Virtual Reality for Sport Training

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ABSTRACT

Virtual reality (VR) has been successfully applied to a broad range of training domains; however, to date there is little research investigating its benefits for sport training. In this work we investigated the feasibility and usefulness of using VR for two sport subdomains: sport psychology and sport biomechanics. In terms of sport psychology training, high-fidelity VR systems could be used to display realistic 3D environments to induce anxiety, allowing resilience-training systems to prepare athletes for real-world, high-pressure situations. For sport biomechanical training, we could take advantage of the 3D tracking available in VR systems to capture and display full-body movements in real-time, and could design flexible 3D environments to foster a valuable and engaging training experience.

To address using VR for sport psychology training, in this work we present a case study and a controlled experiment. Our work addresses whether a VR system can induce anxiety in participants, and if so, how this anxiety impacts performance, and what the implications are for VR system design.

To address using VR for sport biomechanical training, in this work we present a case study describing the development of a VR-based jump training application. Our work addresses whether an effective VR biomechanical training system can be achieved using standard computer equipment and commodity tracking devices, and how we should design the user experience of a VR sport training system to effectively deliver biomechanical principles.

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1 Introduction

In this work we investigated the feasibility and usefulness of using virtual reality (VR) to support sport psychology and sport biomechanical training. We wanted to determine if the training benefits that have been observed in other VR domains could also generalize to athletics.

VR has been defined as *a 3D computer-generated world seen from a first-person point of view, where the viewpoint is under the real-time control of the user* (Bowman and McMahan 2007). This definition encompasses a broad range of systems, from desktop 3D games to highly immersive head-mounted displays and surround-screen systems. In many VR systems, 3D tracking of the user's head, hands, and/or other parts of the body plays a major role.

We further relax the definition of VR in this work, not requiring a first-person point of view or viewpoint control. In this thesis, we use the term VR to refer to systems displaying a 3D computer-generated world that respond in real time to user input. Thus, game-like systems that involve a 3rd-person point of view of an avatar, or a fixed view of a 3D environment, would be considered VR systems by this definition.

We consider both immersive and non-immersive VR systems in this work. Sport actions are complex and dynamic, and often involve large areas of space and specialized equipment. Immersive systems that encumber athletes with wires and equipment can significantly impact the ecological validity of sport actions. Systems should be designed so that an athlete can interact with the virtual environment in the same manner as a real-life sport scenario.

There is extensive literature demonstrating the benefits of VR technologies. VR technologies have been applied to many domains including phobia therapy, military training, surgical training, entertainment, education, civil engineering, and architecture. Research has demonstrated that VR technologies can reduce anxiety (Rothbaum, Hodges et al. 1995), train motor and cognitive skills (Torkington, Smith et al. 2001), increase enjoyment (Plante, Aldridge et al. 2003), improve spatial understanding (Raja, Bowman et al. 2004), and benefit learning (Pan, Cheok et al. 2006).

Of special interest to our work is the past success of VR for anxiety management. Research has shown that anxiety can be invoked by immersing users in a virtual world, even with full knowledge that the simulation is not real (Krijn, Emmelkamp et al. 2004). The phobia or anxiety can then be treated in a completely safe and controlled environment. This type of therapy presents a unique advantage over in vivo therapy, in that the therapy protocols can be controlled, repeated, and the phobogenic stimuli can be gradually increased.

The past success of VR for training is also very relevant to our work. Using VR, rare and complex scenarios can be simulated, allowing a user to build the necessary skills and abilities before engaging in the task in real life. Examples of such training include: VR for surgical training, VR for military training, and flight simulator training. By providing a highly realistic simulation using VR, training scenarios that are not safe, controllable, or possible in the real world can be practiced, allowing users to develop the confidence and skill to face the real-world tasks (Smith and Steel 2001).

1.1 Hypothesis and Goals

We hypothesized that the success of VR in other domains could also apply to sport training. We specifically inferred that VR could be leveraged to support sport psychology and sport biomechanical training. For sport psychology training, high-fidelity VR systems can be used to display realistic 3D environments to induce anxiety, allowing resilience-training systems to prepare athletes for real-world, high-pressure situations. For sport biomechanical training, we can take advantage of the 3D tracking available in VR systems to capture and display full-body movements in real-time, and can design flexible 3D environments to foster a valuable and engaging training experience.

However, there are several distinctive characteristics of sport training that make this conjecture questionable. For instance, sport actions often occur at very high speeds, require the coordination of complex motor systems, involve a combination of physiological and psychological components, require split-second decision making skills, and often depend on specialized equipment, playing fields, or large areas of space. On the technological side, immersive VR systems are often expensive, permanent, and not necessarily practical for all sport training scenarios. The goal of this work is to investigate the feasibility and effectiveness of using VR for two types of sport training: (a) psychological training, and (b) biomechanical training.

In terms of psychological training, we addressed three key questions:

1. Can VR systems induce feelings of anxiety or stress in sport-oriented applications?
2. How does the anxiety experienced in VR systems impact performance?
3. How do the various aspects of the VR system design influence the extent of anxiety experienced? Do we need fully immersive VR?

In terms of biomechanical training we addressed two key questions:

1. Can an effective VR biomechanical training system be achieved using standard computer equipment and commodity tracking devices?
2. How can we design the user experience of a sport training system to effectively deliver biomechanical principles?

1.2 Background on Sport Training

In the domain of athletics there is a continual demand for new and innovative training regimens. Professional teams employ high-level coaches, and leverage specialized equipment and technology to push the boundaries on human performance. This trend spreads beyond professional sports to youth sports as well. Often fueled by the goal to attain a college scholarship, parents will invest money and time into providing the right training for their child.

However, there are limited technologies for supporting sport training. While some teams do take advantage of video analysis and scouting software, most training is still based of subjective feedback from coaches. Athletes are often limited by the knowledge of their coach; and their full potential left unrealized. Low-income and rural athletes are also at a disadvantage, since it is difficult to develop the necessary skills to be recognized by college coaches without access to high-level training.

We also see a larger problem when we widen our scope and look at the health and fitness industry. Many people are not following the recommended guidelines for fitness and nutrition, and we are seeing a decline in overall health.

There is potential for VR to support both athletic and general populations. VR systems could target both psychological and biomechanical training to improve skill and prepare athletes for critical game situations. VR could also support general populations by providing immersive, engaging systems that encourage physical activity.

1.3 Our Approach

In order to address the research questions regarding the use of VR systems for sport psychology training, we began by conducting an exploratory case study. In the case study we developed an application titled Virtual Goalkeeper, where users defend against penalty kicks in a simulated soccer environment. Users stand in the middle of the VisCube holding a Nintendo Wiimote in each hand, and click the appropriate trigger button when they recognize the kick direction. We developed an exploratory experiment to study the application, and included three independent variables: field of regard (90° vs. 270°), simulation fidelity (low vs. high), and competitive realism (individual vs. pair). In order to assess the level of arousal/anxiety of participants, we included a variety of dependent variables: heart rate, heart rate variability, save percentage, presence questionnaires, user rankings of anxiety, and a post-experiment interview. We tested the application with a small set of elite soccer goalkeepers, and found promising yet inconclusive results. We therefore expanded the application based on the preliminary results of the case study and feedback from the elite goalkeepers, and designed a controlled experiment to study the effects on a broader population. We removed the dependency on Nintendo Wiimotes, and leveraged head tracking to allow users to defend against the simulated kicks using their own bodies. We added additional character animations and crowd sounds to better simulate a penalty-kick situation, and we improved the save vs. miss thresholds to support all ability levels. We designed a controlled study with three independent variables: field of regard (90° vs. 270°), simulation fidelity (low vs. high), and known anxiety triggers (low vs. high) to address our research questions. Our dependent variables for the experiment were: heart rate, heart rate variability, galvanic skin response, STICSA, CSAI-2R, save percentage, reaction time, and post-experiment interviews.

In order to address the research questions regarding the use of VR systems for biomechanical training, we developed a jump training system titled *Extreme Jump Trainer*. The system uses a Microsoft Kinect to track the full-body of the user, and infuses a lateral jumping exercise into a game-like experience. The system records user performance throughout the entire exercise, and provides biomechanical feedback at the end of that trial. The biomechanical feedback is delivered by superimposing the user's performance at key phases of the jump on an ideal model using static images. The feedback is designed to address key elements of proper jumping technique to both improve jumping performance and reduce the potential for future injuries.

1.4 Contributions

This research is expected to provide a worthwhile contribution to the research fields of virtual reality, human-computer interaction, and computer science. This research provides quantitative evidence to demonstrate that anxiety can be induced in a VR sport-training environment, and provides key insights into the system design for anxiety-based sport training applications. This research also demonstrates that an effective VR biomechanical training system can be achieved using standard computer equipment and commodity tracking devices, and provides key insights for how biomechanical training principles should be delivered to achieve maximum results.

This research also has a broader impact on the fields of athletics and health. This research presents new and innovative ways to deliver training to athletes that are not dependent on coaches or athletic facilities. The sport psychology contributions could be used in conjunction with existing sport-induced anxiety therapy protocols to help athletes visualize high-pressure situations, and could even be useful for conducting sport psychology research. The biomechanical contributions could reduce the amount of time athletes need to be in the gym working with coaches, and help prevent long-term injuries. It could also allow low-income or rural athletes access to high-level biomechanical training for a low-cost.

2 Related Work

In this work, we were interested in investigating the feasibility and effectiveness of using VR for two types of sport training: (a) psychological training, and (b) biomechanical training. In the following sections we will review the existing research and important findings from each of the two fields.

2.1 VR for Sport Psychology Training

Using VR as a platform to administer sport psychology training represents a new direction in research, and there is limited previous work investigating its feasibility. So in order to fully describe the motivations for our work, we will present research from a variety of domains that influenced our investigations. We will begin by providing a background on the field of sport psychology, and describe its relevance to sport performance. We will then discuss why VR is a good candidate for supporting sport psychology training, and present the important findings from existing applications and research in the domain. Since this research is limited, we will then discuss the related fields of VR for anxiety, VR for military training, and flight simulator training. Finally, we will summarize the key points from the related work, and discuss the important considerations for our research.

2.1.1 Background on Sport Psychology Training

Sport psychology is an interdisciplinary field that involves the study of how psychological factors affect sport performance (Weinberg and Gould 2010). While there are many different branches of sport psychology, for our work we are most interested in the analysis and treatment of *competitive anxiety*. Often commonly associated with the term ‘choking’, competitive anxiety can be defined as *“a tendency to perceive competitive situations as threatening and to respond to these situations with feelings of apprehension and tension”* (Martens, Vealey et al. 1990).

An athlete experiencing competitive anxiety will often make poor decisions in high-pressure situations, and fail to perform as he/she is expected. It has been theorized that this decrease in performance is associated with cognitive processing; that anxiety is expressed in the mind as cognitive thoughts of fear and worry, and reduces the mental capacity of an athlete to focus on the relevant elements in the sport task (Eysenck, Derakshan et al. 2007, Oudejans and Nieuwenhuys 2009). Wilson et al. investigated this theory in a controlled study with basketball athletes (Wilson, Vine et al. 2009). Athletes performed basketball free throws in both low and high anxiety conditions. In the high anxiety conditions, athletes were given negative feedback. The results demonstrated that the athletes experienced impaired cognitive processing (measured by visual scanning patterns) and decreased performance in the high-anxiety conditions.

Even though high levels of anxiety can negatively impact performance, it is important to note that optimal performance is not achieved by completely eliminating anxiety. The physiological changes that occur in athletes with controlled levels of anxiety (or arousal) are initially beneficial to sport performance (Gelinas and Munroe-Chandler 2006). Rather, optimal performance is achieved by maintaining an optimal level of anxiety. This is demonstrated by the Hebbian version of the Yerkes/Dodson law of arousal vs. performance (see Figure 2.1) (Diamond, Campbell et al. 2007). The Hebbian version is based on the original Yerkes/Dodson law (Yerkes and Dodson 1908); however, focuses on the inverted-U shaped curve corresponding to complex tasks. Initially, anxiety has an energizing effect on performance by increasing the attention and interest; however, after some threshold anxiety begins to have a negative impact and impairs performance. This relationship has been studied extensively, and has been validated in many research studies involving both animals and humans (Broadhurst 1959, Anderson 1994).

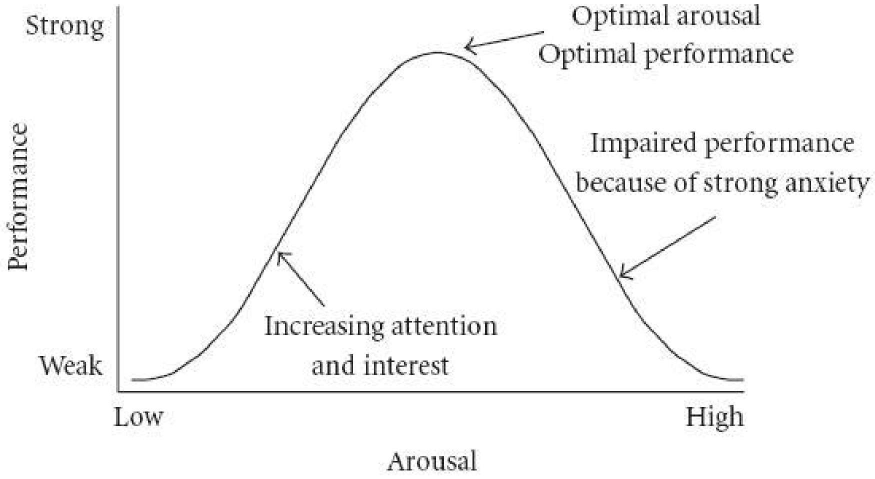


Figure 2.1: Hebbian version of the Yerkes/Dodson law of arousal vs. performance (Diamond, Campbell et al. 2007).

[Fair Use]

There are several techniques to train athletes to manage competitive anxiety and achieve optimal levels of arousal during competition. A common and widespread method is to have athletes practice in high stress situations. This is the standard practice for many athletic teams, where coaches arrange drills and scenarios in practice to mimic competitive situations. Often coaches put pressure on athletes by threatening physical punishment (i.e., sprints, pushups), providing negative criticism, and yelling/shouting at the team members. There have been numerous studies demonstrating that training in a high-stress environment leads to improved performance in future competitive situations. (Oudejans and Nieuwenhuys 2009, Oudejans and Pijpers 2009, Nieuwenhuys and Oudejans 2011, Oudejans, Kuijpers et al. 2011).

Sport psychology research has demonstrated that another, and possibly more effective, method for preparing athletes for high-pressure situations is *sport imagery* (also referred to as *visualization* and *mental practice*) (Short, Ross-Stewart et al. 2006). As defined by Moran et al., sport imagery is *"the ability to represent in the mind information that is not currently being perceived"* (Moran 2002). Sport imagery is a heavily researched field, and it has been demonstrated that athletes who habitually employ imagery techniques exhibit characteristics such as: increased confidence, reduced anxiety, better technical execution of skill, and improved performance (Moran 2002, Short, Ross-Stewart et al. 2006). However, there are two primary issues limiting the success of sport imagery. For one, the subjective nature of the activity makes it very difficult to study and analyze. Researchers are still trying to define what constitutes an effective sport imagery session, and sport psychologists are greatly varied in the techniques they choose to promote (Moran 2002). Another issue limiting sport imagery's success is the individuality of the practice. Since sport imagery is completely based on an athlete's ability to generate mental scenarios, the success of the therapy is correlated with the individual's imagery abilities.

While there are varied methods of sport imagery, it has been found that athletes who focus on imagery of successful performance generally have the highest levels of perceived confidence, and succeed more often than those who practice other (or no) imagery techniques (Short, Ross-Stewart et al. 2006). It is therefore no surprise that when comparing elite and novice athletes, elite athletes were found to embody better imagery practices and have a higher success rate during performance (Greenleaf, Gould et al. 2001, Moran 2002).

Even though sport psychology practices such as sport imagery have been proven to be beneficial for athletes, there are very few athletes who choose to seek out help (Ferraro and Rush 2000). In a controlled study investigating the perceptions high school and college athletes hold towards sport psychology, it was found that many athletes avoid services because of the stigma associated with seeking help (Martin 2005). It has also been theorized that the avoidance could be related to typical patterns of resistance seen in clinical psychology; where individuals avoid therapy services because they are afraid of confronting the emotions underneath the surface problems (Ferraro and Rush 2000).

2.1.2 Why We Believe VR Can Help

Virtual reality poses an interesting option for sport psychology training. It could support both high-stress training and sport imagery, and even foster additional control for coaches and sport psychologists to manage the training.

In terms of high-stress training, VR could be used to simulate large crowds, specific environments, and recreate key situations for athletes. Using VR as a platform to administer such training would also allow precise control of the flow and administration of the training. Tasks could be repeated multiple times, and replays of the simulation could be viewed to enhance learning.

VR could also support sport imagery. By simulating key environments and scenarios in a VR system, athletes would not be limited by their own sport imagery skills. This would free athletes from the cognitive load of imagining such a situation, and allow them to focus on the relaxation and cognitive therapies for improving performance.

We also believe using VR could help address the stigma associated with traditional sport psychology practices. We suspect that the 'coolness' factor of VR technologies would interest many athletes, and allow their perceptions to be changed.

2.1.3 Prior Work Using VR for Sport Psychology

The existing research regarding VR for sport psychology training is rather anecdotal in nature. Sorrentino et al. developed a head-mounted display (HMD) system that allowed speed skaters to prepare for the 2002 Winter Olympic Games (Sorrentino, Levy et al.). An environment of the competition venue was created, and the system allowed the athletes to navigate within the scene and become acclimated to the surroundings. The athletes reported positive experiences with the system, but no controlled experiment was performed to validate the observations. Another recent study also looked at using VR to assist a golfer in learning relaxation techniques (Lagos, Vaschillo et al. 2011). Biofeedback training was administered to a college athlete using a golf simulator over a 10-week period, and psychometric tests and physiological measurements were recorded. The results demonstrated that the athlete had improved anxiety control after using the training system. The authors plan to study the protocol with a larger population of athletes to validate the findings.

While both of these studies suggest using VR for sport psychology training would be beneficial, controlled experiments are needed to validate the feasibility and effectiveness of the systems.

2.1.4 Prior Work Using VR in Similar Domains

Since there was limited research involving VR for sport psychology training, we expanded our literature review to include a variety of related research areas. In this section we will describe the findings from three research domains: VR exposure therapy (VRET), VR for military training, and flight simulator training.

2.1.4.1 VR Exposure Therapy

Perhaps the most influential VR domain in terms of anxiety is virtual reality exposure therapy (VRET). VRET has a (relatively) long history, and is actively used in mental health therapy to treat a large variety of phobias including: arachnophobia, acrophobia, fear of public speaking, and post-traumatic stress disorder (PTSD) (Rothbaum, Hodges et al. 1995, Rothbaum, Hodges et al. 2000, Rothbaum, Anderson et al. 2006, Powers and Emmelkamp 2008). VRET combines VR and therapy to allow phobic patients to systematically work through their fears in a completely safe, controlled environment.

The success of VRET is largely due to the graded-exposure methodology, where the flow of the therapy is carefully controlled to gradually increase the anxiety level in the environment as the patient accommodates to the stimuli (Rothbaum, Hodges et al. 1995). As Krijn et al. describe in their review of VRET research, in order for VRET to be effective the following conditions should be met (Krijn, Emmelkamp et al. 2004):

1) Patients need to feel present in the virtual environment
2) The environment should be able to elicit emotions
3) The cognitive changes need to be generalizable to real-life situations

Krijn et al. also describe several advantages of VRET over in vivo therapies, such as cost effectiveness, ability to control the sequence and intensity of treatment, and ability to repeat assignments multiple times. To further this point, research has demonstrated that VRET is comparable in effectiveness to traditional, in vivo phobia therapies (Emmelkamp, Krijn et al. 2002, Rothbaum, Anderson et al. 2006, Powers and Emmelkamp 2008).

Interesting considerations in the administration of VRET are the concepts of *immersion* and *presence*. As defined by Slater, *immersion* refers to the objective level of sensory fidelity a VR system provides, and *presence* refers to the user's subjective psychological response to a VR system (Slater 2005). Research in the field of VRET has demonstrated that even low immersion systems can still trigger anxiety and a high sense of presence in phobic patients (Robillard, Bouchard et al. 2003, Krijn, Emmelkamp et al. 2004). However, research regarding anxiety in general (non-phobic) populations demonstrates that higher levels of immersion increase the presence and anxiety users experience in a VR system (Meehan, Insko et al. 2002, Slater, Khanna et al. 2009). In Slater et al.'s study, participants wore an HMD and were immersed in an environment depicting a precipice. The environment for one group of participants was rendered with real-time recursive ray tracing with shadows and reflections, and the environment for the other group used ray casting with no shadows or reflections. Participants in the recursive ray-tracing group exhibited increased galvanic skin response values, and higher presence scores. Meehan et al. conducted three experiments comparing a non-threatening virtual room environment to a stressful virtual heights simulation to gauge the usefulness of physiological measurements. Results demonstrated that the stressful environment caused increased heart rate and increased galvanic skin response in participants.

2.1.4.2 VR for Military Training

We also gain some important insights from looking at the domain of VR for military training. Using VR for military training has become a common practice, because: it is economical compared to field training; tasks are repeatable; trials are reviewable and analyzable; and it allows control over the simulation (Smith and Steel 2001). There are a wide variety of VR military training systems targeting different military tasks, but in this review we were only concerned with systems associated with anxiety.

Military tasks involve the complex coordination between physiological, cognitive, and emotional systems. Deployed soldiers must face extreme circumstances in combat, and often need to make critical, high-pressure decisions. It is therefore important that the training appropriately prepares them for the combination of physical and emotional situations they will face in combat. Research has demonstrated that it is important for VR training systems to provide an ecologically valid experience (Cruz-Neira, Reiners et al. 2011, Williamson, Wingrave et al. 2011). Allowing soldiers to interact in the VR training system the same way they would in combat fosters improved learning and training transfer. Research has also demonstrated that using emotionally evocative training scenarios that closely resemble real-life scenarios the soldiers may face is crucial to induce the appropriate psychological reaction in training simulations (Rizzo, Morie et al. 2005).

Many soldiers also struggle in post-combat recovery, as it is common for post-traumatic stress disorder (PTSD) to develop after the extreme circumstances of war. Research has demonstrated that VRET protocols can be applied to soldiers suffering from PTSD with great success (Reger, Gahm et al. 2009, Rizzo, Reger et al. 2009), and are possibly even better than in vivo treatments (McLay, Wood et al. 2011). Recently, researchers have also started looking at using VR for stress resilience training (Rizzo, Buckwalter et al. 2012). The concept is to prepare soldiers for the psychological stress they will face in combat by using stressful VR training scenarios that closely resemble combat situations, and to use physiological measurements to key out individuals with biomarkers that might predispose them to PTSD.

2.1.4.3 Flight Simulator Training

Flight simulators have been used for decades to support pilots in aviation training. Training in a simulator allows pilots to learn airplane controls in a safe, controlled manner before flying in a real airplane. Simulator training also supports pilots to develop the appropriate skills and confidence to make fast, complex decisions in emergency situations.

Recently research has looked at incorporating stress training into flight simulator applications (McClernon, McCauley et al. 2010). McClernon et al. compared two groups of pilots, one trained in a normal simulator environment, and the other trained in the same simulator environment with a cold pressor applied to the left foot at 9°C. Both groups were then compared in a simulated meteorological storm scenario. The results demonstrated that the stress-trained group performed better in the storm scenario, both in terms of smoothness of flight and performance evaluations.

2.1.5 Key Implications

The previous research related to VR for sport psychology training highlights a number of key points for us to consider in our work. First, it is important to consider that the goal in treating competitive anxiety is not to eliminate all anxiety, but to achieve a level of arousal where performance is optimized. It will be important for us to look at a combination of physiological, subjective, and performance measures to get a complete perspective on how anxiety is impacting our participants.

The related work provides some anecdotal evidence to support the potential of using VR for sport psychology training. The potential is further strengthened by the success of VRET, VR for military training, and flight simulator training. However, an important foundation in VRET therapy is that the simulation needs to trigger an anxious reaction in the patient for the protocol to be effective. Therefore, the first step in exploring the feasibility of VR for sport psychology training is to determine if a simulated sport environment can trigger anxiety in participants.

