diverse game-based learning capabilities. This dissertation examines what it is that youth bring to their gameplay experience that impacts effective game-based learning outcomes and further relates these diverse capabilities to the designed aspects of a science game environment using data from the game *MAX5*.

10.1 KEY FINDINGS

The key findings of this research are as follows:

- Previous genre experience is found to be a significant predictor of learning and affect for an educational science game highlighting the importance of genre choice by designers and educators. A qualitative analysis of interviews suggests that physical presence, an understanding of symbols, and the speed of interactions vary by genre and are factors in how players experience and learn the game environment.

- Types of messages shared in chat are a significant predictor for learning outcomes in an educational science game suggesting the need for scaffolding and support by designers for certain information sharing activities. A qualitative analysis of chat logs shows the importance of accounting for dynamic affect in message sharing behaviors.
- An analysis of multiple data types, both quantitative and qualitative, at different stages of the design process is useful for a robust understanding of learning.
- A complex systems approach is both appropriate and useful for an understanding of game-based learning, and a qualitative data analysis identifies five dynamic layers of interaction between the player and the game environment: the *input*, as players input signals into the game environment to move and interact; the *sensory sphere*, which acts as the extension of players' perceptual selves going from task to task collecting sensory signals along the way; the *structural dynamics*, that work to govern where and how the sensory sphere operates within the game; *semiotic translation*, in which players translate and filter noisy sensory signals into more meaningful information using symbolic encodings; and *memory-action patterns* (MAPs), in which players compare current patterns of behavior to previously stored patterns of behavior to decide on appropriate actions to take. Information and affect are exchanged and stored among these layers and within a larger network of players and games, the *exchange network*. These layers provide an opportunity for game designers to broaden learning by accounting for diverse player capabilities, while mapping these to domain relevant knowledge in STEM.

10.2 OPPORTUNITIES FOR THE FUTURE

The primary data used in this research was collected within the context of a classroom learning environment. The choice of this research environment was highly rewarding and provided an

opportunity to use gameplay to reach a broad array of high school youth and introduce them to bioinformatics and computing topics that they typically would not encounter until university-level biology and computer science courses. This choice of research site also notably shaped the flavor of the research as was immediately apparent in pilot studies. While 97% of U.S. youth might play video games (Lenhart et al., 2008), there were a wide variety of titles, devices, experiences, and capabilities evident in gameplay (Figure 6.2 showing genre experience within a single classroom reflects this diversity). In the classroom setting, I was also able to observe students playing and interacting in a more natural environment than in a lab setting and could follow-up on questions that emerged in a manner I would likely not have been able to do had data been collected solely from online play.

Along with the benefits of this classroom setting, there were several notable challenges. One challenge was that data collection required months of planning to find times that worked with the teacher's curriculum schedule, and it was necessary to book appropriate technological resources. In many of the classrooms used for the study, the computers within the classroom itself were outdated making it necessary to reserve a computer room many weeks in advance. Another challenge was the limited gameplay time provided. Class periods were under one hour making it necessary to provide ample set up time along with gameplay within that hour. This provided a shorter gameplay experience than youth would likely experience at home or in a more informal setting.

These factors, in part, limited the scope of data collected as well as the power of statistical results. Several thousand data points pale in comparison to the terabytes of data a day collected with larger gaming populations (e.g., Alqwbani et al., 2014). That said, there is much opportunity to use the growing number of datasets available from other STEM games to further

apply the findings of this dissertation. In particular the findings on genre, social chat, and learning outcomes are well suited to testing with larger data sets and more agile data collection methods.

One of the more exciting yet challenging opportunities offered by this dissertation is the application of the proposed complex system layers for game-based learning. While Van de Ven's (1989) aptly and boldly titled work proclaims, "Nothing is quite so practical as a good theory", I would add to that, nor as hard and laborious to develop. Innumerable hours have been spent poring over data, jotting down memos, staring in perplexed wonder at arrows on diagrams, and then doing this all over again in the service of getting it right, or, at the very least, one step closer to right as presented in the data.

A complex systems approach to game-based learning provides what I believe is a much needed paradigm shift in how educational games have been understood. While categorizations and typologies of players and learners (e.g., Jovanovic et al., 2008; McCue, 2005; Rapeepisarn, 2008; Yee, 2006;) hold useful truths, I argue in this dissertation for a more dynamic and networked model of game-based learning that has emerged out of the empirical data. In many ways, learning has gone through a similar shift in the past few decades transitioning from static snapshots of behavioral changes to more adaptive models that coevolve with the learner and her or his environment (de Houwer, 2013, Lachman, 1997).

This shift to a more dynamic and complex model of game-based learning for educational games has been in many ways inevitable, and, in this sense, I am merely standing on the shoulders of those that have come before me. Previous work by Holland (2006), Rosas et al. (2003), and Van Bilsen, Bekebrede and Mayer (2010) have long made the connection between complex systems and games suggesting that the interactions in games accurately reflect the

adaptive and emergent processes of complex systems. While Holland has formed useful comparisons across domains as varied as biology, economics, and games (2006), he has also noted the need for understanding differences in how these various systems might apply and operate based on their particular domain context (2012). Chapter 9 offers the building blocks for an applied context of complex systems for game-based learning answering this call to action.

Good theory should both advance knowledge within a scientific discipline while also providing applications for professionals (Van de Ven, 1989). Therefore, I encourage researchers to use the building blocks of the model as described in the five interlinked layers: the *input*, the *sensory sphere*, the *structural dynamics*, *semiotic translation*, and *memory-action patterns (MAPs)*. Test these against your own educational game data sets, use a variety of data collection and analysis methods, and collect data from various perspectives. Tools using eye tracking may be relevant to observing the movement of the sensory sphere or as a manner to process the visual spatial MAPs of players. A/B tests on aspects of semiotic translation could provide compelling insights into whether players' read the game environment differently based on experience or previous gameplay. Interviews and videos of gameplay could provide further insights into how players use inputs effectively. These are just a few of the possible applications of this work. The challenge is then connecting data findings to each other and not treating the game-based learning layers in isolation. When, at times, the model might seem more static than dynamic, more a straightforward system than a complex one, think about how these identified layers are repeated in multiple, if not potentially thousands, of interlinked nodes, forming learning networks of numerous players and numerous games. In this way, the information and affect synopsis of game-based learning connect and disconnect in a dizzying multitude of patterns and structures across many varied contexts of interaction.

I encourage designers to consider how these layers are applicable to various aspects of the game's built environment. Think critically about ways to design and test games that provide more adaptable aspects of gameplay that can better grow and evolve according to the player's capabilities. Teachers and educators: I encourage careful thinking about ways to integrate a multitude of types of games within the classroom, and for you to watch, listen, and observe how members of the class interact with them as part of the "rich experience" of learning (Moran, 2006). Youth: you have been instrumental to the design process of *MAX5* and my thinking on games, I encourage you to continue to find ways of getting your voices and many capabilities heard, in workshops, in classrooms, on chat forums, wherever and whenever educational games are played.

If digital games are truly meant to broaden participation in STEM topics and to attract a diverse group of learners, the entire ecosystem of educational games must do better to understand the diverse gameplay experiences and capabilities of players. This argument is not just one of educational equity, but also one based on a concern for adequately preparing the next generation for careers in science and engineering fields that are all the more multidisciplinary, distributed, and collaborative. The fact that players have diverse gameplay capabilities offers an opportunity for the design of games that better map these player capabilities to attributes of a scientific workforce that increasingly cuts across numerous domains, uses a staggering variety of software and hardware tools, and requires a knowledge base that is not just technical, but also social and innovative in nature.

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