If anxiety can be triggered in participants, then an interesting next step would be to examine the relationship between immersion and the level of anxiety experienced. In VRET, several studies have demonstrated that low fidelity systems can effectively trigger anxiety in patients. However in non-phobic patients, research has demonstrated that the amount of anxiety experienced is correlated to the immersive qualities of the VR system. The anxiety an athlete experiences likely falls somewhere between phobic and non-phobic users, so it would be interesting to investigate the impact of immersion on competitive anxiety in a VR sport psychology system.

The related work also highlights some important characteristics for creating successful VR anxiety training systems:

- The systems should elicit high sensations of presence in the users.
- The systems should engage the users emotionally.
- The training elements should be transferable to real-life situations.
- The training tasks and simulation scenarios should be ecologically valid. Ideally, users should be able to interact with the training system in the same manner they would engage the scenario in real life.

2.2 VR for Sport Biomechanical Training

Our work also investigates the potential of using VR as a platform for sport biomechanical training. We should note that in this section of our work we were not investigating VR in the traditional sense (i.e. stereoscopic displays, 3D visualizations), but rather in the sense of a 3D virtual environment with interactive user control. In this section we will begin by providing a background on sports biomechanics. We will then discuss why VR is a good candidate for supporting sport biomechanical training, and present the important findings from earlier work in the field. Since the research is limited, we will also present related findings from the research domains of VR for surgical training and VR for sport enjoyment. We will then summarize the key points from the related work, and discuss the implications for our research.

2.2.1 Background

Biomechanics is defined by Boone et al. as "*the study of the structure and function of biological systems by means of the methods of "mechanics" – which is the branch of physics involving analysis of the actions of forces*" (Boone 2013). In sports biomechanics, the objective is to analyze and improve the mechanics, or movements, of an athlete. There are generally two main objectives in sports biomechanics: (1) to improve athletic performance, and (2) to reduce the potential for injuries (Linthorne 2001, Lees, Vanrenterghem et al. 2004, Yu, Lin et al. 2006, DiStefano, Padua et al. 2010).

Traditionally, sport biomechanical training is accomplished by visually assessing athletes in practice. Coaches use their experience and knowledge to provide feedback to the players. However, knowledge and perceptual abilities vary drastically from coach to coach, and sport biomechanical training tends to be delivered more through general guidelines than calculated principles. In high-level athletics, it is common to use video analysis to improve the efficacy of the training. Coaches often compare videos of a specific athlete to videos of an expert to determine specific issues to address. However, this type of analysis cannot be done in real-time, and requires precise setup to obtain video from specific angles. Recently, 3D analysis has emerged in the athletic domain, and there are a number of commercial options available to athletes. However, these analyses are expensive, require the careful setup and calibration of multiple video cameras, and involve extensive offline processing of the data.

2.2.2 Why We Believe VR Can Help

We propose that there is potential for VR to support sport biomechanical training. Being able to analyze complex sport actions and provide feedback in real-time would be greatly beneficial to the athletics domain. Athletes could get immediate feedback on their performance, and even visualize their actions from multiple viewpoints and angles. 'Ideal' models could also be superimposed on the visualizations to provide athletes with visual representations of how to improve, and provide real-time feedback on what the body is doing.

Adding VR sport biomechanical tools to current training practices would also foster consistent, quantitative sport training. Coaches would not need to rely on their own knowledge to train athletes; but could allow the technology to provide consistent, reliable feedback.

Recently, commodity tracking hardware has become readily available to the public. Devices such as the Microsoft Kinect provide low-cost, accurate, full-body tracking in real-time. We believe that combining VR sport biomechanical training and commodity devices is an exciting possibility. High-level training could be provided to a broad audience of athletes, allowing rural and low-income athletes access to otherwise unavailable training options. VR sport biomechanical training systems could even be targeted to young athletes to teach proper techniques to reduce the risk of injuries from poor biomechanics.

2.2.3 Prior Work Using VR for Sport Biomechanical Training

There have only been a few research studies investigating the feasibility of using VR for sport biomechanical training. Chua et al. developed a VR Tai Chi training system using wireless tracking and a lightweight HMD to investigate if training benefits could be observed by exploiting training modalities that are not possible in the real-world (Chua, Crivella et al. 2003). In the system, users followed the instruction of a virtual trainer to learn basic Tai Chi movements. The system was studied using five different training modalities: (1) one on one, (2) four teachers, (3) four teachers and four students, (4) five normally rendered students with superimposed red wireframe teachers, and (5) five wireframe and transparent students with a superimposed red stick figure teacher (see Figure 2.2). A controlled between-subjects study was conducted to determine any of the conditions were more effective in delivering Tai Chi principles. The results indicated that none of the conditions varied significantly in their effectiveness to deliver Tai Chi instruction. This suggests that there is not a significant advantage to the training modalities that are only possible in a VR environment. However Chua et al. describe how the system featured a high latency (170ms) that may have impacted the results.

(a) One on One (b) Four Teachers (c) Side by Side

(d) Superimposition 1 (e) Superimposition 2

Figure 2.2: The five training modalities employed in Chua et al.'s VR Tai Chi training system (Chua, Crivella et al. 2003). [Fair Use]

More recently, Eeaves et al. have studied the potential of combining real-time tracking and large screen display for teaching a dance task (Eaves, Breslin et al. 2011). In the application, users stood in front of a large projection screen that displayed a video of an expert performing a dance task. The real-time position data for the participant was tracked using a Vicon Motion Capture system, and specific joint locations were superimposed on top of the expert in the video (see

Figure 2.3). There were three variations for the biomechanical feedback: full feedback (16 points of interest superimposed on the expert), reduced feedback (4 points of interest), and no feedback. The results demonstrated that the reduced feedback condition was the most effective at training the dance task. This suggests that providing limited but relevant feedback to athletes in a VR sport biomechanical system is more beneficial than providing full feedback.

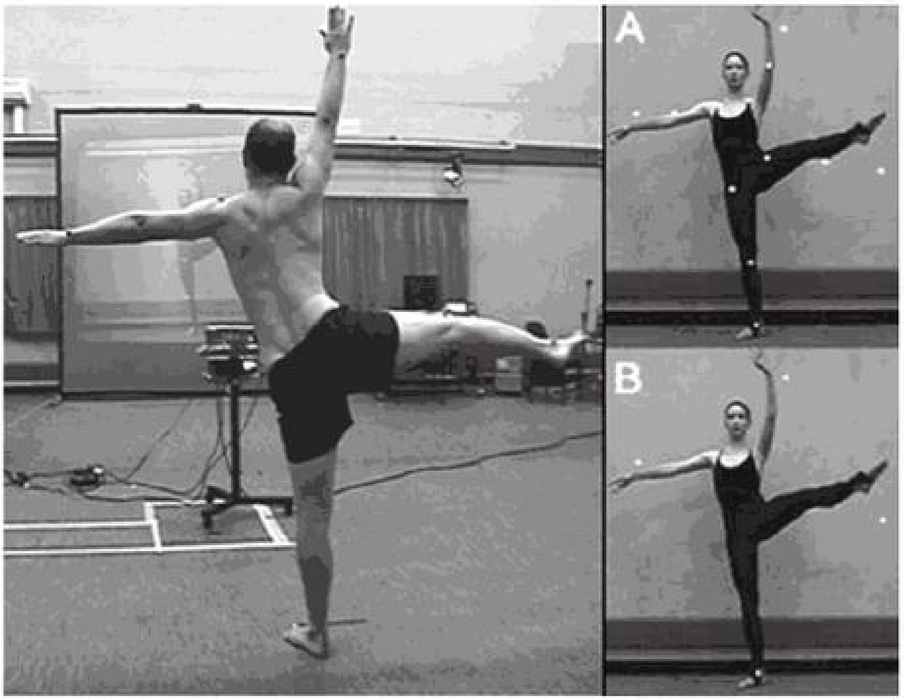


Figure 2.3: The system setup for Eaves et al.'s real-time dance training system (Eaves, Breslin et al. 2011). (A) Depicts how the biomechanical data was displayed in the full feedback condition, (B) the reduced feedback condition.

[Fair Use]

VR has also been used to explore the usefulness of sport biomechanical training in a non-real-time system (Kelly, Healy et al. 2010). Kelly et al. developed a VR system for analyzing previously recorded golf swings. The system allows athletes or coaches to analyze performance by comparing the biomechanical actions of a given golfer to an ideal model. The ideal model is computed from a variety of expert users. The two performances (user vs. ideal) can then be visualized within the system, and viewed from various viewpoints and at various speeds. The system also highlights joints of interest throughout the visualization, to represent the biomechanical factors that differ the most from the ideal model. No controlled study was performed to assess the usefulness of training within the system.

2.2.4 Prior Work in Similar Domains

Since there was limited research involving VR for sport biomechanical training, we expanded our literature review to include related research from two other domains: VR for surgical training, and VR for sport enjoyment.

2.2.4.1 VR for Surgical Training

There is extensive research regarding the use of VR for surgical training. VR surgical training is relevant to our work, as both surgery and athletics involve a complex combination of motor and cognitive skills. By looking at the successes of VR for surgical training, we can gain insight into important elements to factor into the design of VR sport biomechanical training systems. The premise in VR surgical training systems is simple – allow medical students or doctors to practice surgical procedures and develop the necessary preoperative skills before operating on a live patient (Torkington, Smith et al. 2001). Several studies have demonstrated that training in VR surgical simulations is beneficial for developing surgical skills (Gallagher, Ritter et al. 2005) and reducing error rates (Ahlberg, Enochsson et al. 2007), and that the training is transferable to surgeries on live patients (Seymour, Gallagher et al. 2002). Recent studies have also shown that allowing surgeons to warm-up in a short VR simulation before beginning a Laparoscopic task improves their efficiency (Calatayud, Arora et al. 2010).

One of the most important factors for skill acquisition in VR surgical training is the ecological validity of the simulation (De Visser, Watson et al. 2011). De Visser et al. describe how VR surgical training systems need to provide high levels of visual, haptic, and dynamic realism. Virtual organs and tissues need to be visualized with correct texture and color; the system needs to provide accurate haptic feedback when organs and tissues are touched; and the organs and tissues need to behave as they would in real life. Essentially, the simulation needs to be highly relatable to the real-life surgical task for effective training transfer.

2.2.4.2 VR for Sport Enjoyment

While not intended to improve the biomechanical technique of an athlete, there are a number of VR sport systems that are designed purely for enjoyment. Sport simulators are a great example, and have seen tremendous success in the commercial sector. Some simulators do provide basic biomechanical feedback, but for the most part sport simulators are designed to foster a visually stimulating and novel experience. The standard sport simulator consists of a large screen display, some form of user tracking, and an open area for the user to perform a stationary athletic task. Golf simulators are the most prominent, but simulators exist for a wide variety of sports including skiing, snowboarding, basketball, soccer, baseball, football, cycling, and hockey (http://www.eballinternational.com/ , http://www.sportsentertainmentspecialists.com/MultiSportSimulators/). Extensive detail is generally put into the visual detail of the virtual environment. The success of sport simulators suggests that an interactive experience with a sports-oriented system is exciting for many users. By putting care and detail into the simulated environment, many users will be excited and motivated to interact with the system.

This is supported by a research study by Plante et al., where a VR-based cycling system was developed to determine if an engaging experience could enhance the psychological benefits of exercise (Plante, Aldridge et al. 2003). A study was conducted with three between-subjects conditions: (1) bicycling at a moderate intensity on a stationary bike, (2) playing a VR computer bicycle game, or (3) an interactive VR bicycle experience on a computer while exercising on a stationary bike at moderate intensity. The results suggest that VR paired with exercise enhances enjoyment, energy, and reduces tiredness.

2.2.5 Key Implications

The previous research related to VR for sport biomechanical training provides evidence that training benefits can be achieved in a VR environment, and highlights several key characteristics for achieving maximum training effectiveness:

- The systems should limit the biomechanical feedback to a small set of important training elements.
- The training tasks and simulation scenarios should be ecologically valid to achieve the best training transfer to real-world activities. Precise tracking and accurate simulation of the task are especially important for biomechanical training.
- The systems should leverage fun, engaging elements to motivate users.

3 Case Study: Virtual Goalkeeper

Figure 3.1: Screenshot of the virtual goalkeeper application (high simulation fidelity environment)

3.1 Introduction

In order to the study the potential of VR for training elite athletes for high-pressure athletic situations, we developed a virtual goalkeeper application for the VT Visionarium VisCube (see Figure 3.3). In the application, participants defend against penalty kicks in a simulated soccer environment (see Figure 3.1). Participants hold a Nintendo Wiimote in each hand, and press the trigger button on the corresponding Wiimote to indicate the direction of the ball. We designed an exploratory study for the system with three independent variables: field of regard (FOR), simulation fidelity (SF), and competitive realism (individual versus pair conditions). The participants for our study were three elite soccer goalkeepers, all with Division 1 goalkeeper experience. During the experiment we tracked the participants heart rate (HR), heart rate variability (HRV), and used presence questionnaires and user rankings to gauge their mental states.

The results indicate that neither presence questionnaires nor user rankings are very useful for determining the level of anxiety experienced in a given condition. The presence questionnaires and user rankings contradicted each other in terms of competitive realism, and did not correlate to the physiological data. Perhaps using validated questionnaires for gauging anxiety would be a better solution for future research. Anecdotally, the presence questionnaires and user rankings did seem to indicate that increasing the fidelity of the system in terms of FOR and SF increased the anxiety experienced by the participants. In terms of physiological reactions, the high FOR/high SF conditions were the only conditions to elicit a visible spike in the HRV data (excluding the initial condition of each session). This suggest that there may be an interaction between FOR and SF, with the combination of the two causing higher levels of anxiety in participants.

The results of the experiment are encouraging, and suggest that both FOR and SF are influential in triggering anxiety in participants. However the low number of participants and confounding factors in the experimental design made the results difficult to interpret. Further research with larger subject pools, counterbalanced conditions, and validated, anxiety surveys is needed before any conclusions can be drawn.

3.2 Background and Motivation

In this study, we wanted to investigate whether a VR system could be beneficial for training elite athletes for high-pressure situations. Based on our background research (see Chapter 2), we knew that anxiety was associated with immersion and a user's sense of presence in the virtual environment (Robillard, Bouchard et al. 2003, Krijn, Emmelkamp et al. 2004). Therefore in this study we wanted to investigate whether a highly immersive system could trigger anxiety in an elite athlete, and if so, to what effect did the immersive components of the system impact the anxiety.

We wanted to see how immersion impacted anxiety in VR for sport psychology systems, so we decided to look at two immersion elements: field of regard (FOR) and simulation fidelity (SF).

3.3 Experimental Design

To investigate the potential benefits of VR for training elite athletes for high-pressure situations, we designed an experiment targeting soccer goalkeepers. We specifically selected the penalty kick situation as our task, since the interaction required relatively little equipment, and the application could be developed without too many constraints. Other high-pressure athletic situations such as putting in golf and free throws in basketball presented design issues that we did not wish to tackle in this initial exploratory study. We chose a within-subjects design, since we were interested in observing the individual differences between the various conditions.

3.3.1 Goals

Our main goal in designing this study was to investigate whether a VR penalty kick simulation could trigger the same physiological response that athletes experience in game situations. We wanted to see if our VR application could cause changes in heart rate and heart rate variability, and to explore how different components of immersion and realism affected these changes.

Since this was an exploratory study, we also desired to gain knowledge and experience in the field to inform future directions for the research.

3.3.2 Hypotheses

Our hypotheses for the study are as follows:

Hypothesis #1 (H1): Increasing the level of each of the three independent variables (FOR, SF, competitive realism) will cause an increase in anxiety.

Hypothesis #2 (H2): Competitive realism will be most significant variable in terms of induced anxiety, followed by simulation fidelity, and finally FOR.

3.3.3 Apparatus

The study was conducted using the VisBox VisCube in the VT Visionarium lab at Virginia Tech (see Figure 3.3). The VisCube is a 4-walled CAVE-like projection system, with each wall having dimensions of 10' x 10', and featuring a resolution of 1920 x 1920 pixels (see Figure 3.2). The application was projected in stereo with head tracking using an Intersense IS-900 tracking system. Users wore stereo glasses, with a wireless head-tracker mounted to the top frame (see Figure 3.3). Suunto heart rate monitors and a USB receiver were used to track and record user heart rates in real-time (see Figure 3.4). Users held a Nintendo Wii Remote (or "Wiimote") in each hand, and only the 'A' button was enabled for interaction (see Figure 3.4). Participants would press the 'A' button to start each trial, and to indicate which direction they believed the ball to be traveling.

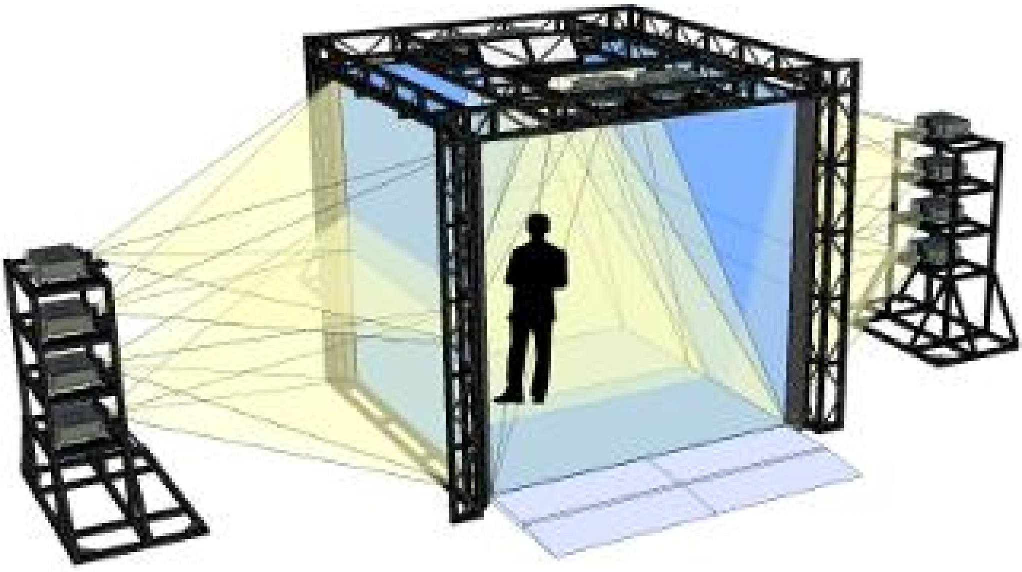


Figure 3.2: Graphical depiction of the VisCube display.

Figure 3.3: The VT Visionarium VisCube (L), and stereo glasses with a mounted IS-900 wireless tracker (R).

The sport stadium models and character meshes were developed using Google Sketchup, and real motion capture data was added to the characters using the Biped tool in 3D Studio Max. The motion capture file was acquired from the Carnegie Mellon University Graphics Lab Motion Capture Database (http://mocap.cs.cmu.edu/). Six unique ball flight variations (three left and three right) were developed using the Havoc 3 physics engine in 3D Studio Max.

The software application was developed using X3D encoding the Instant Reality framework. The application was displayed on the VisCube using Instant Reality's Instant Player. Suunto Training Manager Lite software was used to track the heart rate data.

Figure 3.4: Participants held a Wiimote in each hand (L). Heart rate was recorded with a Suunto chest strap (R).

For each trial participants stood in the middle of the VisCube in an athletic stance with one Wiimote in each hand. Each kick animation was initiated by pressing the ‘A’ button on either Wiimote. Participants indicated the direction (left or right) they thought the ball was traveling by pressing the ‘A’ button on the remote in the appropriate hand. Only responses that occurred after the kicker contacted the ball, and within a limited time window were registered as correct. During the individual session this window was set to 250ms, however due to low user performance the value was increased to 300ms during the pair session.

Two forms of feedback were used to indicate correct identification of the kick: one visual and one haptic. The visual feedback was a scoreboard displayed within the environment that updated after each animation. For haptic feedback, the Wiimote in the appropriate hand would vibrate if the participant guessed the correct ball direction.

3.3.4 Independent Variables

The three independent variables in our application were managed as follows:

Field of Regard (Low vs. High)

Our first independent variable was field of regard (FOR), for which we had a low and a high condition. FOR is defined as *the total size of the visual field (in degrees of visual angle) surrounding the user* (Bowman and McMahan 2007). We thought it would be interesting to investigate FOR in our study, since athletes rely extensively on their peripheral vision in athletics (Knudson and Kluka 1997).

For the low FOR conditions, only one wall of the VisCube was turned on, for a total horizontal FOR of 90° deg. For the high FOR conditions, all four walls were used for a total horizontal FOR of 270°.

Simulation Fidelity (Low vs. High)

Our second independent variable was simulation fidelity (SF), for which we had a low (practice-like) and a high (game-like) condition. SF is defined as *the degree to which a model or simulation reproduces the state and behavior of a real world object, feature or condition* (Hays and Singer 1989). In real-life game situations, athletes are often surrounding by crowds, stadiums, and large playing arenas. We thought it would be interesting to investigate whether a game-like environment would contribute to anxiety more than a practice-like environment.

In the low SF (practice-like) conditions, the environment featured a simple green field, a net, a kicker and ball, and a floating scoreboard (see Figure 3.5). In the high SF (game-like) conditions, the environment featured a large stadium, textured spectators, a realistic scoreboard, ambient crowd noise, teammates, opponents, and referees (see Figure 3.6).

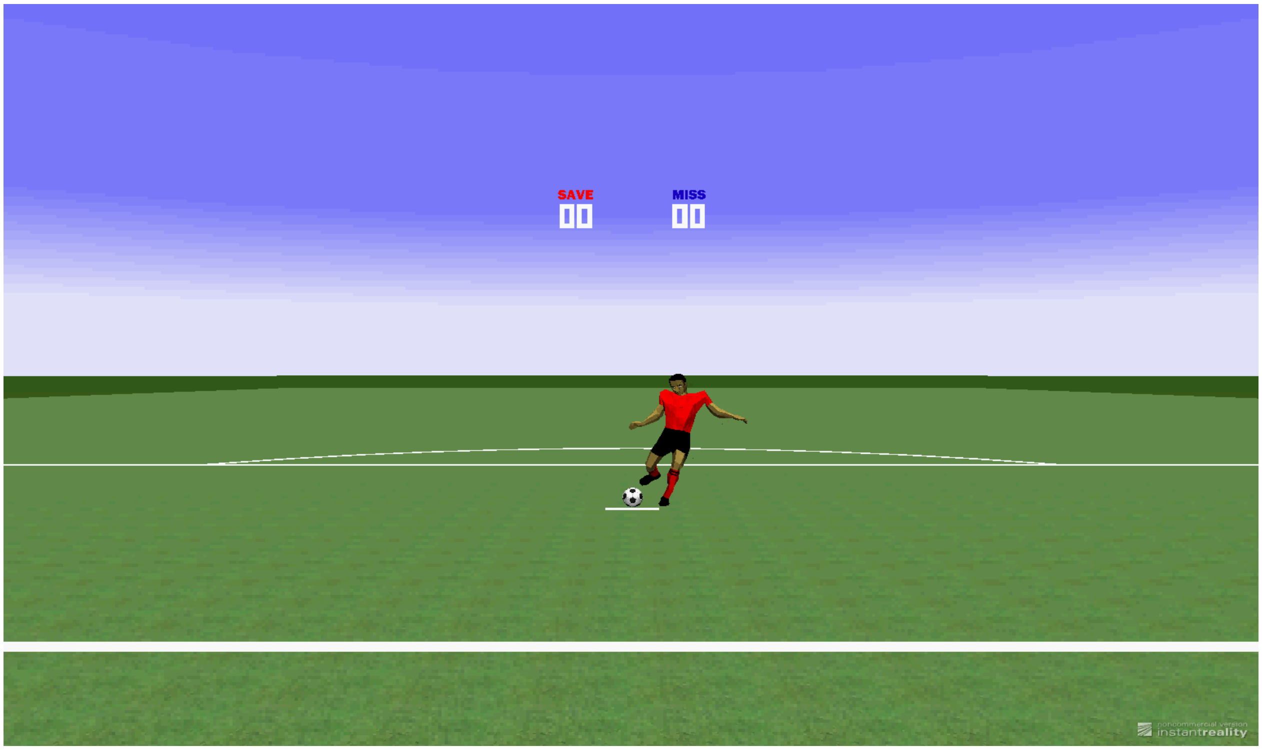


Figure 3.5: Screenshot of the low simulation fidelity environment (Stinson_CA_T_2013_videos.mp4, 17 MB).

Figure 3.6: Screenshot of the high simulation fidelity environment (Stinson_CA_T_2013_videos.mp4, 17 MB).

Competitive Realism (Individual vs. Pair)

Our final independent variable was competitive realism, for which we had an individual and a pair condition. We wanted to see if the natural competitiveness between the athletes would produce changes in their performance and physiological responses.

In the individual conditions, participants were alone in the lab and faced 25 consecutive kicks in each condition. The kicker would vary randomly, but would always be wearing a red jersey. During individual conditions the virtual scoreboard kept track of saves and misses. In the pair conditions, two participants competed against one another in a simulated penalty kick shootout. The virtual scoreboard depicted an actual game scenario, and would update each time the simulated kicker was successful (when the goalkeeper was incorrect). During pair conditions the two active participants alternated. After a participant finished a trial he would hand off the stereo glasses, head tracker, and Wiimotes to the other participant.

3.3.5 Measures

For our study we chose to keep track of the following measures:

- Heart rate (HR), heart rate variability (HRV)
- Performance (saves/misses)
- Presence
- Pre/post experiment questionnaires
- Informal interviews

3.3.5.1 Heart Rate (HR) and Heart Rate Variability (HRV)

We chose to include HR in our experiment, since our background research indicated that HR was a useful measure of anxiety in virtual environments (Meehan, Insko et al. 2002). We also included HRV, since it is known to be a finer-grained measure of anxiety than HR alone (Friedman and Thayer 1998).

There are a variety of methods for analyzing HRV (most notable being time-domain, frequency domain, and non-linear methods) (Malik 1996). In this study, we chose to look at the high frequency percentage (HF%) since it is commonly associated with anxiety (Lagos, Vaschillo et al. 2011). Raw heart rate data was recorded as inter-beat (RR) intervals for each condition in both experimental sessions. Since the raw data included a number of ectopic (missing) and phantom (extra) beats, we chose to filter the data before any analysis. The raw data was initially exported as a single column of RR intervals; however we converted the data into a two column format of total time and RR values (standard EKG format) before any filtering to maintain the experimental time context. We then made an initial pass thru the raw data and filtered out any beat values below 300ms (instantaneous heart rate of 200 beats/min) and above 1500ms (instantaneous heart rate of 40 beats/min). These values were chosen based on an initial assessment of the mean RR intervals for all participants. We then made a second pass thru the data and removed any values outside two standard deviations of the individual participant's mean. The raw data for each condition was then analyzed using Kubios HRV software. The data was corrected for artifacts using the 'Artifact Correction' option (threshold of 0.3), and then high-pass filtered using the 'Trend Removal' option (lambda of 500, or 0.035Hz). An interval of 150 seconds was selected from each segment, at specifically 30 seconds into the segment. A standard time interval was used, since heart rate variability values can be artificially inflated when examining unequal time samples (Malik 1996). The mean heart rate (HR) and high frequency percentage (HF%) were recorded for each segment from the output of the Kubios HRV software.

It should be noted that this is not a standard method for processing HR and HRV. The data in our experiment was especially noisy, and included more ectopic and phantom beats than would normally be expected. This may have been due to using commodity HR devices, or to signal interference in the lab.

3.3.5.2 Performance

We kept track of performance throughout the study by keeping track of the number of saves and misses in each condition. It was considered a save if the participant pressed the trigger button on the correct Wiimote (according to the direction of the kick) within the allotted timeframe.

3.3.5.3 Presence

Our background research demonstrated that anxiety is related to the sense of presence in VR, so we chose to include presence questionnaires as a measure. We based our presence questionnaire off the Slater-Usoh-Steed (SUS) presence questionnaire (Slater, Usoh et al. 1994), and slightly changed the questions to better represent our experiment (see Appendix B).

3.3.5.4 Pre/Post-Experiment Questionnaires

We also included pre/post-experiment questionnaires and informal interviews to gather data from the participants. The pre-questionnaire gathered data about the participants' goalkeeping experience, training regimens, and confidence (see Appendix A). The post-questionnaire gathered data about their perceived anxiety responses during the experiment (see Appendix C). The interviews were used to extract further details from the participants, including reasons for their responses on the questionnaires, and overall impressions about the Virtual Goalkeeper system.

3.3.6 Participants

We wanted to investigate the potential of VR for training elite athletes, so we limited our participants to current goalkeepers on the NCAA Division I varsity soccer team at Virginia Tech. In total three participants volunteered for the study. All participants were male, and ages were 19, 21, and 21 respectively.

3.3.7 Procedure

The study was broken into two sessions: an individual session and a pair session. All three participants completed the individual session; however, due to scheduling conflicts only two of the participants took part in the pair session. Both sessions lasted for approximately 90 minutes.

Individual Session

Upon arrival, the experimenter greeted the participants, and asked them to read and sign a consent form. Participants were then asked to fill out a brief background questionnaire detailing their experience, perceived ability, and overall confidence as a goalkeeper. The experimenter showed participants one of the heart rate monitor straps, and demonstrated where it needed to be positioned on their chest. One by one the experimenter asked participants to move to a private location and put on a strap. Once the strap was in place, the experimenter had participants sit in a chair and recorded a baseline reading of the participant's heart rate. Following, the experimenter introduced participants to the VisCube, and demonstrated how to properly interact with the system using stereo glasses and head tracking. The experimenter then showed participants the Wiimotes, and demonstrated how to initiate the animations and how to make a prediction on ball direction by pressing the trigger button. The experimenter informed participants that they had a limited timeframe in which to correctly identify the ball direction, and how the corresponding Wiimote would vibrate in their hand if they made the correct choice. Each participant was given five trials in the VisCube to practice the technique. After each trial the experimenter provided the participant with verbal information about their performance. If the participant did not guess correctly, the experimenter informed them whether they were early or late, and whether they chose the correct direction or not.

Once the training was complete, the experimenter asked all but one participant to move outside the lab and to sit and wait in a connected waiting area. Refreshments and reading material were provided to these participants to allow them to relax in between the different experimental conditions.

Once isolated, the active participant was put through one experimental condition with 25 trials. Once complete, the participant was asked to complete the post-stage questionnaire (see Appendix B). After completing the questionnaire, the participant was asked to leave the room, and the next participant was brought in and put through the same experimental condition. Once all participants completed a condition the study moved forward.

Due to the limited number of participants and explorative nature of the study, we decided to keep the order of conditions constant. Since it was possible that physiological responses from one condition could confound future conditions, we chose to order the conditions from the least to most anxiety-inducing (based on our hypotheses). This is the order we chose:

1. Individual, low FOR, low SF
2. Individual, high FOR, low SF
3. Individual, low FOR, high SF
4. Individual, high FOR, high SF

Pair Session

During this session the experimenter conducted all the *pair* experimental conditions, according to the same order used for the individual session. This is the order we used:

5. Pair, low FOR, low SF
6. Pair, high FOR, low SF
7. Pair, low FOR, high SF
8. Pair, high FOR, high SF

In each condition the participants completed two simulated penalty kick shootouts. After each condition both participants were asked to complete a post-stage questionnaire (see Appendix B). Since only two participants participated in this session, both participants were active at all times.

In order to ensure their physiological state returned to normal in between the conditions, there was a 15-minute break between all conditions.

After the participants finished all the experimental conditions, they were asked to complete a post-experiment questionnaire. This questionnaire contained questions related to their perceived level of arousal, personal preference, and opinions about the potential of the research. After the participants finished filling out the questionnaire, each was isolated for an informal interview to expand on their answers, and to gain insight for future iterations of the VR application. Once completed, the participants were thanked for their time and dismissed.

3.4 Results

Since only three participants were included in this study, there was not enough data for a meaningful statistical analysis. The results are presented below, and discussed in 3.5.

3.4.1 Performance

Performance data was kept for all participants (see Table 3.1). We did not see any obvious trends in the data, largely because the participants admitted to guessing rather than reacting to the conditions. The total number of trials is varied in the pair conditions, since these conditions simulated a penalty shootout situation. Once one participant was a clear winner, the condition ended.

	Low FOR Low SF Individual	High FOR Low SF Individual	Low FOR High SF Individual	High FOR High SF Individual	Low FOR Low SF Pair	High FOR Low SF Pair	Low FOR High SF Pair	High FOR High SF Pair
P1	5 saves 20 misses	6 saves 19 misses	6 saves 19 misses	12 saves 13 misses	-	-	-	-
P2	7 saves 18 misses	12 saves 13 misses	6 saves 19 misses	13 saves 12 misses	0 saves 9 misses	6 saves 5 misses	4 saves 6 misses	2 saves 8 misses
P3	9 saves 16 misses	13 saves 12 misses	13 saves 12 misses	7 saves 18 misses	3 saves 4 misses	4 saves 7 misses	4 saves 5 misses	4 saves 4 misses

Table 3.1: Performance data for each participant in each condition.

3.4.2 Heart Rate and Heart Rate Variability

When we look at the heart rate data (see Figure 3.7), we see a strong trend for a peak in the initial condition for each session. When we look at the heart rate variability data (see Figure 3.8), we see varied results between the participants. P1 appears to experience increased anxiety (evidenced by a decrease in the HF%) in the high FOR conditions. P2 does not exhibit any strong trends, except perhaps a slight decrease in anxiety in the high FOR conditions. The data for P3 was very noisy in the pair conditions (with one condition needing to be dropped completely); however, in the individual conditions there appears to be an increase in anxiety for the high FOR/high SF condition.

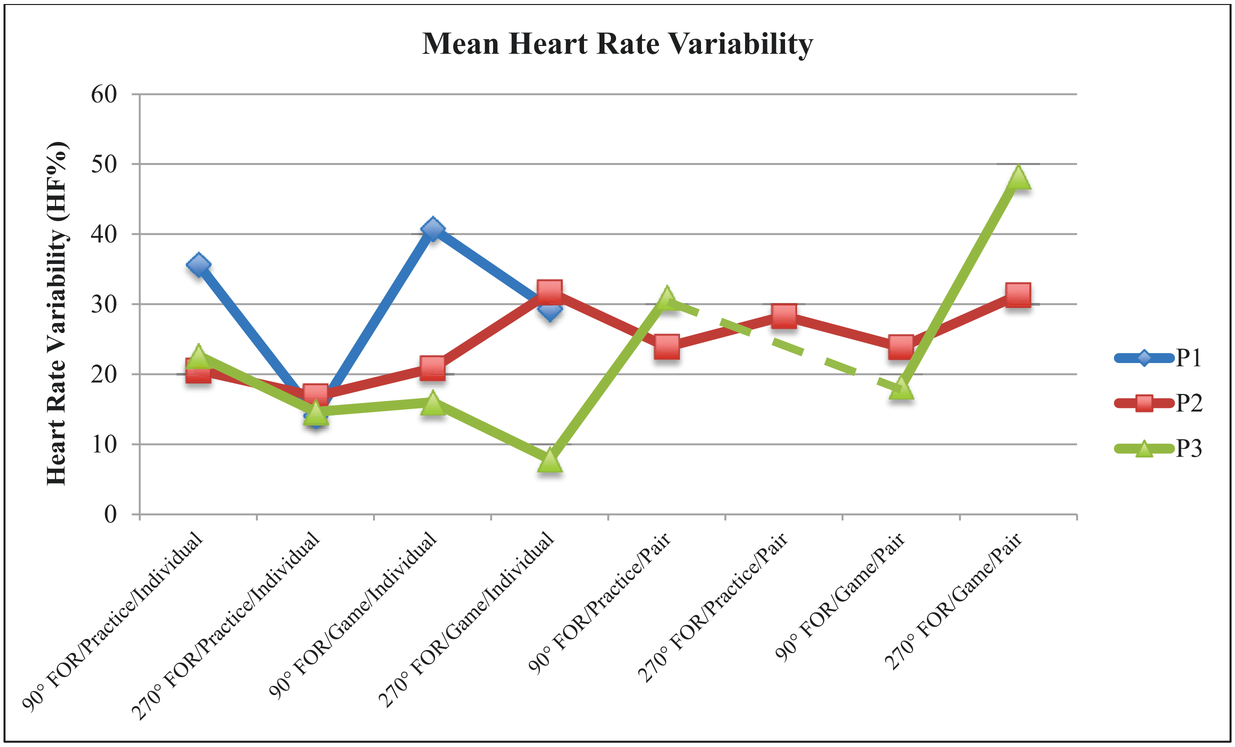


Figure 3.7: Mean heart rate for each participant in each condition.

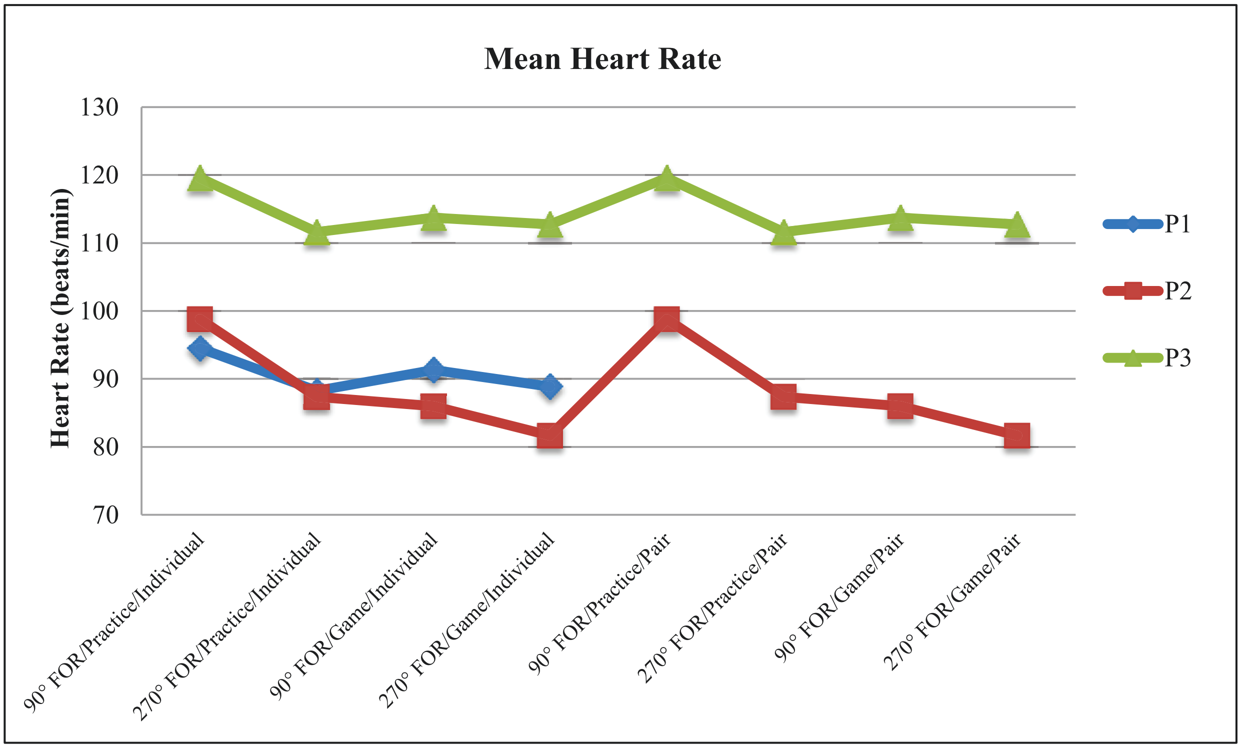


Figure 3.8: Mean heart rate variability for each participant in each condition.

3.4.3 Presence

Presence data was gathered after all experimental conditions (see Table 3.2, Figure 3.9). The typical standard for measuring presence using the SUS presence questionnaire is to sum the number of questions answered with a six or seven (Slater, Usoh et al. 1994). However since no participants ever indicated a score above five, we chose instead to use the mean value to represent the overall presence score. The results demonstrate that the participants experienced higher levels of presence in the individual conditions over the pair conditions. We also see differences among the participants. FOR appears to be the highest contributing element for P1, whereas SF appears to be the highest contributing factor for P2 and P3.

In the individual conditions, 270° FOR was the greatest contributor to presence, followed by game-like environmental complexity. This was reversed in the pair conditions, where game-like environmental complexity was the greatest contributor, followed by the 270° FOR condition. Comparing the overall values between the individual and pair conditions, it can be seen that the individual conditions trended towards higher presence. We also see a difference between P1 and the other two participants. P1 indicated the highest presence scores for the high FOR conditions, whereas P2 and P3 indicated a steadily increasing sense of presence according to the condition ordering.

	Low FOR Low SF Individual	High FOR Low SF Individual	Low FOR High SF Individual	High FOR High SF Individual	Low FOR Low SF Pair	High FOR Low SF Pair	Low FOR High SF Pair	High FOR High SF Pair
P1	2	4	2.67	4.33	-	-	-	-
P2	2.83	3.17	3.5	3.83	1.83	2	2.33	2.67
P3	2.83	3.83	3.83	3.83	1.83	2	2.33	2.83

Table 3.2: SUS mean presence for each participant.

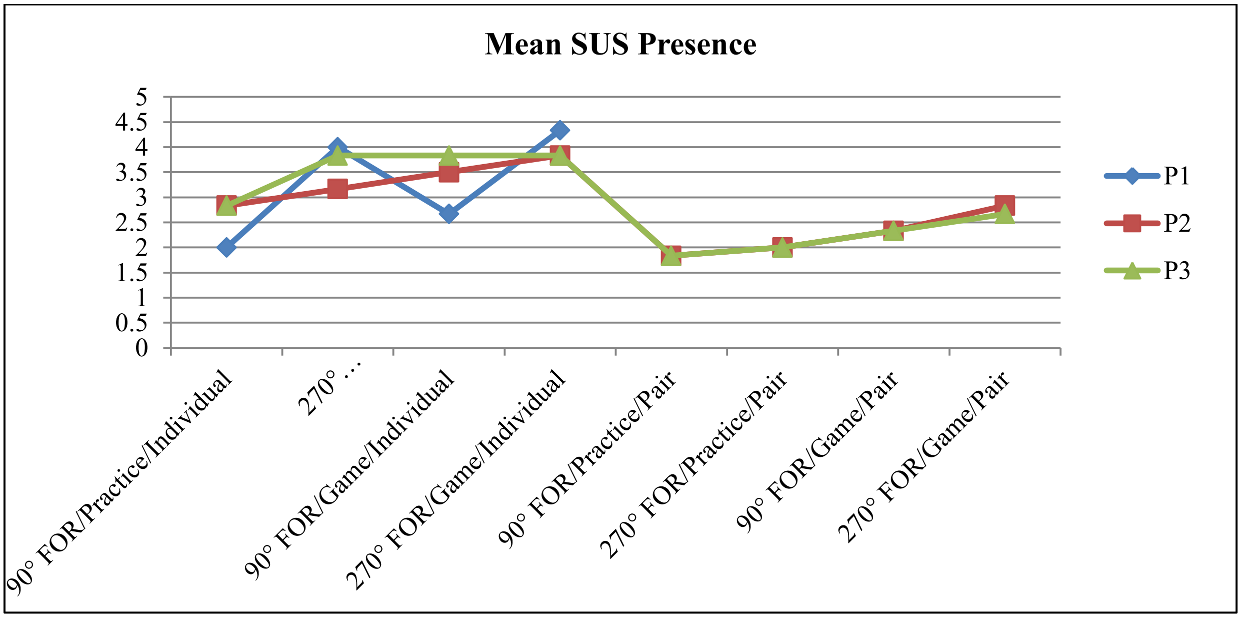


Figure 3.9: SUS mean presence

3.4.4 User Rankings

After participants completed all the experimental conditions, they were asked to rank the conditions according to the anxiety they experienced (see Table 3.3, Figure 3.10). Since only two participants were present for the second session, they were the only ones to complete the user rankings. Overall the results indicate that the participants experienced higher levels of anxiety in the pair conditions. The results also indicate that the participants experienced greater levels of anxiety in the higher fidelity conditions. The highest values are seen for the conditions with high FOR and high SF, with a trend for SF to be more influential than FOR.

	Low FOR Low SF Individual	High FOR Low SF Individual	Low FOR High SF Individual	High FOR High SF Individual	Low FOR Low SF Pair	High FOR Low SF Pair	Low FOR High SF Pair	High FOR High SF Pair
P1	1	2	3	8	4	5	6	7
P2	1	2	4	6	3	5	7	8
Mean	**1**	**2**	**3.5**	**7**	**3.5**	**5**	**6.5**	**7.5**

Table 3.3: User preference presence for each participant (1 - least anxiety experienced, 8 - most anxiety experienced).

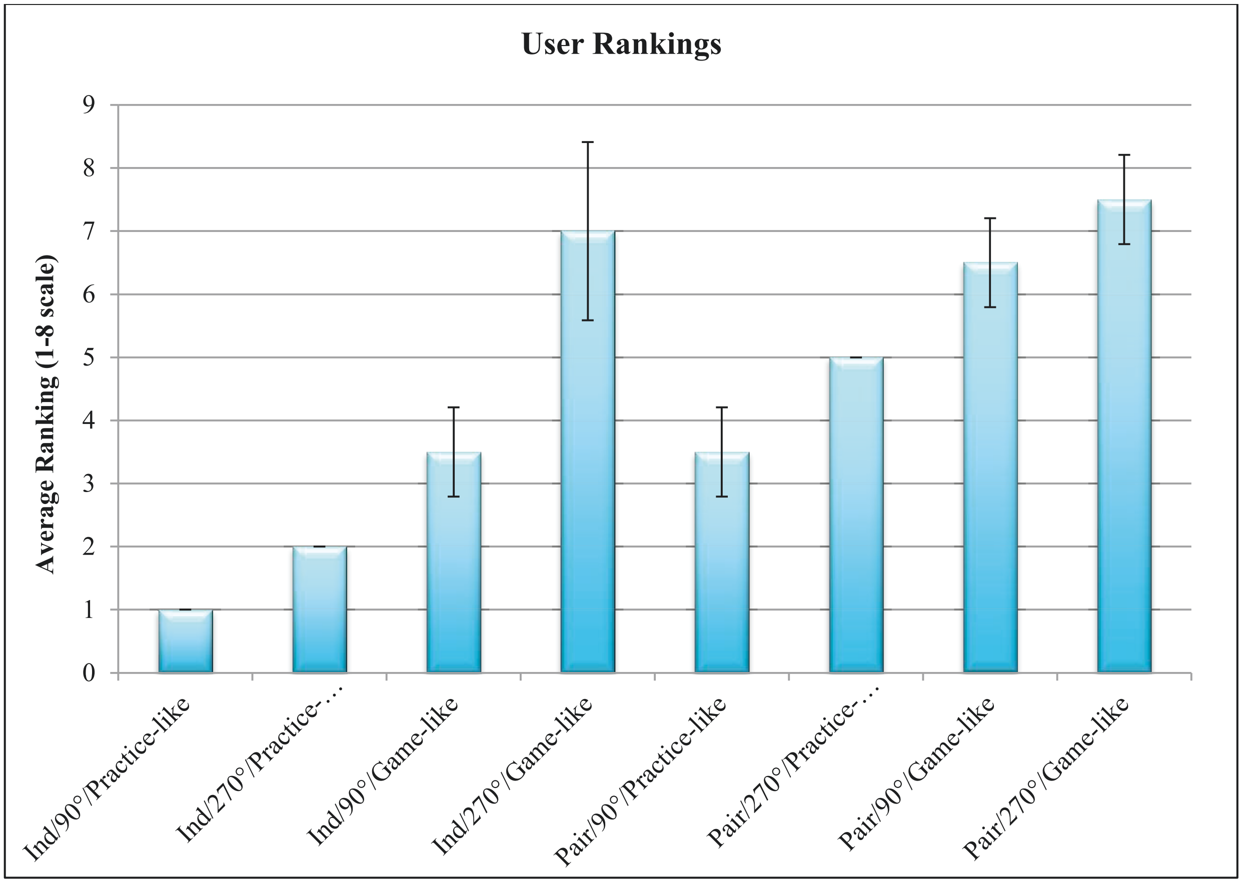


Figure 3.10: Average participant rankings for all experimental conditions (1 - least anxiety experienced, 8 - most anxiety experienced).

3.5 Discussion

3.5.1 H1: Increasing the level of each of the three independent variables (FOR, SF, competitive realism) will cause an increase in anxiety.

In terms of physiological reactions, it is evident that the initial condition of each session resulted in the highest HR values. This contrasts our hypothesis, since the first condition featured the lowest fidelity (low FOR and low SF) for both the individual and pair sessions. We expected these conditions to cause the least anxiety in the participants. It is unlikely that the combination of low FOR and low SF triggered anxiety in the users. Rather, it is more plausible that the newness of the experiment, or simply anticipation for the experiment to begin, caused a spike in the physiological data. It is possible that this physiological increase is simply standard in the beginning of any experiment, and unrelated to the anxiety associated with the condition parameters. This suggests that future experiments should counterbalance the conditions between participants to account for this effect.

We also looked at HRV (specifically HF%), since research has shown that it can be more sensitive to changes in the participants' physiological data (Malik 1996). Although we do not see any overall trends across all participants, we do see some interesting individual differences. Increased anxiety is generally expressed by a decrease in HF%. Therefore it appears P1 experiences greater levels of anxiety in the high FOR conditions, P3 experiences the most anxiety in the high FOR/high SF/low competitive realism condition, and P2 maintains a fairly stable level of anxiety throughout all conditions. This suggests that anxiety is very individualistic. We believe that an individual's background and predisposition to anxiety likely impacts the extent of anxiety experienced in the system. There are too few participants to draw any firm conclusions; however, there is some anecdotal evidence suggesting that both FOR and SF contribute to increased anxiety in certain participants. Future experiments with larger subject pools and counterbalanced conditions between participants are needed to explore these possibilities further.

The HR and HRV measures appear to contradict one another, since HR indicates the initial condition causes the most anxiety whereas HRV appears to be more individualistic. We believe that HRV is a better measure of anxiety, since it appears to align closer with our measures of presence and user rankings. For instance, if we look at P1, we see that the high FOR conditions invoke the lowest HRV values (indicating increased anxiety) and the highest presence values. In future studies, it would be worthwhile to include additional measures of anxiety to better understand the usefulness of both HR and HRV for measuring anxiety.

3.5.2 H2: Competitive realism will be most significant variable in terms of induced anxiety, followed by simulation fidelity, and finally FOR.

Interestingly, we do not see any clear HR or HRV differences between the individual and pair conditions. This suggests that counter to our hypothesis; competitive realism is not the most influential factor for triggering anxiety. It is also possible that this result was due to the experimental design. Since there is only one head tracker for the system, participants needed to exchange the head tracker, stereo goggles, and Wiimotes in between each trial. In contrast, during the individual conditions participants remained in the VisCube for 25 trials in a row. This caused a substantial increase in the time between trials for the pair condition. It also meant that each participant was only interacting with the system 50% of the time. It is therefore possible that the equipment exchange and lack of persistence with the system affected the results. This is confirmed by the interview responses, where the participants stated they enjoyed the competitive nature of the pair conditions; yet found the need to constantly trade equipment frustrating. This is a difficult issue to address, since without a second VisCube system or additional trackers and Wiimotes there is no simple way for two users to use the Virtual Goalkeeper application at the same time. Major changes to the experimental design would be needed in order to effectively study the impact of competitive realism.

When we look at the results from the presence questionnaires and user rankings, we see a lot of confusing data. We expected the presence questionnaires and user rankings to align with each other, since our background research indicated anxiety had a direct relationship to presence (see Chapter 2). We also expected the presence questionnaires and user rankings to correlate directly to our physiological measurements of HR and HRV. While there are some elements that are in agreement, others are completely opposing. For instance, the presence questionnaires suggest that the individual conditions were the most anxiety inducing – whereas the user rankings favor the pair conditions. It could be that sport anxiety is much different than the anxiety a phobic patient experiences, and that presence is not that important a factor for measuring anxiety. It is also possible that the results were confounded by the administration of the presence questionnaires and user rankings. The presence data was acquired after each individual session, whereas the user rankings were acquired at the end of the second session. It could be that the users did not remember the first session well when making the rankings, or that the presence results were confounded by external factors differing between the two session such as mood and tiredness. Due to scheduling conflicts and lab availability issues, the pair session needed to be conducted at 6am right at the end of the semester. The participants admitted in the interview to being overtired and stressed out. In future experiments, it would be wise to hold only one experimental session so that external confounds could be reduced. We also plan to move away from presence questionnaires and user rankings, and use validated surveys for measuring anxiety after each condition.

We can draw some anecdotal evidence from the presence questionnaires and user rankings if we separate the individual and pair conditions and consider them separately. Without considering competitive realism as a factor, we see a trend for higher presence and user ranking values for the higher fidelity conditions. It is important to note that there are individual differences between the participants. FOR appeared to be a bigger factor for anxiety in P1, whereas P2 and P3 were more influenced by SF. Even with the individual differences, all users still gave the highest presence scores and highest anxiety rankings for the highest fidelity condition (high FOR, high SF). This provides additional weight to the physiological data, suggesting that higher fidelity conditions (in terms of FOR and SF) contribute to greater levels of anxiety.

3.6 Conclusions and Future Work

In conclusion, this study suggests that there is potential for VR as a platform for preparing athletes for high-pressure situations. HRV data and anecdotal evidence from the presence questionnaires and user rankings show increased levels of anxiety for higher levels of FOR and higher levels of SF condition. This suggests that both FOR and SF are important factors for triggering anxiety in users. The HRV data also suggests that individuals react differently to different experimental conditions. Background experience and predisposition to anxiety may influence how much anxiety an athlete experiences while using the system.

The initial conditions in each of the experimental sessions produced the highest HR results. Since these conditions featured the lowest levels of fidelity (low FOR and low SF) it is likely that this was due to a sense of newness or anticipation in the user separate from the experimental condition. Future studies should use larger subject pools and counterbalance the condition ordering to account for this fact.

The presence questionnaires and user rankings used in this study provided confusing results. The presence questionnaires showed higher values for the individual conditions, whereas the user rankings showed higher anxiety for the pair conditions. It is possible that presence is not related to anxiety in a sport-oriented application, or that there were confounds in the experiment that led to these results. Future experiments should use only a single experimental session to avoid changes in participants' moods and levels of focus, and use validated surveys for measuring anxiety after each condition.

Based on the interview questions at the end of experiment, there are also several recommended changes for the system:

- Instead of using Wiimotes, create an application that allows participants to step in the direction of the kick.
- Acquire motion capture data that incorporates more of the penalty kick situation (opponent placing the ball, opponent's gaze, opponent's approach and hesitations, etc.).
- Include more auditory cues such as the referee whistle, and crowd cheers and boos in response to their performance.
- Allow for more environmental conditions (day/night, sunny/overcast, etc.).
- Use environments that are familiar to the participants (home stadium, or rival stadiums).

Incorporating some or all of these elements into future iterations of the project will provide a more accurate representation of a true penalty kick situation.

The results of the experiment are encouraging, and suggest that both FOR and SF are influential in triggering anxiety in participants. However the low number of participants and confounding factors in the experimental design made the results difficult to interpret. Further research with larger subject pools, counterbalanced conditions, and validated anxiety surveys is needed before any conclusions can be drawn.

4 Effects of Training Simulation Characteristics on Anxiety

Figure 4.1: Screenshot of the refactored Virtual Goalkeeper application.

4.1 Introduction

Based on the preliminary findings from the Virtual Goalkeeper case study (see Chapter 3), we decided to expand the application and design a new experiment to gain further insight into the potential of using VR for treating sport-induced anxiety.

We designed a controlled, within-subjects experiment with three independent variables: known anxiety triggers (ANX), field of regard (FOR), and simulation fidelity (SF). The primary goal of the study was to determine if any of the conditions could induce anxiety, and if so, to model the relationship between anxiety and performance. Secondary goals included investigating how the VR-specific variables of FOR and SF compared to known anxiety triggers, how background characteristics impacted the anxiety experienced, and to establish the usefulness of the different measures used in the study.

The task for the experiment was the same as the Virtual Goalkeeper case study – to defend against penalty kicks in a simulated soccer environment in the VT Visionarium VisCube. The application was refactored from the Virtual Goalkeeper case study to enable a more ecologically valid experience. Rather than using Nintendo Wiimotes, participants used their own bodies to defend against the simulated kicks. Head tracking was leveraged to determine if the participant moved in the right direction and within the correct timeframe. The timing threshold to determine if a participant made a SAVE was also adapted. Rather than using a pre-determined value, the threshold was calibrated for each participant based on his or her performance during the training phase. Additional environmental elements were also added to the high SF condition to create a more realistic penalty kick scenario.

A variety of dependent variables were used to measure anxiety and performance throughout the study. The physiological measures included: heart rate (HR), heart rate variability (HRV), and galvanic skin response (GSR). The subjective measures included: the State Trait Anxiety Inventory for Cognitive and Somatic Anxiety (STICSA), the Competitive Sport Anxiety Inventory-2 Revised (CSAI-2R), and post-experiment interviews. The performance measures included save percentage and reaction time.

Rather than focus on elite athletes, the subject pool was opened to all students at Virginia Tech over the age of 18. In total 25 participants were included in the study, with varied sport backgrounds.

The findings demonstrate that anxiety can be induced in a VR sport environment. There was a direct relationship between cognitive anxiety, HR, and GSR with using the system, and an inverse relationship with confidence and HRV (all of which indicate an increase in anxiety). A variety of main effects and interactions were also seen between the independent conditions. The extent of anxiety experienced and the impact on performance varies between individuals; however through visual analysis of participant data we see a representation of the Hebbian version of the Yerkes/Dodson law of arousal vs. performance (Diamond, Campbell et al. 2007).

4.2 Background and Motivation

This study was motivated by the success of the previous Virtual Goalkeeper case study (see Chapter 3). Since the previous study only offered anecdotal evidence to support VR for sport psychology training, we redesigned the study and refactored the application to elicit more conclusive results. This involved addressing flaws in the experimental design of the previous study, improving the measurements for anxiety and performance, and modifying the application to increase the ecological validity of the penalty kick simulation.

4.2.1 Flaws in the experimental design of the Virtual Goalkeeper case study

Our previous Virtual Goalkeeper case study (see Chapter 3) provided some evidence that VR could be leveraged for sport psychology training; however the findings were largely anecdotal, and the results were difficult to analyze due to confounds in the experimental design. Since we ran only three participants, we chose to order the conditions from the least to most anxiety inducing, based on our hypotheses. However the physiological data indicated that the first condition in each session (the low FOR/low SF conditions) caused the greatest increase in HR. It is likely that it was simply the newness of the experiment, or anticipation for the task that caused this increase; however since we did not counterbalance the conditions between participants we could not make any conclusive observations.

Another flaw in our previous experimental design was that we targeted a very small subject pool of elite goalkeepers. Having only three participants made it difficult to analyze the results, especially since we observed individual variances. Two of the participants indicated SF to be the most anxiety inducing, whereas the third indicated FOR. Without more participants we are unable to determine whether this variance is generalizable, or is due to outliers in the data. The participants also reported very high confidence scores on the background surveys, which made them unlikely candidates for sport psychology training.

The pair conditions were also problematic, since they required the participants to trade equipment after each trial, and were conducted during a second experimental session. While the participants felt the pair conditions were more anxiety inducing than the individual conditions on the user ranking scales, the presence scores were very low for all pair conditions. It is possible that this discrepancy could be due to the equipment exchanging. It is also possible that the discrepancy could be a result of holding multiple experimental sessions. The participants' moods, levels of tiredness, and focus could have been drastically different between the two experimental sessions. Due to these issues, we chose to exclude the pair conditions from our current experimental design.

4.2.2 Measurements of anxiety

A major issue in the previous study was the difficulty in determining the extent of anxiety experienced in the various conditions. We saw big discrepancies between the presence questionnaires, user rankings of anxiety, and physiological measurements. We clearly need better measures for assessing the anxiety experienced in the various conditions.

In the current study, we chose to drop the presence questionnaires and user ranking scales. Instead we chose to include two validated anxiety inventories: the State Trait Anxiety Inventory for Cognitive and Somatic Anxiety (STICSA) (Ree, MacLeod et al. 2000), and the Competitive State Anxiety Inventory-2 Revised (CSAI-2R) (Cox, Martens et al. 2003). The inventories are both described in detail in sections 4.3.4.3 and 4.3.4.4 respectively.

In the previous study, we had some anecdotal evidence indicating that anxiety could be triggered in a VR sport environment, however we had no way of measuring how this anxiety compared to real-life situations. In the current study, we added an additional independent variable, known anxiety triggers, in order to investigate this question. Based on sport psychology literature, we included elements in this condition that are known to induce anxiety such as lack of control, unpredictability, and negative reinforcement (Oudejans and Pijpers 2009). By including these conditions, we could look at how VR-specific conditions (FOR and SF) compared in terms of the extent of anxiety induced.

4.2.3 Measurements of performance

In our previous study, the measurements of performance were not very useful, since the protocol for determining a save vs. a miss was unrefined. The threshold was a static value based on some preliminary pilot testing, which did not accommodate variances in reaction time well. Since reaction can vary drastically between users (for instance in the current study we saw a 300ms variance between the best and worst users), setting the threshold to a static value resulted in some users needing to guess on every trial in order for a chance to be correct. If some participants are reacting, and some participants are guessing, it makes the results very difficult to interpret.

Therefore for the current study we chose to improve our protocol for determining a save vs. a miss. Instead of a static value, we calibrated the threshold automatically for each participant during the training phase. The threshold was set to the participant's average reaction time during successful training trials. By calibrating to each participant individually, all participants could rely on reacting rather than guessing.

4.2.4 System improvements

Participants also provided feedback after the Virtual Goalkeeper case study, which suggested that the application needed to be refactored to enable a more realistic penalty kick simulation. First and foremost we removed the dependency on Nintendo Wiimotes, and allowed participants to interact with the system using their own bodies. Participants would take a small step in the correct direction to defend against the simulated kicks, and we monitored their position using head tracking.

The participants from the previous case study also indicated that the system was lacking several important elements to accurately simulate a penalty kick situation. The participants (all elite soccer goalkeepers) indicated that some of the most important elements for triggering anxiety during real-life penalty kicks were: the kicker preparing for the kick, the kicker making eye contact and gestures with their body before the kick, the referee and the sound of the whistle before the kick, crowd reactions such as cheers and boos, and kicker reactions after either a save or miss. We included many of these suggestions in our new version, and the changes are described in detail in section 4.3.3.3.

4.3 Experimental Design

In order to continue investigating the potential for VR as a platform for treating sport-induced anxiety, we extended the application from our earlier Virtual Goalkeeper case study (see Chapter 3). We made extensive changes to the system and experimental design to address the issues described in Section 4.2.

We began by refactoring the Virtual Goalkeeper application to make it a more ecologically valid simulation of a penalty kick task. Instead of using Nintendo Wiimotes, we allowed participants to defend against the simulated kicks by moving naturally within the VisCube. Participants would take a step in the appropriate direction to defend against a kick, and we monitored their position using head tracking. We also added pre- and post-kick animations to the main kicker, and animated many of the secondary characters in the application. We created a timing threshold protocol that calibrated automatically to each user, so that the difficulty of the task was equivalent across all participants. We also removed the pair condition, since the constant exchanging of equipment was frustrating for the participants.

We then designed a new, controlled experiment that addressed confounds from our previous case study. We opened up the study to a broader subject pool instead of focusing on elite athletes. The larger number allowed us a more in-depth analysis of the individual variances, and allowed us to counterbalance the experimental conditions. We also added an additional physiological measure, GSR, and leveraged validated anxiety inventories instead of presence questionnaires and custom-made, user ranking scales.

4.3.1 Goals

The primary goal for the study was to determine whether or not VR is a suitable platform for treating sport-induced anxiety. More specifically we wanted to determine the following: (a) if anxiety could be triggered in a VR sport training application and (b) if we could observe effects similar to the Hebbian version of the Yerkes/Dodson law of arousal vs. performance (Diamond, Campbell et al. 2007). If our application was capable of triggering anxiety, and the anxiety affected performance in the system, we could project that a VR platform had potential for treating sport-induced anxiety.

Secondary goals for the study included:

- Understanding the individual and combined effects of field of regard (FOR), simulation fidelity (SF), and known anxiety triggers on various measures of anxiety and performance.
- Determining the relationship between trait anxiety and anxiety experienced in the system.
- Determining the relationship between competitive sport and competitive soccer goalkeeper experience and anxiety experienced in the system.
- Establishing the usefulness of the various measures used in the experiment for gauging anxiety in a VR sport training application.

4.3.2 Hypotheses

Hypothesis #1 (H1): There use of the system (in any condition) will raise anxiety over baseline levels.

We hypothesized that using the system would cause an increase in anxiety. We expected all subjective (STICSA, CSAI-2R) and physiological (HR, HRV, GSR) measures to significantly demonstrate an increase in anxiety between the baseline and in-condition means.

Hypothesis #2 (H2): All three independent variables (known anxiety triggers, FOR, and SF) will have a direct relationship to anxiety.

We hypothesized that all three independent variables (known anxiety triggers, FOR, and SF) would have a direct relationship to anxiety. We expected known anxiety triggers to have the largest effect, with FOR and SF having a lesser effect.

Hypothesis #3 (H3): There will be a direct relationship between trait anxiety and anxiety experienced in the system.

We also hypothesized that there would be a direct relationship between trait anxiety and the extent of anxiety experienced in the system. We expected that individuals with high trait anxiety would experience more anxiety than individuals with low trait anxiety.

Hypothesis #4 (H4): There will be a direct relationship between goalkeeper experience and anxiety experienced in the high FOR and high SF conditions.

We also hypothesized that participants with competitive sport experience (and especially past goalkeeper experience) would experience more anxiety in the high FOR and high SF conditions than those without any sport experience. Elite athletes rely heavily on peripheral vision to acquire important cues and make quick decisions (Knudson and Kluka 1997), and have extensive memories relating to competitive situations and crowds. We therefore expected that their previous experience with competitive sport situations would allow them to associate better to the high FOR and high SF conditions, leading to an increase in arousal/anxiety.

Hypothesis #5 (H5): The relationship between anxiety and performance will resemble an inverted-U shaped curve.

Finally, we also hypothesized that there would be a correlation between anxiety and performance in the system similar to the Hebbian version of the Yerkes/Dodson law (Diamond, Campbell et al. 2007). We expected that small increases in anxiety would have an energizing effect on participants and positively impact performance, but that after some threshold anxiety would begin to negatively impact performance. We expected to see an inverted U-shaped curve when examining anxiety vs. performance.

4.3.3 Independent Variables

We designed a controlled experiment with a 2x2x2 within subjects design (see Table 4.1) to study our hypotheses. The three independent variables for the experiment and their respective levels were: known anxiety triggers (LOW/HIGH), field of regard (LOW/HIGH), and simulation fidelity (LOW/HIGH). We choose a within-subjects design, since we were interesting in observing individual differences between the various conditions. In our previous research (see Chapter 3) we noticed that participants had varied reactions to the experimental conditions. We wanted to investigate these differences on an individual basis, in order to determine if certain results could be correlated to background characteristics such as trait anxiety and sport experience.

Anxiety Triggers (ANX)	Field of Regard (FOR)	Simulation Fidelity (SF)
Low ANX	**Low FOR**	**Low SF**
		High SF
	High FOR	**Low SF**
		High SF
High ANX	**Low FOR**	**Low SF**
		High SF
	High FOR	**Low SF**
		High SF

Table 4.1: Representation of the 8 experimental conditions.

In our previous research, we also noticed a trend for the highest physiological reactions to occur in the first condition, regardless of the condition parameters. We therefore chose to counterbalance our conditions using a Latin square of order 8 (see Table 4.2). This order was repeated after the eighth participant. The conditions for the experiment were structured as follows:

- C1: Low ANX, Low FOR, Low SF
- C2: Low ANX, Low FOR, High SF
- C3: Low ANX, High FOR, Low SF
- C4: Low ANX, High FOR, High SF
- C5: High ANX, Low FOR, Low SF
- C6: High ANX, Low FOR, High SF
- C7: High ANX, High FOR, Low SF
- C8: High ANX, High FOR, High SF

Participant	1st	2nd	3rd	4th	5th	6th	7th	8th
1	C1	C2	C8	C3	C7	C4	C6	C5
2	C2	C3	C1	C4	C8	C5	C7	C6
3	C3	C4	C2	C5	C1	C6	C8	C7
4	C4	C5	C3	C6	C2	C7	C1	C8
5	C5	C6	C4	C7	C3	C8	C2	C1
6	C6	C7	C5	C8	C4	C1	C3	C2
7	C7	C8	C6	C1	C5	C2	C4	C3
8	C8	C1	C7	C2	C6	C3	C5	C4

Table 4.2: Ordering of the experimental conditions.

4.3.3.1 Known Anxiety Triggers (LOW/HIGH)

Our background research revealed a variety of techniques that are known to elevate anxiety in participants such as lack of control, unpredictability and negative feedback (Oudejans and Pijpers 2009). In order to help trigger anxiety in participants, and investigate the extent to which VR-specific conditions can impact anxiety we chose to control the inclusion/exclusion of such techniques as part of our experimental design.

Known Anxiety Triggers – LOW

- *Control* – If the participant chose the correct direction and reacted within a specific time threshold (based on the participant's average reaction time during training) it was considered a SAVE. Choosing the wrong direction or taking longer than the threshold was considered a MISS.
- *Predictability* – The kick always occurred after a consistent delay of 4 seconds, after the trial faded in and the whistle was blown.
- *No negative feedback* – After each trial ended the system faded out to a blank screen, and then immediately faded back in for the next trial to start.

Known Anxiety Triggers – HIGH

- *Lack of control* – The result (SAVE or MISS) was pre-determined and not impacted by the participants' actions. Out of the 15 trials in these conditions, only two were displayed as MISSES.
- *Unpredictability* – The delay before the kick occurred was varied randomly between the trials. After the trial faded in and the referee blew the whistle, the kicker's approach was delayed by 0, 2, 4, 8, or 16 seconds.

- *Negative feedback* – After 3 MISSES (displayed misses, not actual misses), the system provided negative feedback to the participant. Once the trial faded out, a message in large red letters was displayed on the front screen of the VisCube. The negative feedback message was randomly selected from the following set:
    - ‘YOUR PERFORMANCE IS POOR’
    - ‘PLEASE TRY HARDER’
    - ‘YOUR RESULTS ARE UNUSUALLY LOW’
    - ‘YOU NEED TO IMPROVE’
    - ‘REDUCE THE NUMBER OF MISSES’
    - ‘YOUR RESULTS ARE WELL BELOW AVERAGE’
    - ‘YOU ARE NOT PERFORMING VERY WELL’
    - ‘ARE YOU TRYING?’
    - ‘YOU NEED MUCH MORE PRACTICE’

4.3.3.2 Field of Regard (LOW/HIGH)

The second independent variable in our experimental design was field of regard (FOR). Our previous case study provided some anecdotal evidence that FOR was an important factor for triggering anxiety in participants, so we wanted to investigate this variable in a controlled manner.

Field of Regard – LOW

In the LOW conditions, only the front screen of the VisCube was used, resulting in a horizontal FOR of 90°. During these conditions, the other 3 walls were blacked out.

Field of Regard - HIGH

In the HIGH conditions, all four screens of the VisCube were used, resulting in a horizontal FOR of 270°.

4.3.3.3 Simulation Fidelity (LOW/HIGH)

The third independent variable in our experimental design was simulation fidelity (SF). Similar to FOR, our previous case study (see Chapter 3) provided some preliminary findings suggesting that SF was an important factor for triggering anxiety in participants. However, in the case study post-interviews, participants revealed that the Virtual Goalkeeper system did not create a realistic penalty kick simulation since it was missing some important elements. The participants stated that incorporating more of the kicker’s actions (preparing for the kick, eye contact, celebrating goals, etc.) and more auditory elements (crowd cheers and boos based on result) would improve the SF. We therefore expanded the SF variable from the previous study to include a number of these elements.

Simulation Fidelity – LOW

In the LOW condition, the participants were immersed in a simple training environment with a field, net, kicker and ball (see Figure 4.2). There was no crowd or stadium, there were no other characters in the environment, and the score was displayed using floating numbers in the sky. The only sounds were the referee whistle and the ball being kicked.

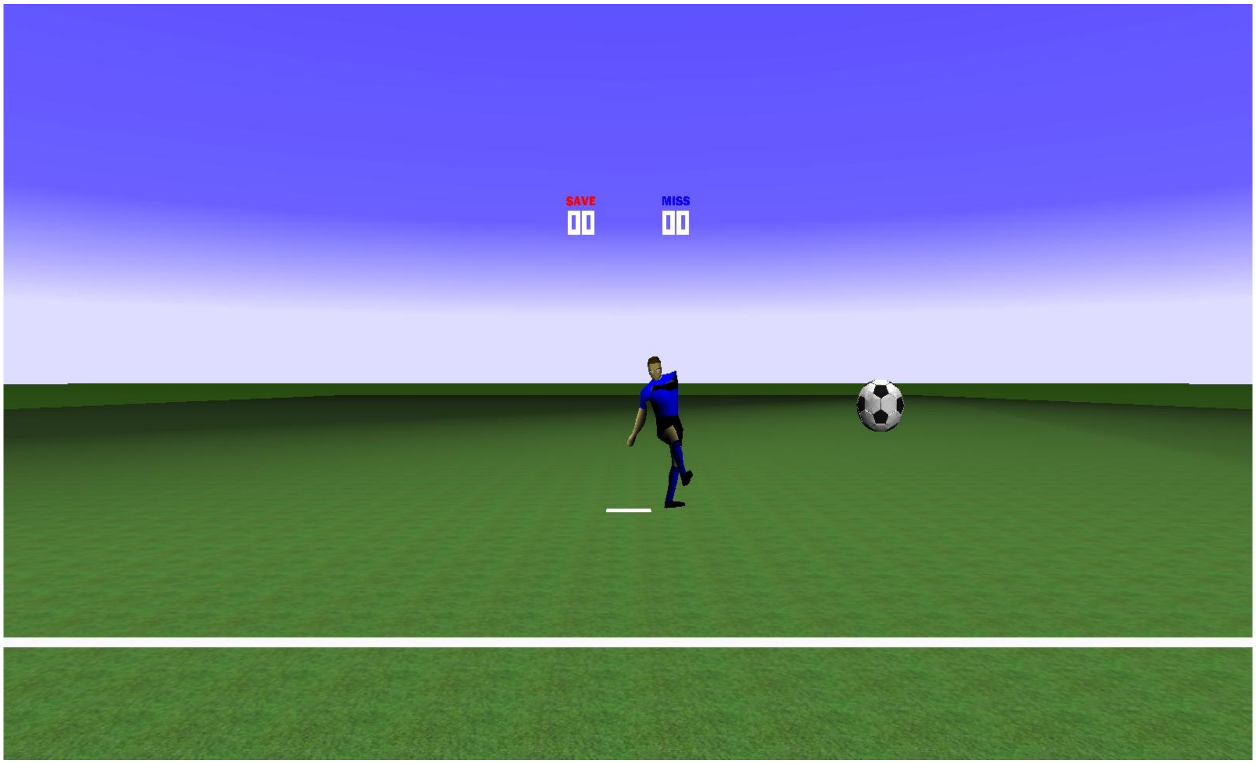


Figure 4.2: Screenshot of the low simulation fidelity (SF) condition (Stinson_CA_T_2013_videos.mp4, 17 MB).

Figure 4.3: Screenshot of the high simulation fidelity (SF) condition (Stinson_CA_T_2013_videos.mp4, 17 MB).

Simulation Fidelity – High

In the HIGH condition, the participants were immersed in a complex game-like environment with a large stadium and crowd, a huge scoreboard, teammates, opponents, referees, a kicker and a ball (see Figure 4.3). There were many sounds in addition to those in the LOW condition including cheers, boos, and constant crowd noise. A variety of animations were used to animate the kicker, teammates, opponents, and referees throughout the trial. The teammates, opponents and 2nd referee were animated with looping cycles of basic idle movements. The 1st referee began each trial by blowing a whistle, then backing away from the kicking zone. The kicker idled with small movements up until the standard kick animation, and then after the kick either celebrated by running towards his teammates waving his hand in exclamation (for a miss), or bowed his head in his hands and walked off in frustration (for a save).

4.3.4 Dependent Variables

A variety of dependent variables were included in the experimental design, in order to capture a multi-dimensional reflection of the anxiety experienced and the associated impact on performance.

Three physiological variables were recorded throughout the study: heart rate (HR), heart rate variability (HRV), and galvanic skin response (GSR). Two validated anxiety inventories were leveraged: the State-Trait Inventory of Cognitive and Somatic Anxiety (STICSA), and the Competitive State Anxiety Inventory-2 Revised (CSAI-2R). Performance was measured in two ways: save percentage, and reaction time. Each participant was also asked a number of open-response questions during a post-experiment interview.

4.3.4.1 Heart Rate (HR) and Heart Rate Variability (HRV)

Heart rate (HR) and heart rate variability (HRV) are two physiological measures for detecting anxiety (Meehan, Insko et al. 2002). There are a variety of methods for analyzing HRV (most notable being time-domain, frequency domain, and non-linear methods) (Malik 1996). In this study, we chose to look at the high frequency percentage (HF%) since it is commonly associated with anxiety (Lagos, Vaschillo et al. 2011).

Raw heart rate data was recorded as inter-beat (RR) intervals for the entire experimental session. Since the raw data included a number of ectopic (missing) and phantom (extra) beats, we chose to filter the data before any analysis. The raw data was initially exported as a single column of RR intervals; however we converted the data into a two column format of total time and RR values (standard EKG format) before any filtering to maintain the experimental time context. We then made an initial pass thru the raw data and filtered out any beat values below 300ms (instantaneous heart rate of 200 beats/min) and above 1500ms (instantaneous heart rate of 40 beats/min). These values were chosen based on an initial assessment of the mean RR intervals for all participants. We then made a second pass thru the data and removed any values outside two standard deviations of the individual participant's mean. The raw data was separated into fifteen segments corresponding to each of the eight conditions and the seven breaks. Each segment was then analyzed using Kubios HRV software. The data was corrected for artifacts using the 'Artifact Correction' option (threshold of 0.3), and then high-pass filtered using the 'Trend Removal' option (lambda of 500, or 0.035Hz). An interval of 150 seconds was selected from each segment, at specifically 30 seconds into the segment. A standard time interval was used, since heart rate variability values can be artificially inflated when examining unequal time samples (Malik 1996). (The uneven length of our conditions was due to the delays and negative feedback messages in the high anxiety conditions). The mean heart rate (HR) and high frequency percentage (HF%) were recorded for each segment from the output of the Kubios HRV software.

It should be noted that this is not a standard method for processing HR and HRV. The data in our experiment was especially noisy, and included more ectopic and phantom beats than would normally be expected. This may have been due to using commodity HR devices, or to signal interference in the lab. The HR and HRV measures for nine of the participants were immediately excluded from our analysis, since over 5% of their data was determined to ectopic and/or missing beats. The data for the remaining sixteen participants was processed using the steps outlined above to minimize the noise and acquire cleaner data for our analysis.

4.3.4.2 Galvanic Skin Response (GSR)

Galvanic skin response (GSR), also referred to as skin conductance, is another known measure for detecting anxiety in individuals (Meehan, Insko et al. 2002). Sweat glands are controlled by the sympathetic nervous system, so an increase in the conductance level of the skin can be interpreted as an indication of psychological arousal or anxiety. We decided to include GSR as a dependent variable in our experiment to expand our physiological measures of anxiety beyond HR and HRV.

The data acquired from the GSR sensor used in our experiment did not suffer from the same noise as the HR and HRV data, and thus did not require the same level of preprocessing. The data was simply segmented according to the various conditions and breaks, and smoothed using a 5-point moving average. The mean GSR was calculated for each experimental condition, as well as the overall mean across all conditions and the overall mean across all breaks.

4.3.4.3 State-Trait Anxiety Inventory of Cognitive and Somatic Anxiety (STICSA)

The State-Trait Anxiety Inventory of Cognitive and Somatic Anxiety (STICSA) is a validated anxiety inventory that deconstructs the overall anxiety an individual experiences into two classifications: cognitive and somatic (Ree, MacLeod et al. 2000). Cognitive anxiety refers to the mental aspects of anxiety such as negative thoughts and worry about failure. Somatic anxiety refers to the physiological aspects of anxiety such as trembling, racing pulse, and clammy hands. There are two versions of the STICSA: the STATE version and the TRAIT version. Both versions have the same questions, but differ in the instructions. The TRAIT version inquires into the individual’s general mood state, whereas the STATE version inquires into the individual’s mood in the current moment.

We decided to include the STICSA as a dependent variable in our experiment due to its broad applicability as a validated measure of anxiety. It also allowed us to separate overall anxiety into dimensions of cognitive and somatic anxiety, and to compare between participants based on their trait anxiety.

The TRAIT and STATE version were administered at the beginning of the study as part of the pre-experiment questionnaire (see Appendix D) before any experimental conditions. The STATE version was also administered immediately after each experimental condition as part of the post-experiment questionnaire (see Appendix E).

The standard method of analyzing STICSA results is to separately sum the somatic (11 items) and cognitive (10 items) responses. We had a number of missing data points in our data, likely since we collected the data on an iPad. So instead of summing the items, we found the mean of the items completed.

4.3.4.4 Competitive State Anxiety Inventory-2 Revised (CSAI-2R)

The Competitive State Anxiety Inventory-2 Revised (CSAI-2R) is a validated anxiety inventory geared specifically towards competitive activities (Cox, Martens et al. 2003). The questions on the CSAI-2R target three different dimensions of anxiety: cognitive anxiety, somatic anxiety, and confidence. The dimension of confidence is included since an individual's confidence is often inversely correlated to their cognitive anxiety.

We decided to include the CSAI-2R as a dependent variable in our experiment due to its relevance to competitive activities. Since our experiment revolved around a sport scenario, we decided it would be beneficial to include a measure specific to competitive anxiety. Unlike the STICSA, the CSAI-2R has one just STATE version; therefore it was administered at the beginning of the study as part of the pre-experiment questionnaire (see Appendix C) before any experimental conditions, and immediately after each condition as part of the post-condition questionnaire (see Appendix D).

The standard method of analyzing CSAI-2R results is to separately sum the somatic (7 items), cognitive (5 items), and confidence (5 items) responses. We had a number of missing data points in our data, likely since we collected the data on an iPad. So instead of summing the items, we found the mean of the items completed.

4.3.4.5 Save Percentage

Since we were interested in looking at the relationship between anxiety and performance, we kept track of the save percentage in each experimental condition. The save percentage was computed using the participant's actual performance in the system (not by the displayed saves in the high anxiety conditions). In order to be a SAVE, the participant needed to move in the correct direction and within the allotted time threshold. The time threshold was determined during the training phase, and was the average time a participant needed to move 0.15m in the correct direction (only trials where the participant moved in the correct direction were included in this calculation). The time threshold was computed separately for both the 1st and 2nd stages of the training phase in case there was a strong learning effect between the two. The lower of the two threshold values was used for the experimental conditions.

Each experimental condition had 15 trials; however, a number of these trials were discarded in our analysis. The two performance measures, save percentage and reaction time, were calculated in our application using separate processes. The process to calculate save vs. miss was driven by a timer event, executed at a precise moment (*kick time* + *threshold*) after the kick occurred. If the participant was beyond 0.15m in the correct direction at the time the process executed it was considered a save. The process to calculate reaction time was executed at millisecond intervals, and if the participant was beyond 0.15m in either direction the reaction time was logged. During our analysis, we noticed a discrepancy in our performance results, where occasionally a trial would be logged as a save even though the reaction time was outside the time threshold. After further investigation, we realized that this was due to a latency issue in the application. The workstation driving the VisCube is a networked machine, and occasionally our application suffered performance decreases due to background processes and remotely logged in users. Occasionally the processes to determine save vs. miss and reaction time were delayed, and occurred up to ~20ms later than expected. Since the save percentage process simply checked if the participant was beyond 0.15m in the correct direction when the process ran, it could consider a trial to be a save even if the time had already passed the time threshold. There was no way to determine if the affected trials were actually saves or not, so we excluded them from our analysis.

4.3.4.6 Reaction Time

In addition to save percentage, we also kept track of the reaction time for each trial where the participant made a move. While save percentage is a more holistic variable in terms of performance (since it incorporates both direction and timing), it does not offer any differentiation among trials that are saves, or among trials that are misses. We therefore also kept track of reaction time, since it offers a finer-grained representation of the performance between trials. In our experiment, reaction time refers to the amount of time that passed from the onset of the kick to when the participant had moved 0.15m in either direction.

As described above, the application occasionally suffered from a latency issue, impacting the precision of our performance metrics. While we were able to drop all trials that impacted the save percentage metric, we were unable to do the same for reaction time, since there was no way to isolate all the affected trials. We excluded the trials with save/reaction time mismatches, but latency could also have affected trials without mismatches. Therefore it is important to note that the reaction time variable in this experiment contains some inherent error.

4.3.4.7 Post-experiment Interview

We included an informal post-experiment interview in our experimental design to get detailed information about the reactions and emotions participants experienced throughout the study. The interview asked participants to describe any emotions experienced, to discuss the specific environmental elements that were the most impactful, and to state their preferred conditions.

4.3.5 Task

The task for the application was to defend against penalty kicks in a simulated soccer shootout. In each condition the participants faced 15 kicks, between which the application would fade to black and then fade back in. The participants stood in the middle of the VisCube in a ready position with knees slightly bent, and waited until the ball started moving before making any move. Once the participants could see the direction of the kick, they were instructed to take a small step in the correct direction. Since the participants' movements were tracked using the head tracker, it was imperative that their heads move to the side along with their bodies in order for the system to detect an attempt. Therefore we instructed participants to lead with their heads when taking a step in the direction of the kick. We ensured participants were using a safe and biomechanically sound technique during the training to avoid causing any head or neck strain. After the trial was over, participants were instructed to return to the center of the VisCube and prepare for the next trial.

In order to achieve a SAVE, the participant needed to move in the correct direction, and within the allotted timeframe. The timeframe varied for each participant, and was determined by finding his or her threshold during the training phase. The reaction times (defined for this study as the time needed to move 0.15m in the correct direction) were recorded for each successful trial during the training phase. The reaction times were averaged for each of the two stages during the training phase, and the lesser of the two values was used as the timing threshold throughout the rest of the study. Any reaction time greater than this threshold was considered too slow, and thus considered a MISS.

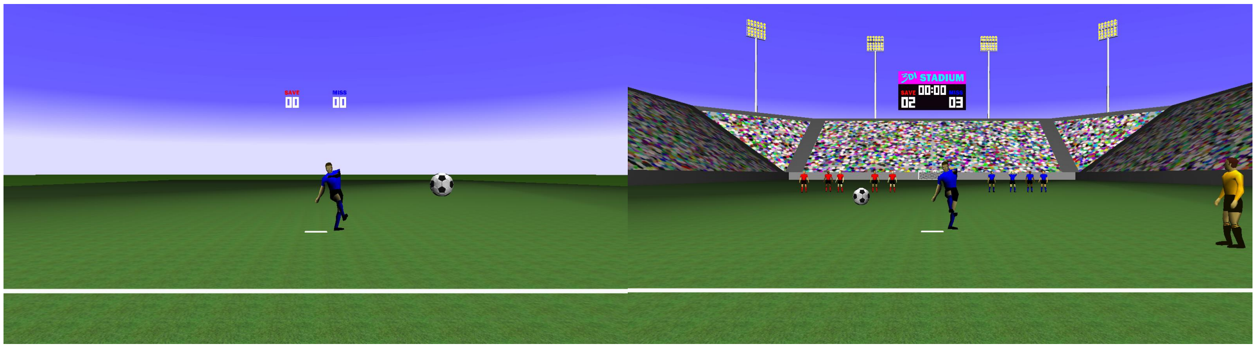


Figure 4.4: Screenshots during the kick of the low (L) and high (R) simulation fidelity environments.

4.3.6 Environment

The environment for the application was a soccer field that featured a variety of objects, characters, and sounds that differed depending on the level of SF (see Figure 4.4). The two SF conditions shared a few elements in common: a grass soccer field, a net, a soccer ball, a kicker, the sound of a referee whistle, the sound after a save (the sound of a ball smacking a goalkeeper's hands), and the sound after a miss (the sound of a ball swooshing into the net). The base animation for the kicker and the two animations for the ball (one left, one right) were the same in both conditions. Both conditions displayed the score; however the fidelity of the scoreboard differed. In the LOW SF condition, numbers floating in the sky displayed the score. In the HIGH SF condition, a large, detailed scoreboard was attached to the soccer stadium.

The HIGH SF condition also featured a variety of additional objects, characters, and sounds. This included a soccer stadium and a large crowd, four teammates and five opponents lined up on the centerline (as would be the case in a real shootout situation), two referees (one near the top of the penalty box, the other on the goal line), and the opposing goalkeeper. The background crowd was animated by continuously flipping through a series of static images of small, colored dots. In the HIGH SF condition the main kicker had additional pre- and post-kick animations. The pre-kick animation was a simple idle animation as the kicker prepared for his approach to the ball (this animation would be cycled multiple times depending on the length of the delay before the kick). There were two post-kick animations: one for a save and one for a miss. In the save version, the kicker would bow his head and walk off frustrated. In the miss version, the kicker would run towards his teammates waving a hand into the air in celebration. This condition also featured a few additional sounds. There was a constant background crowd noise, as well as crowd reactions for both a save (cheers) and for a miss ('ahhs').

4.3.7 Apparatus

4.3.7.1 Hardware

The study was conducted using the VisBox VisCube in the VT Visionarium lab at Virginia Tech (see Figure 3.3). The VisCube is a 4-walled CAVE-like projection system, with each wall having dimensions of 10’ x 10’, and featuring a resolution of 1920 x 1920 pixels (see Figure 3.2). The application was projected in stereo with head tracking using an Intersense IS-900 tracking system. Users wore stereo glasses, with a wireless head-tracker mounted to the top frame (see Figure 3.3).

Suunto heart rate monitors and a USB receiver were used to track and record user heart rates in real-time. Participants wore a Suunto chest strap (see Figure 3.4) that sent the heart rate data wirelessly to a laptop running Suunto Training Manager Lite software.

Galvanic skin response (GSR) was recorded using the eSense Skin Response Biofeedback system (see Figure 4.5). Fingertip sensors were worn on the 1st and 2nd fingers of the participants’ right hands, which connected to an iPhone strapped to the participants’ upper arm. The eSense application ran on the iPhone, and tracked and recorded the participants’ GSR throughout the study.

Figure 4.5: The eSense Skin Response Biofeedback system.

An Apple iPad was used throughout the study to capture the questionnaire responses.

4.3.7.2 Software

The application ran using the Instant Reality framework, and the code was written in X3D. All the environmental objects and characters for the application were modeled using Google SketchUp. The elements were then imported into 3D Studio Max, and inner skeletons were added to the characters using the biped tool. The primary kick animation was accomplished by animating the main kicker biped with a motion capture file from the Carnegie Mellon University

Motion Capture Database (http://mocap.cs.cmu.edu/). The motion capture file was edited slightly using Bvhacker freeware to correct misaligned posture. All other character animations for the application were created manually. These included looping animations for the secondary characters (referees, teammates and opponents), and for the main kicker's pre and post kick animations. The two soccer ball animations were created (one left and one right) using the 3D Studio Max Havoc 3 physics engine to achieve realistic flights. All the elements were exported into VRML format, and then converted to X3D format using the online X3D encoding converter. Once in X3D format, the biped nodes were removed. At this point the character meshes were managed with coordinate interpolators, and the inner bipeds were no longer needed. The biped nodes were removed; since otherwise the biped skeletons could occasionally be seen protruding from the character meshes in X3D.

4.3.8 Participants

After receiving approval from the Virginia Tech Institutional Review Board, participants were recruited by placing an advertisement in the weekly email newsletter sent to all Virginia Tech graduate students. In total 30 participants were recruited, and 28 of the participants completed the study. Two participants needed to be dismissed, since the heart rate monitoring system could not detect any signal. Participants were paid in order to encourage them to focus and stay motivated throughout the entire study. In a real deployed VR training system, this motivation would be internal (desire to improve), but since our participants were not actually training for goalkeeper performance, we felt that external motivation was needed. All participants were paid according to the payment schedule ($12 base + $0.15/save, for a total possible payout of $30). Since there were real-world monetary stakes based on performance, we expected that participants would care about performing well and would experience anxiety if they didn't perform well.

Of the 28 participants that completed the study, only 25 were included in the analysis. System settings were adjusted slightly after the first three participants, so they were treated as pilot participants and excluded from the analysis. All participants were graduate student at Virginia Tech, and ages ranged from 22 to 32. Nine of the participants were female, and 15 were male. In terms of sport experience, 23 participants had competitive sport experience, 15 had competitive soccer experience, and seven had soccer goalkeeper experience. Nine of the participants indicated they regularly played video games, and four participants reported previous experience with VR systems.

4.3.9 Procedure

Upon arrival each participant was greated and asked to fill out the IRB consent form. The experimenter demonstrated how to put on the heart rate chest strap, and then left the lab to provide the participant privacy. The participant was then asked to sit down in a designated chair and the HR monitoring application was initiated. Once the HR monitoring was set up, the experimenter helped the participant put on the GSR unit. The fingertip sensors were secured to the 1st and 2nd fingers on the participant's right hand, and the iPhone was secured to the participant's right upper arm using a velcro strap. Once the unit was in place the GSR monitoring application was initiated. The experimenter then handed an iPad to the participant, and asked them to fill out a pre-experiment questionnaire (see Appendix D). The questionnaire asked about the participant's demographics and competitive background, and included two anxiety inventories: the STICSA and the CSAI-2R. Both the STATE and TRAIT versions for the

STICSA were included in the baseline questionnaire.

The participant was then introduced to the VisCube and the system controls, and asked to put on the stereo glasses with the mounted head tracker. The stereo glasses were secured tightly to the participant's head with a strap to ensure they wouldn't jostle as the pariticpant moved throughout the experiment. The participant was then put through a two-stage training process. Both stages of training used the low anxiety, high FOR, low SF environment. This configuration was chosen to allow participants to become familiar with the full FOR of the VisCube, and to allow full focus on the training task without added distractors and anxiety-inducing elements. The first training stage began with detailed instructions on how to interact with the application. The participant was told to stand in the middle of the VisCube and wait until they saw the direction of the kick before making any move. Once they perceived the direction of the kick, they were instructed to take a quick step in that direction, leading with the head. The experimenter explained to the participant that after each trial the system would give them feedback messages of either "Good", "Too early", "Too late", or "Wrong direction". The participant was informed that this phase of the training would continue until they had achieved 15 "Good" trials. Once the participant acknowledged that they understood the instructions and were ready to begin, the 1st training phase was started. After 15 "Good" trials, the participant moved to the 2nd phase of the training.

During the 2nd stage of training, the application functioned in a similar manner to the main experimental conditions. No detailed feedback was given to the participant, only a message of either SAVE or MISS after each trial. To be a SAVE, the participant had to move in the correct direction, and in the correct timeframe. Moving to the wrong direction, moving before the kick occurred, or moving too slowly were all considered a MISS. (Note: The correct timeframe for the 2nd training phase was based on the average reaction time for the 15 "Good" trials during the 1st training phase. If the participant moved faster than their average reaction time it was considered a SAVE, and if they moved slower it was considered a MISS. The participant was not informed of these details, just instructed to move as quickly as possible once they recognized the correct kick direction.) The participant was informed that the 2nd training phase would continue until they had achieved five saves, and once ready the 2nd training phase was started. After achieving five saves, the participant was instructed to sit in the designated chair, and tilt the stereo glasses up onto their forehead. The experimenter then handed an iPad to the participant, and asked them to fill out the post-condition questionnaire (see Appendix D). The post-condition questionnaire consisted of two parts: the STICSA STATE and the CSAI-2R. The participant was given five minutes to complete the questionnaire and rest before the main portion of the study.

After the break the participant was informed that the paid portion of the study was about to begin, and that for every SAVE in the following eight conditions they would be awarded $0.15. The participant was reminded of the instructions, and asked to get ready. The experimenter then led the participant though each of the eight conditions. After each condition, the participant was instructed to sit in the designated chair and tilt the stereo glasses up onto their forehead. The experimenter then handed an iPad to the participant, and asked them to fill out the post-condition questionnaire (see Appendix D). The participant was given five minutes to complete the questionnaire and rest before moving on to the next condition.

Once all eight conditions were complete, the experimenter sat with the participant for a short interview. The participant was asked about their experience during the study, their emotional reactions, and their perceptions of the various conditions. The experimenter helped the participant remove the GSR unit, and then left the room to allow privacy so the participant could remove the HR chest strap.

After the post-experiment interview, the experimenter had the participant read a written statement describing the deception used in the experiment. The participant was informed that during the conditions with the known anxiety triggers their performance results were contrived, but that they would be paid according to their true performance. The participant was then compensated according to the payment schedule, and thanked for their participation. Each study session took approximately 90 minutes. Even though the length of the study was relatively long, we did not notice any decrease in motivation or interest throughout the study. We believe that the monetary incentive to perform well in the study negated the potential for decreased focus and attention.

4.4 Results

In this section, we will present the results of the study in the context of our five hypotheses:

- **H1:** Use of the system (in any condition) will raise anxiety over baseline levels.
- **H2:** All three independent variables (known anxiety triggers, FOR, and SF) will have a direct relationship to anxiety.
- **H3:** There will be a direct relationship between trait anxiety and anxiety experienced in the system.
- **H4:** There will be a direct relationship between goalkeeper experience and anxiety experienced in the high FOR and high SF conditions.
- **H5:** The relationship between anxiety and performance will resemble an inverted-U shaped curve.

Measure	Variable	Mean	Std. Error	Sig.
STICSA Somatic	Baseline Conditions Mean	16.36 15.01	1.51 0.87	.337
STICSA Cognitive*	Baseline Conditions Mean	13.31 15.02	0.68 0.65	**.041***
CSAI-2R Somatic	Baseline Conditions Mean	14.57 15.29	0.87 0.69	.457
CSAI-2R Cognitive*	Baseline Conditions Mean	15.80 18.00	1.09 1.12	**.043***
CSAI-2R Confidence*	Baseline Conditions Mean	27.44 24.89	1.46 1.13	**.039***
GSR*	Baseline Conditions Mean	6.58 6.90	0.73 0.79	**.016***
HR*	Baseline Conditions Mean	82.15 95.57	2.94 3.28	**< .001***
HF%*	Baseline Conditions Mean	27.96 19.04	3.05 2.45	**.006***

Table 4.3: Paired samples tests for the various measures. Significant findings ($p < 0.05$) are marked in bold.

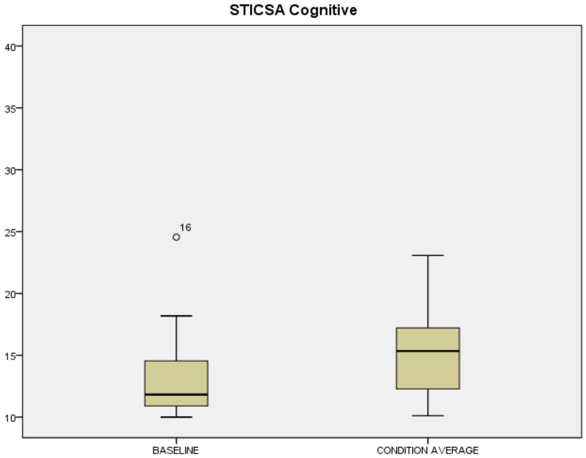


Figure 4.6: STICSA Cognitive variance between the baseline and within the conditions (p = .041).

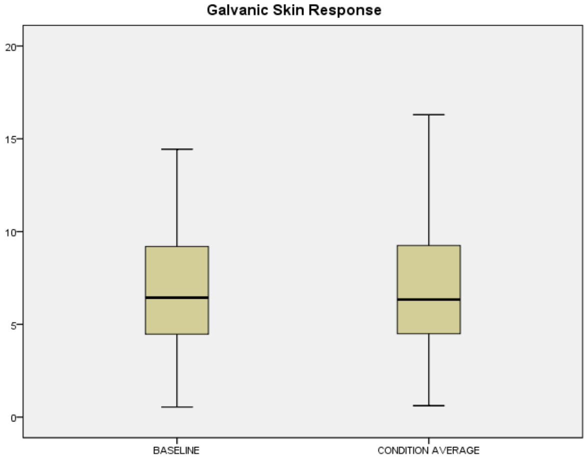


Figure 4.9: GSR variance between the baseline and within the conditions (p = .016).

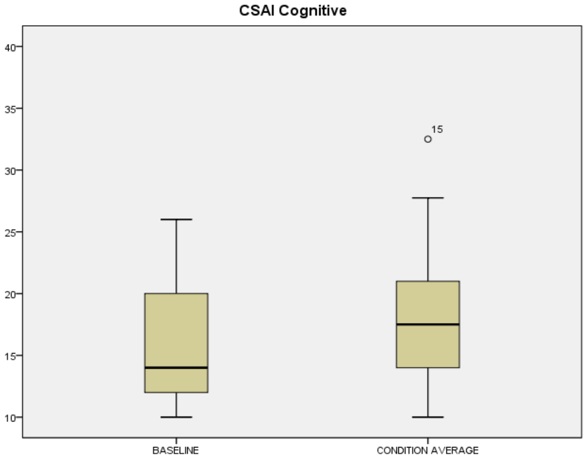


Figure 4.7: CSAI-2R Cognitive variance between the baseline and within the conditions (p = .043).

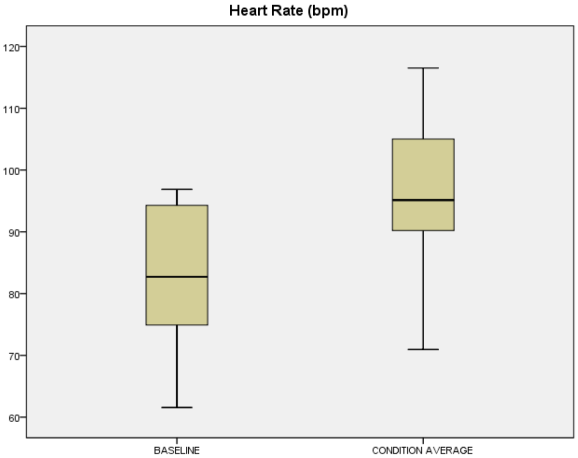


Figure 4.10: HR variance between the baseline and within the conditions (p < .001).

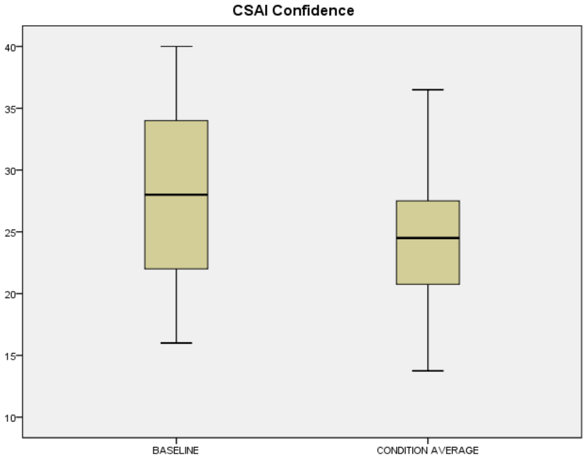


Figure 4.8: CSAI-2R Confidence variance between the baseline and within the conditions (p = .039).

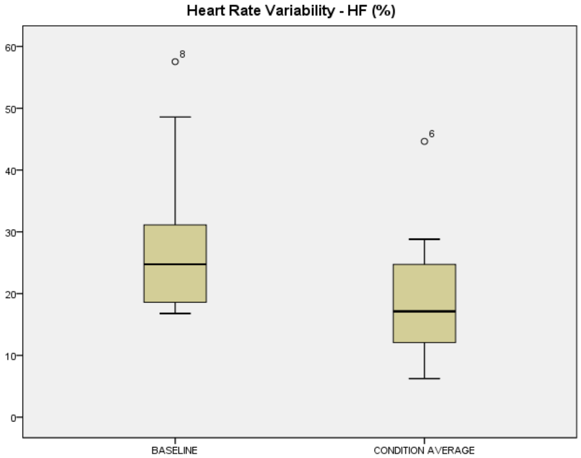


Figure 4.11: HRV (HF%) variance between the baseline and within the conditions (p = .006).

For all graphs included in the results section, error bars refer to standard error. The yellow box and whisker plots have the following features: the solid line in the middle of the box is the median, the bottom of the box indicates the 1st quartile, the top of the box the 3rd quartile, the T-bars extend to the 95% confidence interval, and the points represent outliers. The blue box and whisker plots have the following features: the solid line in the middle of the box is the median, the diamond is the mean, the bottom of the box indicates the 1st quartile, the top of the box the 3rd quartile, and the T-bars extend to the min and max values.

4.4.1 H1: Use of the system (in any condition) will raise anxiety over baseline levels.

In order to analyze the overall effect of using the system, we compared baseline values with in-condition means for all relevant dependent variables (STICSA Somatic, STICSA Cognitive, CSAI-2R Somatic, CSAI-2R Cognitive, CSAI-2R Confidence, GSR, HR, and HF%). Baseline values for the STICSA and CSAI-2R variables were determined by looking at the STATE version of the inventories that participants filled out during the baseline questionnaire. Baseline values for GSR, HR, and HF% were computed by averaging the values of the break periods between the experimental conditions (as explained in 4.3.4.1, HR and HF% represent a 150 second snapshot beginning 30 seconds into each break period).

A paired samples t-test was conducted on the various parameters. There was a significant increase in STICSA Cognitive (p=.041), CSAI-2R Cognitive (p=.043), GSR (p=.016), and HR (p<.001) for the in-condition parameters, and a significant decrease in CSAI-2R Confidence (p=.039) and HF% (p=.006) (see Table 4.3, Figure 4.6, Figure 4.7, Figure 4.8, Figure 4.9, Figure 4.11, and Figure 4.11). All the increases and decreases are in accordance with typical patterns of anxiety. We can therefore state with assuredness that our system did induce anxiety in participants.

4.4.2 H2: All three independent variables (known anxiety triggers, FOR, and SF) will have a direct relationship to anxiety.

In our initial hypothesis, we expected that all three independent variables (known anxiety triggers, FOR, and SF) would have a direct relationship to anxiety. We expected known anxiety triggers to have the largest effect, with FOR and SF having a lesser effect. We also expected to see an interaction between FOR and SF, with the combination of the high level of FOR and high level of SF causing the most anxiety. We performed a repeated measures MANOVA on the three independent variables, and the findings are summarized in Table 4.4. (Since we only had HR and HRV data for 16 of the participants, we performed a separate repeated measure MANOVA for the HR and HF% measures.)

Test of Within-Subjects Contrasts

Source	Measure	Significance	η_p^2
ANX	**STICSA Somatic***	**.010***	**.258***
	STICSA Cognitive*	**.037***	**.175***
	CSAI-2R Somatic	.254	.056
	CSAI-2R Cognitive*	**.001***	**.407***
	CSAI-2R Confidence*	**< .001***	**.631***
	GSR	.317	.048
	HR	.099	.183
	HF%	.105	.177
	Save %	.755	.004
	Reaction Time	.123	.100
FOR	STICSA Somatic	.165	.082
	STICSA Cognitive	.442	.026
	CSAI-2R Somatic	.332	.041
	CSAI-2R Cognitive*	**.005***	**.293***
	CSAI-2R Confidence*	**.008***	**.272***
	GSR	.087	.133
	HR	.862	.002
	HF%	.429	.045
	Save %	.815	.002
	Reaction Time	.559	.015
SF	STICSA Somatic	.630	.010
	STICSA Cognitive	.085	.124
	CSAI-2R Somatic*	**.010***	**.253***
	CSAI-2R Cognitive	.561	.015
	CSAI-2R Confidence	.476	.022
	GSR	.070	.148
	HR	.353	.062
	HF%	.264	.088
	Save %	.135	.094
	Reaction Time	.057	.148
ANX * FOR	STICSA Somatic	.144	.091
	STICSA Cognitive	.398	.031
	CSAI-2R Somatic	.784	.003
	CSAI-2R Cognitive	.296	.047
	CSAI-2R Confidence	.190	.073
	GSR	.909	.001
	HR	.308	.074
	HF%	.275	.084
	Save %	.702	.006
	Reaction Time	.804	.003
ANX * SF	STICSA Somatic	.444	.026
	STICSA Cognitive	.051	.155
	CSAI-2R Somatic	.461	.024
	CSAI-2R Cognitive	.747	.005
	CSAI-2R Confidence	.777	.004
	GSR	.990	.000
	HR	.140	.149
	HF%	.498	.033
	Save %	.065	.141
	Reaction Time	.293	.048
FOR * SF	STICSA Somatic	.755	.004
	STICSA Cognitive	.087	.122
	CSAI-2R Somatic	.301	.046
	CSAI-2R Cognitive	.160	.084
	CSAI-2R Confidence*	**.016***	**.227***
	GSR	.875	.001
	HR	.632	.017
	HF%	.267	.087
	Save %*	**.034***	**.180***
	Reaction Time	.704	.006

ANX * FOR * SF	STICSA Somatic	.501	.020
	STICSA Cognitive*	**.029***	**.190***
	CSAI-2R Somatic	.819	.002
	CSAI-2R Cognitive	.357	.037
	CSAI-2R Confidence*	**.044***	**.164***
	GSR	.213	.073
	HR	.403	.050
	HF%	.963	< .001
	Save %	.158	.085
	Reaction Time	.408	.030

Table 4.4: Summary of significant findings from repeated measures MANOVA.

4.4.2.1 Main Effects of Known Anxiety Triggers

Our analysis revealed several main effects of known anxiety triggers, namely on STICSA Somatic (p=.010, η_p^2=.258), STICSA Cognitive (p=.037, η_p^2=.175), CSAI-2R Cognitive (p=.001, η_p^2=.407), and CSAI-2R Confidence (p<.001, η_p^2=.631) (see Table 4.5, Figure 4.12, Figure 4.13, Figure 4.14, and Figure 4.15).

Measure	ANX	Mean	Std. Error	p	η_p^2
STICSA Somatic*	LOW	14.497	.890	**.010***	**.258***
	HIGH	15.917	.941		
STICSA Cognitive*	LOW	14.520	.625	**.037***	**.175***
	HIGH	15.281	.743		
CSAI-2R Somatic	LOW	14.896	.665	.254	.056
	HIGH	15.439	.819		
CSAI-2R Cognitive*	LOW	16.188	1.064	**.001***	**.407***
	HIGH	19.729	1.417		
CSAI-2R Confidence*	LOW	28.005	1.291	**<.001***	**.631***
	HIGH	22.271	1.181		
GSR	LOW	6.783	.824	.317	.048
	HIGH	6.891	.817		
HR	LOW	96.490	3.530	.099	.183
	HIGH	95.240	3.497		
HF%	LOW	22.282	3.737	.105	.177
	HIGH	16.998	1.901		
Save %	LOW	62.571	4.308	.755	.004
	HIGH	61.571	4.359		
Reaction Time	LOW	.573	.008	.123	.100
	HIGH	.565	.008		

Table 4.5: Summary of the main effects and means of known anxiety triggers.

Since in our previous experiment (see Chapter 3) we noticed the highest HR and HRV values in the initial conditions, we ran an additional repeated measures MANOVA with condition ordering as a between-subjects variable to see if the order of conditions had an impact on our findings. The analysis revealed no changes to the significance values for all our main effects.

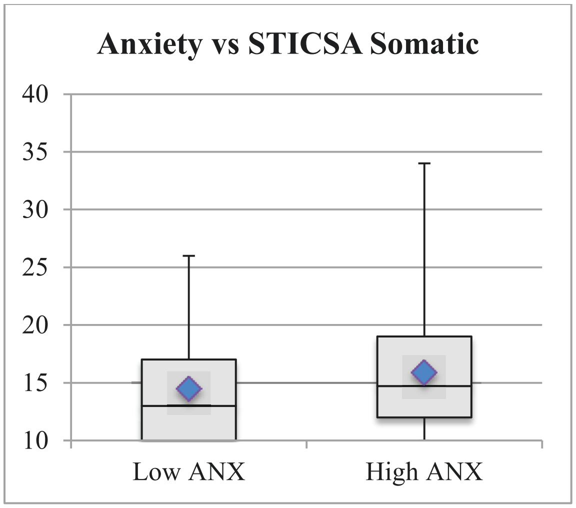


Figure 4.12: STICSA Somatic variance between the low and high anxiety conditions (p = .010).

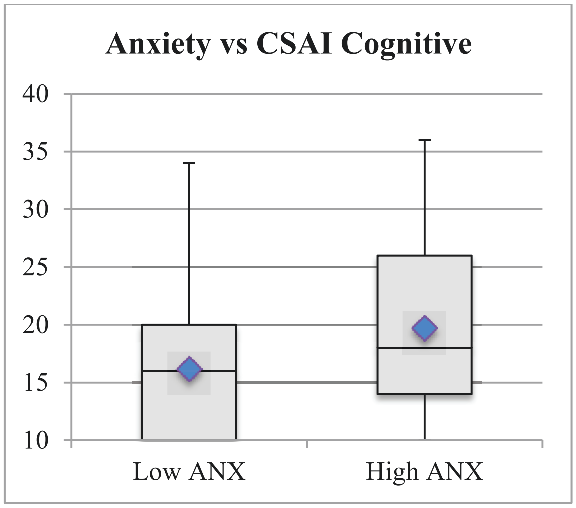


Figure 4.14: CSAI-2R Cognitive variance between the low and high anxiety conditions (p = .001).

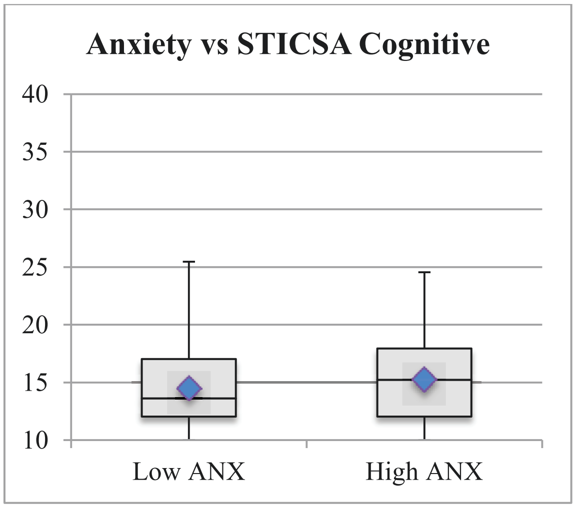


Figure 4.13: STICSA Cognitive variance between the low and high anxiety conditions (p = .037).

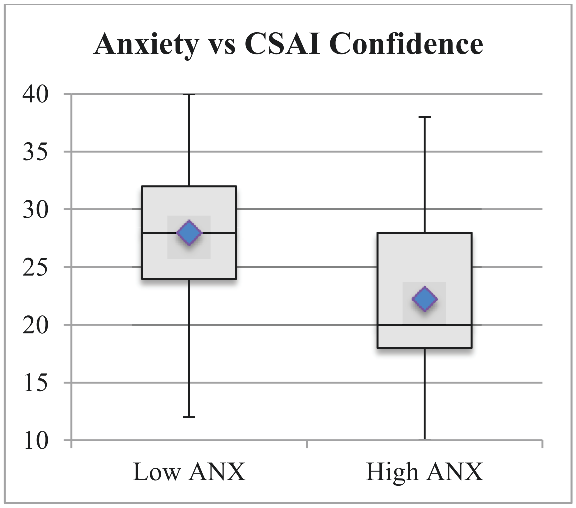


Figure 4.15: CSAI-2R Confidence variance between the low and high anxiety conditions (p < .001).

4.4.2.2 Main Effects of Field of Regard

Our analysis revealed two main effects of FOR, namely on CSAI-2R Cognitive (p=.005, η_p^2=.293), and CSAI-2R Confidence (p=.008, η_p^2=.272) (see Table 4.6: Summary of the main effects and means of field of regard (FOR)., Figure 4.16, and Figure 4.17). The two measures suggest that the low FOR conditions cause more anxiety than the high FOR conditions. It is interesting to note that even though it does not represent a statistically significant difference, the STICSA Cognitive followed an inverse pattern, with slightly higher levels of reported anxiety for the high FOR conditions. The inverse pattern is seen between the STICSA Somatic and CSAI-2R Somatic measures. Participants reported higher levels of anxiety for the high FOR condition on the CSAI-2R Somatic, but lower levels on the STICSA Somatic.

Measure	FOR	Mean	Std. Error	p	η_p^2
STICSA Somatic	LOW HIGH	15.409 15.005	.940 .842	.165	.082
STICSA Cognitive	LOW HIGH	14.805 14.996	.673 .678	.442	.026
CSAI-2R Somatic	LOW HIGH	15.037 15.298	.697 .745	.332	.041
CSAI-2R Cognitive*	LOW HIGH	18.542 17.375	1.180 1.193	**.005***	**.293***
CSAI-2R Confidence*	LOW HIGH	24.438 25.839	1.174 1.174	**.008***	**.272***
GSR	LOW HIGH	6.904 6.771	.834 .805	.087	.133
HR	LOW HIGH	95.818 95.912	3.447 3.563	.862	.002
HF%	LOW HIGH	20.420 18.860	2.846 2.582	.429	.045
Save %	LOW HIGH	61.941 62.373	4.443 4.009	.815	.002
Reaction Time	LOW HIGH	.568 .570	.008 .007	.559	.015

Table 4.6: Summary of the main effects and means of field of regard (FOR).

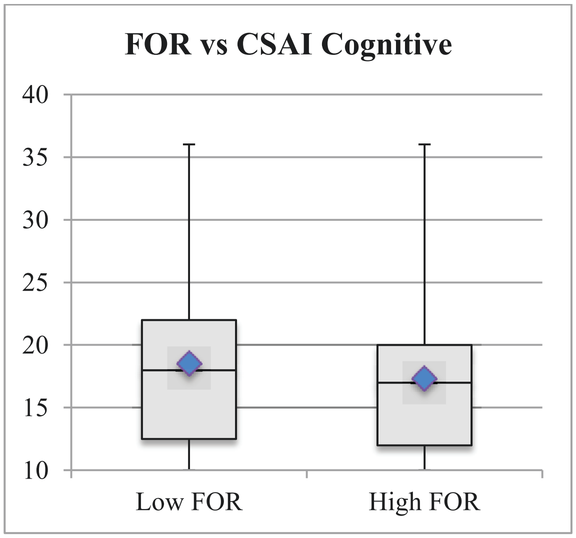


Figure 4.16: CSAI-2R Cognitive variance between the low and high FOR conditions (p = .005).

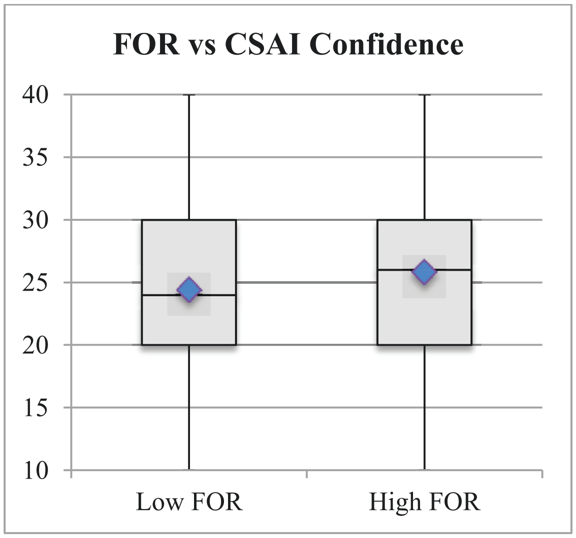


Figure 4.17: CSAI-2R Confidence variance between the low and high FOR conditions (p = .008).

4.4.2.3 Main Effect of Simulation Fidelity

Our analysis revealed a main effect of SF on CSAI-2R Somatic (p=.010, η_p^2=.253 (see Table 4.7 and Figure 4.18). Interestingly the mean CSAI-2R Somatic score increased for the high SF conditions, but the STICSA Somatic score decreased slightly.

Measure	SF	Mean	Std. Error	p	η_p^2
STICSA Somatic	LOW	15.252	.870	.630	.010
	HIGH	15.161	.901		
STICSA Cognitive	LOW	14.754	.647	.085	.124
	HIGH	15.047	.691		
CSAI-2R Somatic*	LOW	14.829	.646	**.010***	**.253***
	HIGH	15.506	.786		
CSAI-2R Cognitive	LOW	17.833	1.151	.561	.015
	HIGH	18.083	1.228		
CSAI-2R Confidence	LOW	25.005	1.101	.476	.022
	HIGH	25.271	1.223		
GSR	LOW	6.800	.814	.070	.148
	HIGH	6.874	.824		
HR	LOW	95.679	3.535	.353	.062
	HIGH	96.051	3.466		
HF%	LOW	20.441	2.631	.264	.088
	HIGH	18.839	2.638		
Save %	LOW	64.276	4.653	.135	.094
	HIGH	60.038	4.029		
Reaction Time	LOW	.566	.008	.057	.148
	HIGH	.572	.008		

Table 4.7: Summary of the main effects and means of simulation fidelity (SF).

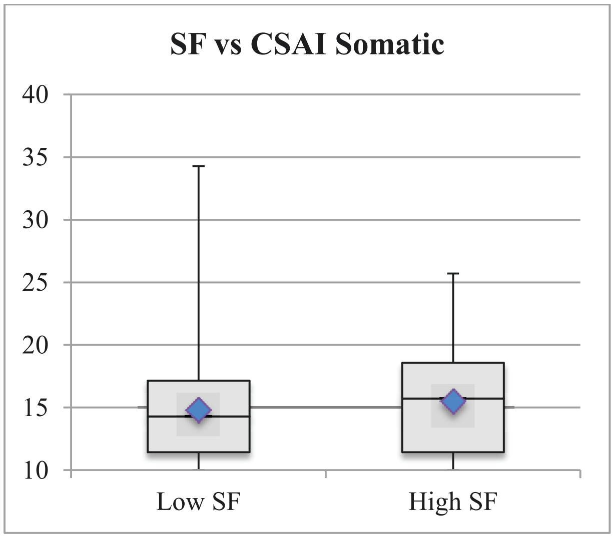


Figure 4.18: CSAI-2R Somatic variance between the low and high simulation fidelity conditions (p = .010).

*4.4.2.4 Interaction Effect (FOR * SF) for CSAI-2R Confidence*

There was a significant interaction between FOR and SF on CSAI-2R Confidence (p=.016, η_p^2=.227) (see Figure 4.19). A post hoc test with Bonferroni correction revealed that two of the pairs were significantly different: (1) Low FOR/Low SF and Low FOR/High SF, and (2) Low SF/Low FOR and Low SF/High FOR (p=0.01) (see Table 4.8 for a summary of all the pairwise comparisons).

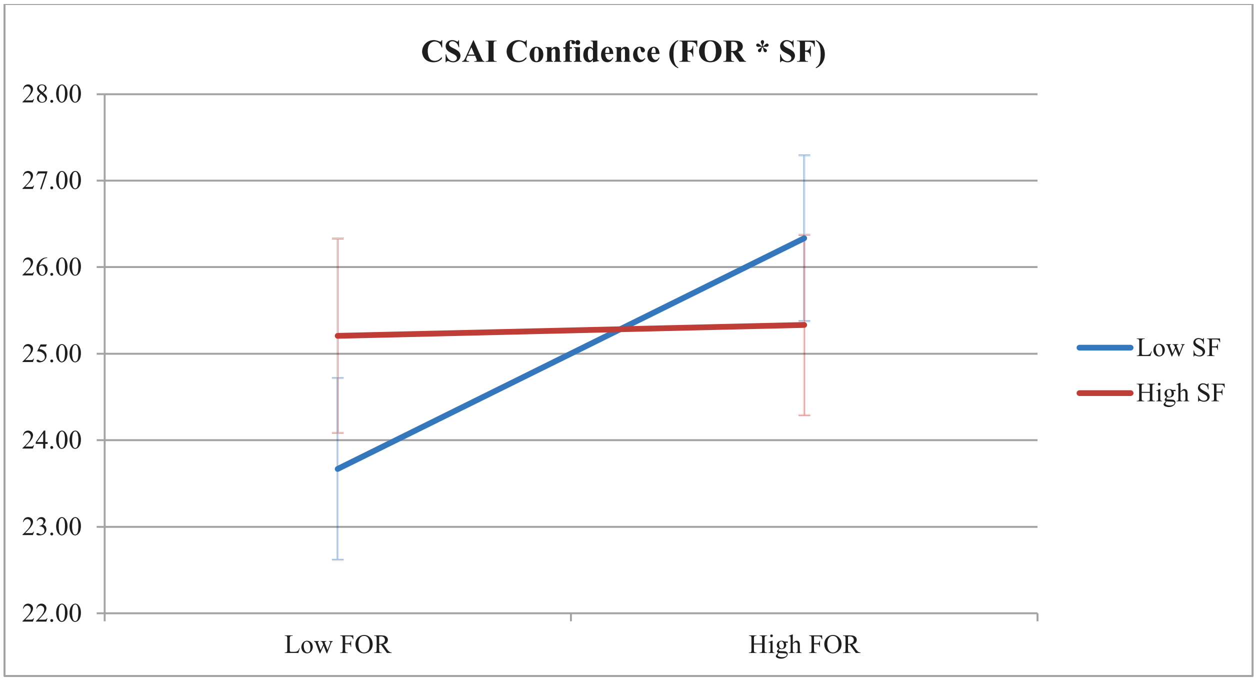


Figure 4.19: Graph depicting the interaction between FOR and SF on CSAI-2R Confidence. The significant pairs are: (1) Low FOR/Low SF & Low FOR/High SF, and (2) Low SF/Low FOR & Low SF/High FOR.

CSAI-2R Confidence Pairwise Comparisons (FOR * SF)				
Factor 1	**Factor 2**	**Mean**	**Std. Error**	**Significance**
LOW FOR	LOW SF	23.667	1.209	**.026***
	HIGH SF	25.208	1.226	
HIGH FOR	LOW SF	26.344	1.097	.092
	HIGH SF	25.333	1.310	
LOW SF	LOW FOR	23.667	1.209	**.001***
	HIGH FOR	26.344	1.097	
HIGH SF	LOW FOR	25.208	1.226	.854
	HIGH FOR	25.333	1.310	

Table 4.8: Summary of the pairwise comparisons between field of regard (FOR) and simulation fidelity (SF) for CSAI-2R Confidence.

*4.4.2.5 Interaction Effect (FOR * SF) for Save Percentage*

There was a significant interaction between FOR and SF on Save Percentage ($p=.034$, $\eta_p^2=.180$) (see Figure 4.20). A post hoc test with Bonferroni correction revealed only the High FOR/Low SF and High FOR/High SF pair were significantly different ($p=.016$) (see Table 4.9 for a summary of all the pairwise comparisons).

Figure 4.20: Graph depicting the interaction between FOR and SF on save percentage. The significant pair was High FOR/Low SF & High FOR/High SF.

Save % Pairwise Comparisons (FOR * SF)				
Factor 1	**Factor 2**	**Mean**	**Std. Error**	**Significance**
LOW FOR	LOW SF	62.293	4.940	.833
	HIGH SF	61.589	4.532	
HIGH FOR	LOW SF	66.258	4.687	**.016***
	HIGH SF	58.488	3.831	
LOW SF	LOW FOR	62.293	4.940	.123
	HIGH FOR	66.258	4.687	
HIGH SF	LOW FOR	61.589	4.532	.199
	HIGH FOR	58.488	3.831	

Table 4.9: Summary of the pairwise interactions between FOR and SF for save percentage.

*4.4.2.6 Interaction Effect (ANX * FOR * SF) for STICSA Cognitive*

There was a significant interaction between known anxiety triggers, FOR, and SF on STICSA Cognitive (p=.029, η_p^2=.190) (see Figure 4.21). A post hoc test with Bonferroni correction revealed that four pairs were significantly different. A full listing of all the pairwise comparisons and their significances can be found in Table 4.10 (L).

STICSA Cognitive Pairwise Comparisons (ANX*FOR*SF)

Factor 1	Factor 2	Factor 3	Significance
LOW FOR	LOW SF	LOW ANX	.084
		HIGH ANX	
	HIGH SF	LOW ANX	**.045***
		HIGH ANX	
HIGH FOR	LOW SF	LOW ANX	**.036***
		HIGH ANX	
	HIGH SF	LOW ANX	.609
		HIGH ANX	
LOW ANX	LOW SF	LOW FOR	.627
		HIGH FOR	
	HIGH SF	LOW FOR	.125
		HIGH FOR	
HIGH ANX	LOW SF	LOW FOR	.217
		HIGH FOR	
	HIGH SF	LOW FOR	.085
		HIGH FOR	
LOW ANX	LOW FOR	LOW SF	.170
		HIGH SF	
	HIGH FOR	LOW SF	**.046***
		HIGH SF	
HIGH ANX	LOW FOR	LOW SF	.089
		HIGH SF	
	HIGH FOR	LOW SF	**.004***
		HIGH SF	

CSAI-2R Confidence Pairwise Comparisons (ANX*FOR*SF)

Factor 1	Factor 2	Factor 3	Significance
LOW FOR	LOW SF	LOW ANX	**< .001***
		HIGH ANX	
	HIGH SF	LOW ANX	**<.001***
		HIGH ANX	
HIGH FOR	LOW SF	LOW ANX	**<.001***
		HIGH ANX	
	HIGH SF	LOW ANX	**.009***
		HIGH ANX	
LOW ANX	LOW SF	LOW FOR	**.004***
		HIGH FOR	
	HIGH SF	LOW FOR	.176
		HIGH FOR	
HIGH ANX	LOW SF	LOW FOR	**.038***
		HIGH FOR	
	HIGH SF	LOW FOR	**.04***
		HIGH FOR	
LOW ANX	LOW FOR	LOW SF	**.009***
		HIGH SF	
	HIGH FOR	LOW SF	.057
		HIGH SF	
HIGH ANX	LOW FOR	LOW SF	.405
		HIGH SF	
	HIGH FOR	LOW SF	.908
		HIGH SF	

Table 4.10: Summaries of the pairwise comparisons for the interaction between ANX, FOR, and SF for (L) STICSA Cognitive and (R) CSAI-2R Confidence.

*4.4.2.7 Interaction Effect (ANX * FOR * SF) for CSAI-2R Confidence*

There was a significant interaction between known anxiety triggers, FOR, and SF on CSAI-2R Confidence (p=.044, η_p^2=.164) (see Figure 4.22). A post hoc test with Bonferroni correction revealed that eight pairings were significantly different. A full listing of all the pairwise comparisons and their significances can be found in Table 4.10 (R).

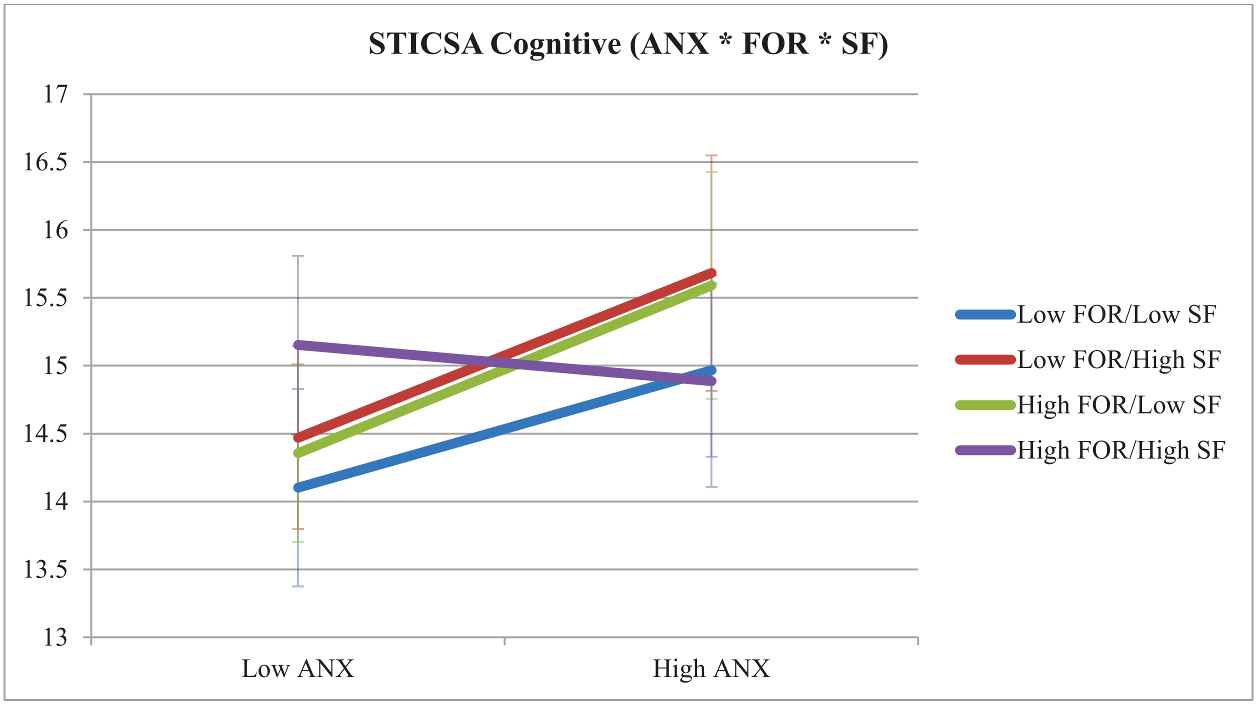


Figure 4.21: Graph depicting the interaction between ANX, FOR, and SF on STICSA Cognitive. The significant pairs are listed in Table 4.10 (L).

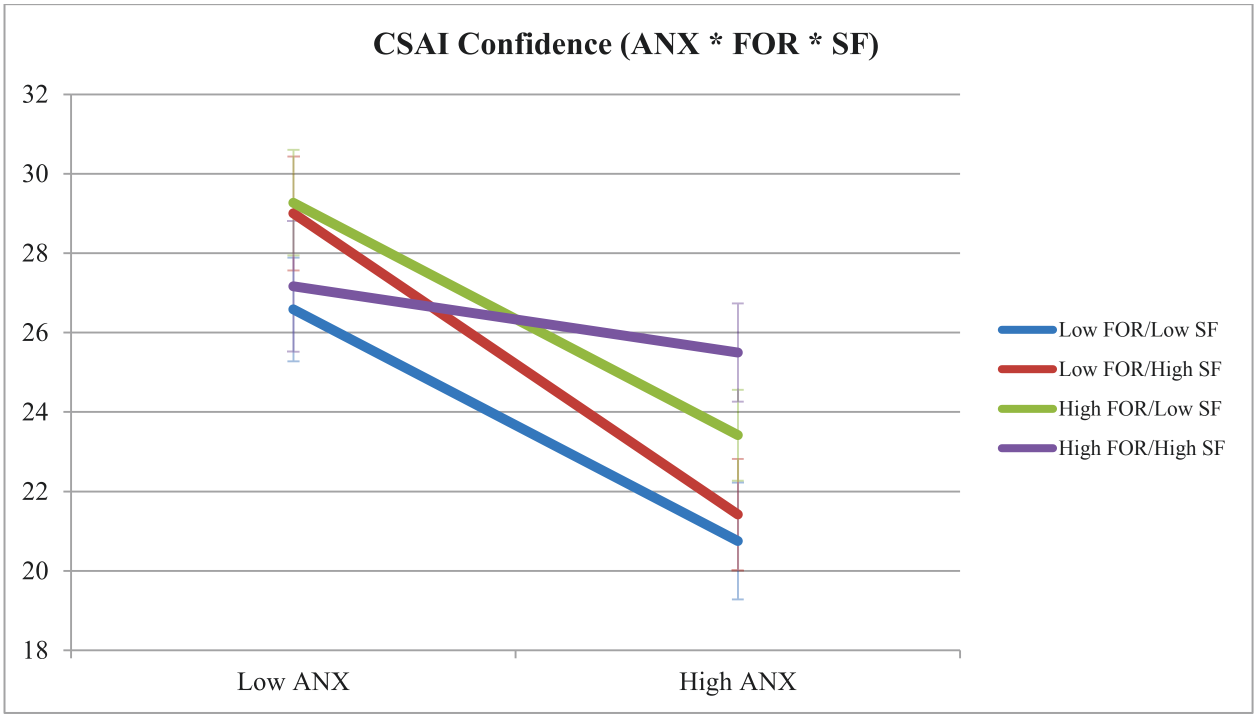


Figure 4.22: Graph depicting the interaction between ANX, FOR, and SF on CSAI-2R Confidence. The significant pairs are listed in Table 4.10 (R).

4.4.3 H3: There will be a direct relationship between trait anxiety and anxiety experienced in the system.

In order to investigate the relationship between trait anxiety and anxiety experienced in the system, we began by looking at the overall variances between the TRAIT and STATE responses. The means across all participants and conditions are reported in Table 4.11. Since only the STICSA provides a TRAIT measure, there are no TRAIT values for the CSAI-2R measures. In designing this study, we expected the participants to represent a broad range of trait anxiety. However, when we compare the trait anxiety scores in our study (see Table 4.11) to those of similar anxiety studies using the STICSA (Gros, Antony et al. 2007, Van Dam, Earleywine et al. 2012), it is apparent that we do not have a good representation of participants with high trait anxiety.

Measure	TRAIT		STATE	
	Mean	Std. Error	Mean	Std. Error
STICSA Somatic	16.360	3.272	15.054	1.070
STICSA Cognitive	13.309	2.662	14.991	1.065
STICSA Total (Som + Cog)	29.669	5.934	29.744	2.103
CSAI-2R Somatic	n/a	n/a	15.263	1.085
CSAI-2R Cognitive	n/a	n/a	17.990	1.278
CSAI-2R Confidence	n/a	n/a	24.952	1.773
CSAI-2R Total (Som + Cog)	n/a	n/a	29.670	5.930

Table 4.11: Summary of mean TRAIT and STATE anxiety measures across all participants and conditions. The TRAIT means were acquired from the responses to the baseline questionnaire at the beginning of the experiment; the STATE means were acquired by averaging the responses across all experimental conditions.

In order to determine the impact trait somatic anxiety had on anxiety experienced in the system, we assigned each of our participants to either a low or high trait somatic anxiety group based on STICSA somatic TRAIT responses from the baseline questionnaire. Most of the participants reported low scores, but at a threshold of twenty we achieved a split of nineteen low six high. We are not claiming that the threshold we chose necessarily represents a meaningful division between high and low trait somatic anxiety; rather it was simply a means of dividing our participants to perform a simple analysis. The mean STICSA somatic values for both the low and high groups are presented in Table 4.12.

Group	Somatic Anxiety (TRAIT)		Somatic Anxiety (STATE)	
	Mean	Std. Error	Mean	Std. Error
Low (< 20)	15.316	3.514	14.168	1.157
High (> 20)	27.333	11.159	17.822	2.572

Table 4.12: STICSA somatic TRAIT and STATE means for the low and high trait somatic anxiety groups.

Our analysis revealed that the high trait somatic anxiety group experienced a close to significant somatic anxiety increase over the low trait somatic anxiety group within the experimental conditions (p=.067) (see Figure 4.23). Interestingly, if we look at change scores (the baseline STATE version minus the experimental conditions mean) we see that the high trait somatic anxiety group experienced a significantly greater decrease in somatic anxiety from the baseline to the experimental conditions (p<.001) (see Figure 4.23).

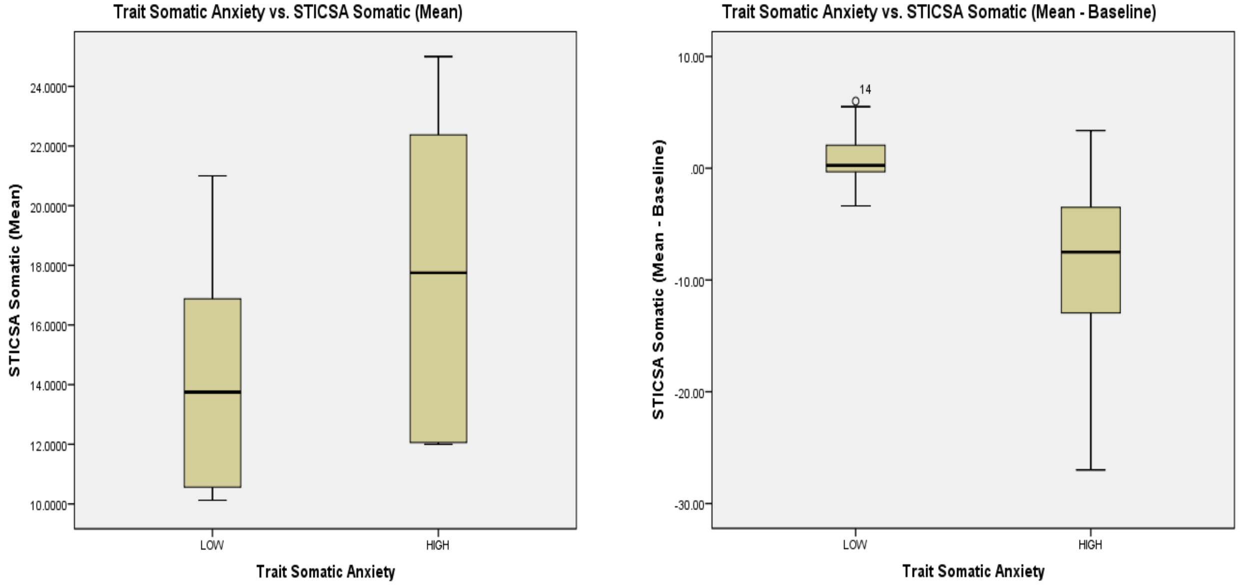


Figure 4.23: The variance between STICSA Somatic anxiety for participants in our low and high trait somatic anxiety groups. (L) Depicts the absolute values, whereas (R) depicts the change from the baseline.

Similarly, in order to determine the impact trait cognitive anxiety had on anxiety experienced in the system, we assigned each of our participants to either a low or high trait cognitive anxiety group based on STICSA cognitive TRAIT responses from the baseline questionnaire. Most of the participants reported low scores, but at a threshold of fifteen we achieved a split of nineteen low six high. Again, we are not claiming that the threshold we chose represents a true division of trait cognitive anxiety; rather it was simply a means of dividing our participants to perform a simple analysis. The mean STICSA cognitive values for both the low and high groups are presented in Table 4.13.

Group	Cognitive Anxiety (TRAIT) Mean	Std. Error	Cognitive Anxiety (STATE) Mean	Std. Error
Low (< 15)	10.833	2.485	14.145	1.147
High (> 15)	17.121	6.990	17.787	2.622

Table 4.13: STICSA cognitive TRAIT and STATE means for the low and high trait cognitive anxiety groups.

Our analysis revealed that the high trait cognitive anxiety group experienced significantly greater cognitive anxiety than the low trait cognitive anxiety group within the experimental conditions (p=.013) (see Figure 4.24). The change scores (baseline STATE version minus the experimental conditions means) do not follow the same pattern as somatic anxiety. The high trait cognitive anxiety group did not experience a significant change in cognitive anxiety from the baseline to the experimental conditions (p=.213) (see Figure 4.24).

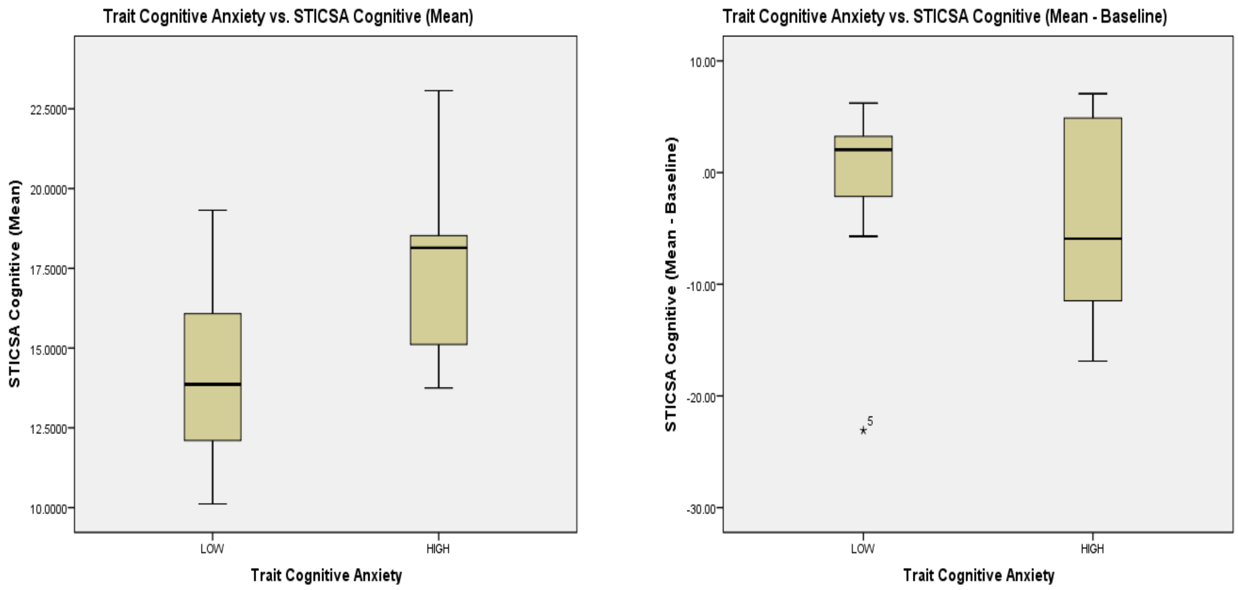


Figure 4.24: The variance between STICSA Cognitive anxiety for participants with low and high trait cognitive anxiety. (L) Depicts the absolute values, whereas (R) depicts the change from the baseline.

4.4.4 H4: There will be a direct relationship between goalkeeper experience and anxiety experienced in the high FOR and high SF conditions.

In order to investigate the relationship between goalkeeper experience and anxiety experienced in the system, we ran a repeated measures MANOVA with three within subjects factors (ANX, FOR, SF) and one between subjects factor (goalkeeper experience). We did not control for goalkeeper experience in our experiment, so we had uneven sets of participants. Included in the goalkeeper experience grouping were all participants who indicated they had previous competitive goalkeeper experience on their background questionnaire. In total there were six participants with previous goalkeeper experience (of which only three had HR data), and nineteen without (of which thirteen had HR data). The analysis revealed four significant interactions:

- Interaction between SF and goalkeeper experience on STICSA Cognitive
- Interaction between ANX, FOR, goalkeeper experience on CSAI-2R Confidence
- Interaction between ANX and goalkeeper experience on HR
- Interaction between FOR, SF, and goalkeeper experience on HR

*4.4.4.1 Interaction Effect (SF * Goalkeeper Experience) for STICSA Cognitive*

There was a significant interaction between SF and goalkeeper experience on STICSA Cognitive ($p=.045$, $\eta_p^2=.170$) (see Figure 4.25). A post hoc test with Bonferroni correction revealed that only the Low Experience/Low SF and Low Experience/High SF pairings were significant ($p=.012$).

*4.4.4.2 Interaction Effect (ANX * FOR * Goalkeeper Experience) for CSAI-2R Confidence*

There was a significant interaction between known anxiety triggers, FOR, and goalkeeper experience on CSAI-2R Confidence ($p=.007$, $\eta=.290$) (see Figure 4.26). A post hoc test with Bonferroni correction revealed that five of the pairwise comparisons were significant:

- Low FOR/Low EXP/ Low ANX & Low FOR/Low EXP/High ANX ($p< .001$)
- High FOR/Low EXP/Low ANX & High FOR/Low EXP/High ANX ($p=.001$)
- High FOR/High EXP/Low ANX & High FOR/High EXP/High ANX ($p=.007$)
- Low ANX/High EXP/Low FOR & Low ANX/High EXP/High FOR ($p=.016$)
- High ANX/Low EXP/Low FOR & High ANX/Low EXP/High FOR ($p=.002$)

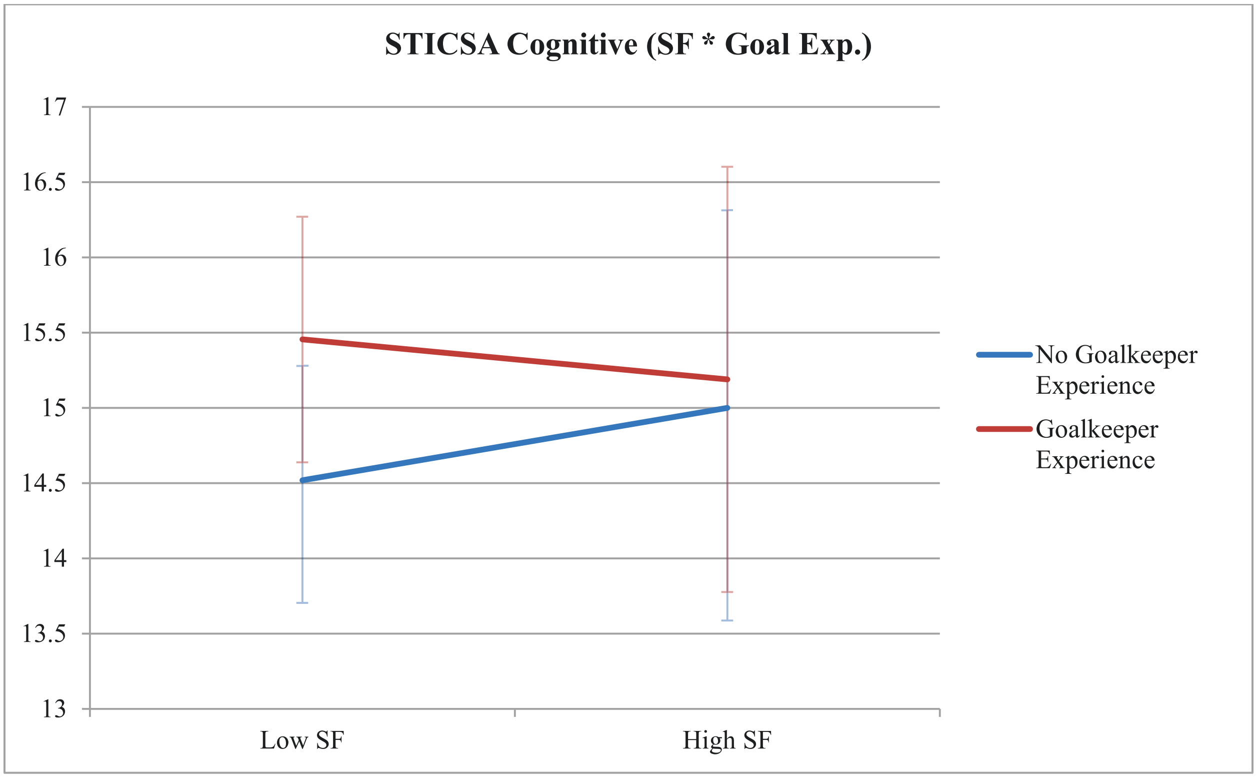


Figure 4.25: Graph depicting the interaction between SF and goalkeeper experience on STICSA Cognitive. The only significant pair is Low Experience/Low SF & Low Experience/High SF.

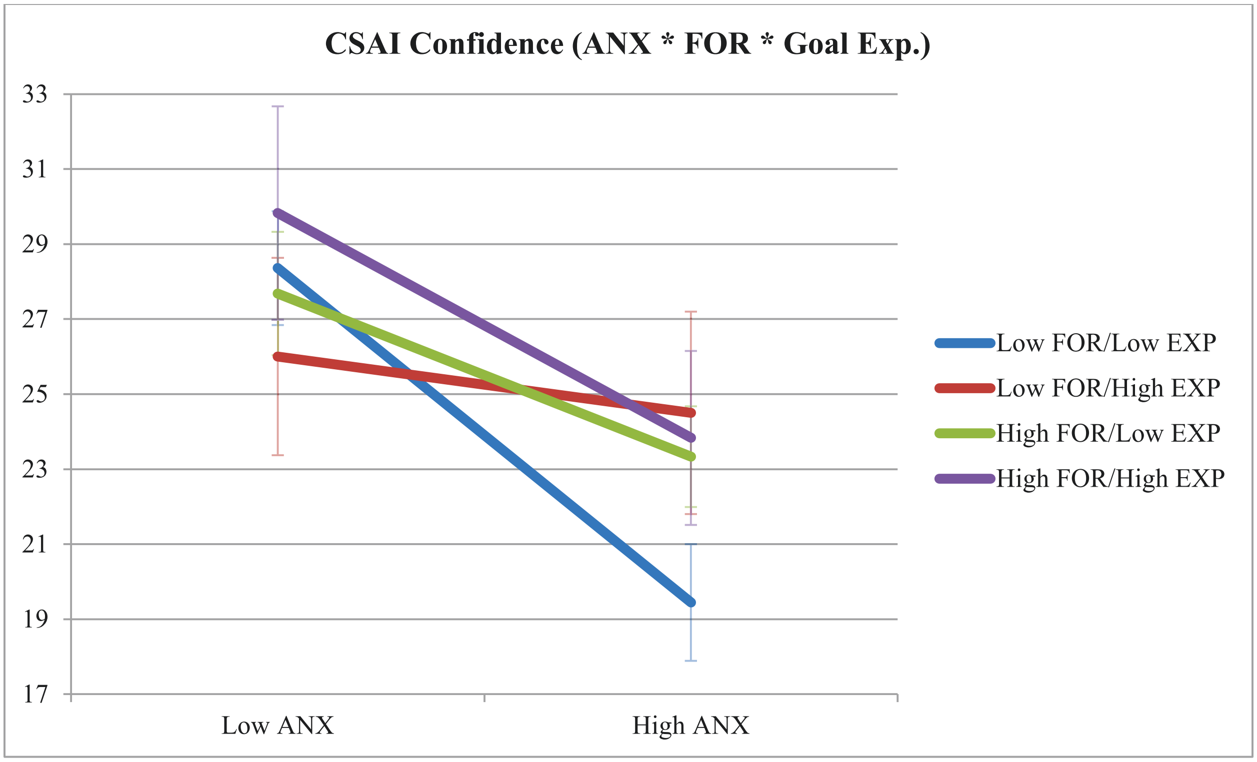


Figure 4.26: Graph depicting the interaction between anxiety, FOR, and goalkeeper experience on CSAI-2R Confidence.

*4.4.4.3 Interaction Effect (ANX * Goalkeeper Experience) for HR*

There was a significant interaction between known anxiety triggers and goalkeeper experience on HR (p=.001, η_p^2=.580) (see Figure 4.27). A post hoc test with Bonferroni correction revealed that only the High Experience/Low ANX and High Experience/High ANX pair was significant (p<.001).

*4.4.4.4 Interaction Effect (FOR * SF * Goalkeeper Experience) for HR*

There was a significant interaction between FOR, SF, and goalkeeper experience on HR (p=.025, η_p^2=.331) (see Figure 4.28). A post hoc test with Bonferroni correction revealed that only the High Experience/Low FOR/Low SF and High Experience/Low FOR/High SF pair was significant (p=.016).

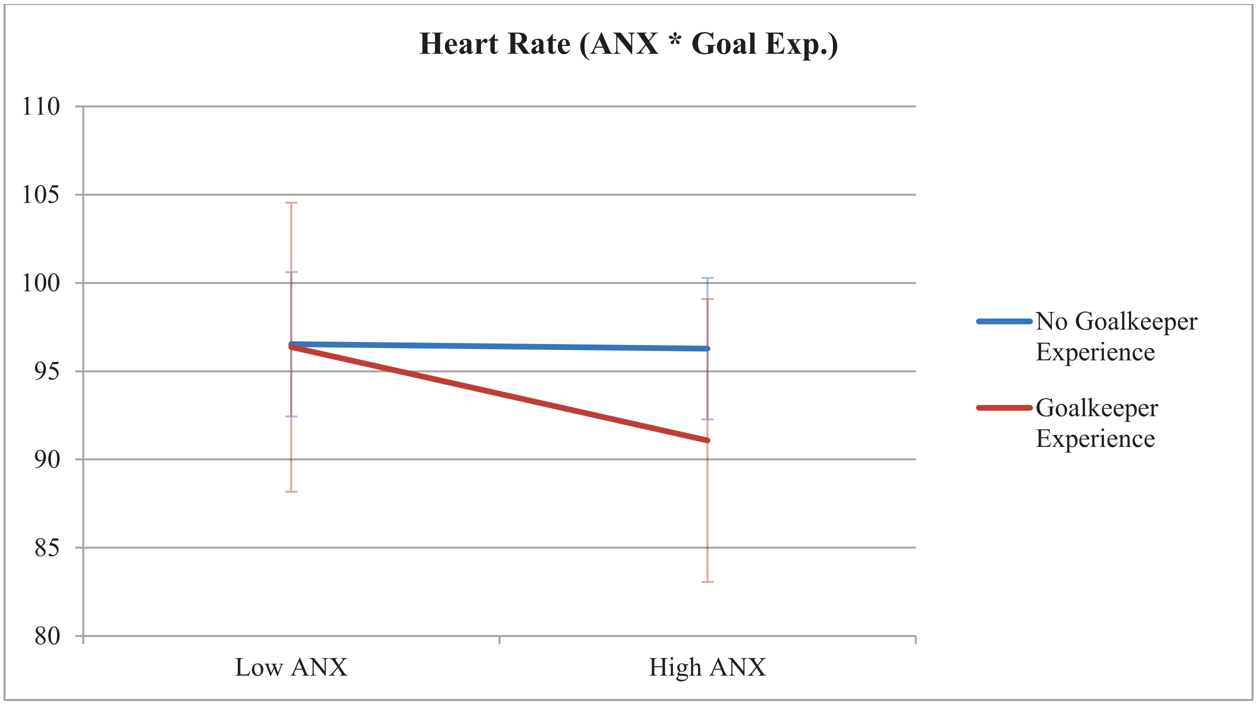


Figure 4.27: Graph depicting the interaction between anxiety and goalkeeper experience on HR.

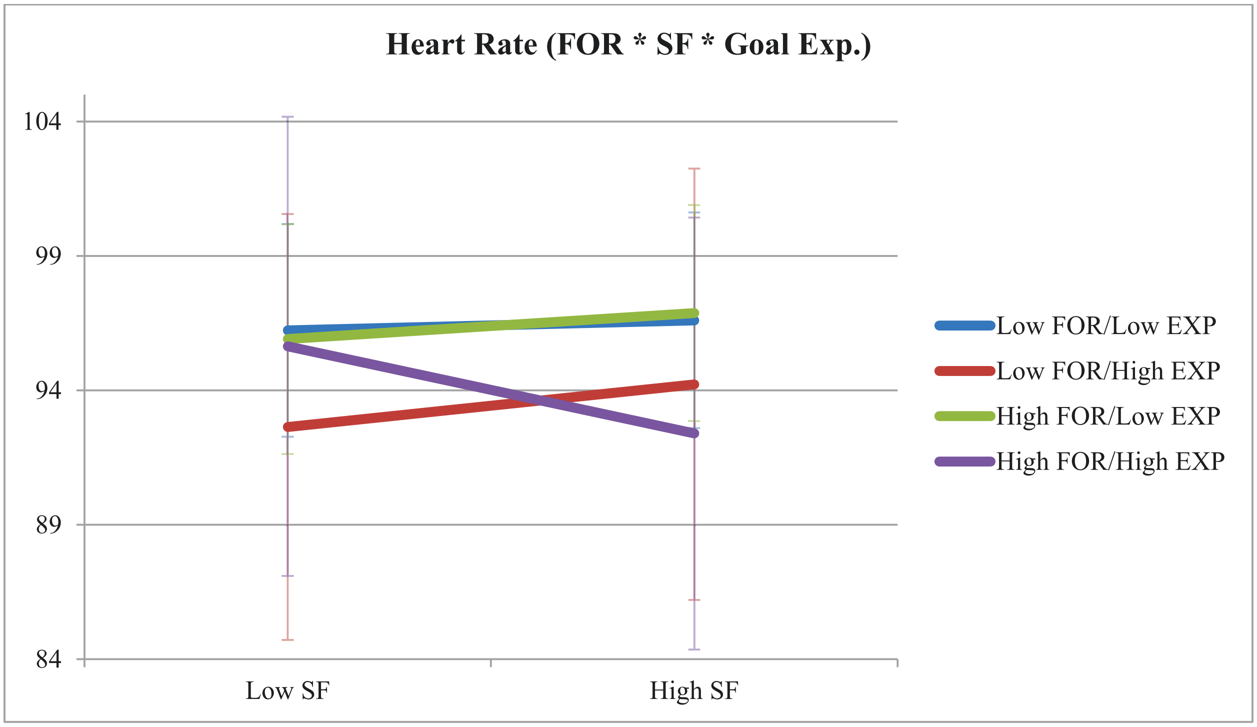


Figure 4.28: Graph depicting the interaction between FOR, SF, and goalkeeper experience on HR.

4.4.5 H5: The relationship between anxiety and performance will resemble an inverted-U shaped curve.

Finally we wanted to see if we our data matched the Hebbian version of the Yerkes/Dobson law of arousal vs. performance (Diamond, Campbell et al. 2007). When we looked at all the data together, we did not see any major trends. Attempts at regression analysis on STICSA Cognitive vs. Reaction Time and GSR vs. Reaction Time are demonstrated in Figure 4.29. The curves do not do a good job of representing the data (R2 = 0.09, and R2 = 0.09 respectively), and in fact contradict one another in terms of the relationship between anxiety and performance.

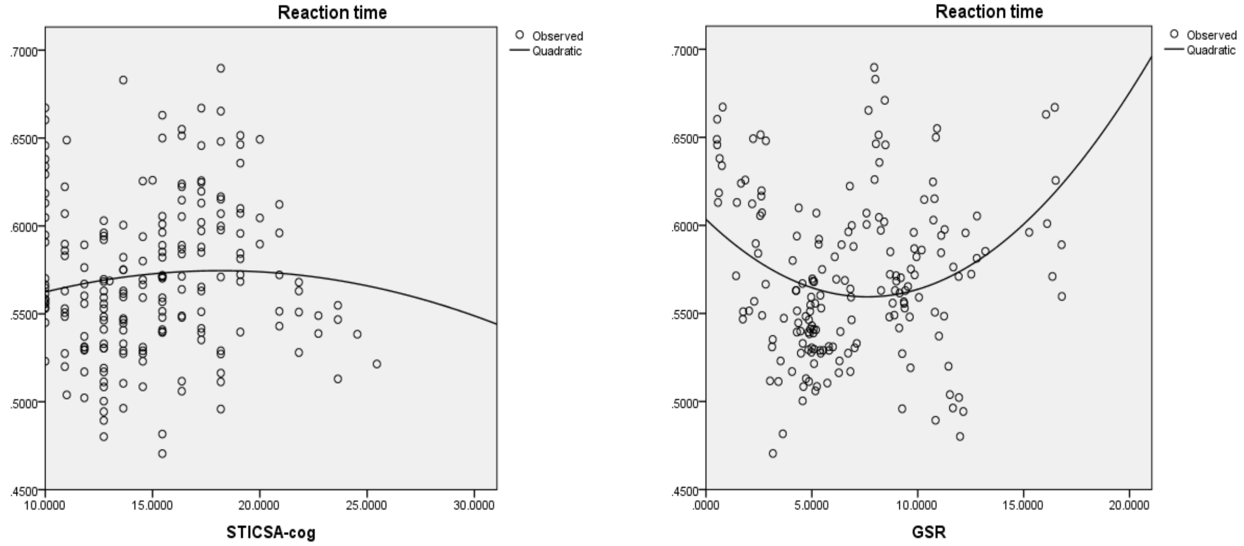


Figure 4.29: Two of the anxiety measures (STICSA Cognitive and GSR) were put through a regression analysis and fit to a quadratic (R^2 =0.08 for STICSA Cognitive vs. Reaction Time, and R^2 = 0.089 for GSR vs. Reaction Time). The fit for both curves was poor.

When we look at the participants individually, we see that the range of anxiety experienced between the various conditions was relatively low. We expected participants to exhibit an inverted-U shaped curve when observing the overall anxiety vs. performance measures; however, instead we observed that individual participants appeared to remain within a subset of the curve. Some participants appeared to experience an improvement in performance as arousal/anxiety increased, whereas others appeared to experience a decrease. There were other participants that did not show any particular up or down trend. We also see individual variances between the specific measures that seem to influence performance. With some participants you see a clear trend between subjective measures of anxiety (STICSA and CSAI-2R) and performance, whereas in others you see the trends with the physiological measures (GSR and HR).

In order to attempt to classify all the participants into one cohesive model of performance vs. anxiety, we took the inverted-U shaped curve representation of the Hebbian version of the Yerkes/Dodson law (Diamond, Campbell et al. 2007) and divided it into five segments (see Figure 4.30). We defined the five segments as follows:

- A: Low arousal, poor performance
- B: Energizing (positive) effect of arousal on performance
- C: Optimal arousal, optimal performance
- D: Negative influence of anxiety on performance
- E: High anxiety, poor performance

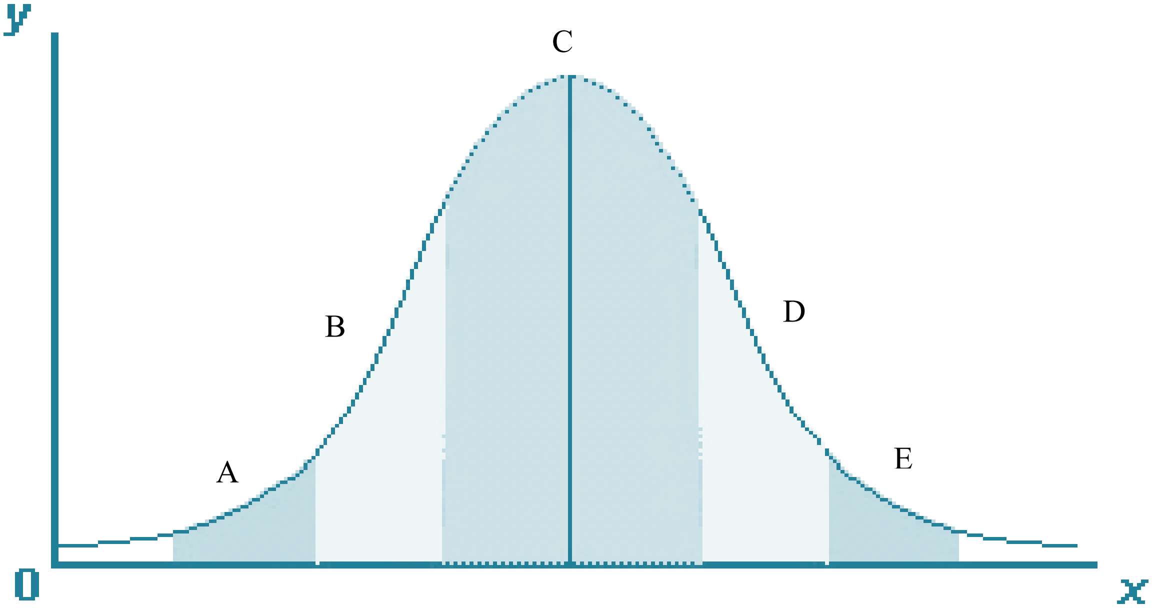


Figure 4.30: Divisions of the anxiety vs. performance curve. A - low arousal/poor performance, B - energizing effect of arousal, C – optimal arousal/peak performance, D - negative impact of anxiety, E - high anxiety/poor performance.

In order to classify each participant, we looked at the following anxiety vs. performance graphs:

- STICSA Somatic vs. Save %
- STICSA Cognitive vs. Save %
- HR vs. Save %
- GSR vs. Save %
- STICSA Somatic vs. Reaction Time
- STICSA Cognitive vs. Reaction Time
- HR vs. Reaction Time
- GSR vs. Reaction Time

We visually assessed the graphs for each participant one by one, and assigned each to the most appropriate segment. Participants with poor performance and low STICSA Somatic/STICSA Cognitive scores were grouped into segment A. Participants with an upward trend of performance with increased anxiety (either subjective or physiological) were grouped into segment B. Participants with optimal performance (mean save percentage over 80%) and steady anxiety scores were grouped into segment C. Participants with a downward trend of performance with increased anxiety were grouped into segment D. Participants with high anxiety scores and poor performance were grouped into segment E. The segments (A, B, C, D, E) and the associated participants are presented in Table 4.14.

Participant Classification for Anxiety vs. Performance Curve Segments				
Segment A	**Segment B**	**Segment C**	**Segment D**	**Segment E**
P23, P25	P1, P3, P5, P14, P19, P21	P2, P4, P8, P10, P11, P12, P13, P15, P18	P7, P16, P17, P20, P22, P24	P6, P9

Table 4.14: Participant classifications for the five arousal vs. performance curve segments.

It is relevant to note that not all participants were easily classified into one segment. Some participants appeared to span multiple segments. In our classifications, we chose to place the participant into the segment that best represented their overall experience in the system.

In order to illustrate the observed differences, we have included the full spread of graphs for five sample participants (one for each segment of the performance vs. anxiety model curve).

> **Segment A:** In Figure 4.31, we see a combination of low STICSA anxiety scores and poor performance in the system. There are slight variances in the physiological measures, but there is no discernable upward or downward trend with performance. It appears this participant was not trying very hard, and was not experiencing any anxiety.
>
> **Segment B**: In Figure 4.32 we see an upward trend for performance with increased anxiety in five of the graphs. Both save percentage and reaction time improved as cognitive anxiety, and GSR increased.
>
> **Segment C**: In Figure 4.33 we see mostly flat lines for trends across all the graphs. There is a slight downward tilt to some of the graphs, so it is possible this participant is on the verge between Segment C and D. The performance is consistently high throughout all conditions.
>
> **Segment D**: In Figure 4.34 we see a downward trend for performance with increased anxiety. Interestingly this participant reports high ranges of somatic anxiety, yet the physiological measures do not show much fluctuation.
>
> **Segment E**: In Figure 4.35 we see a clear downward trend for performance with increased anxiety. The participant reports very high levels of anxiety, and the overall performance is very poor.

The participant classifications for the anxiety vs. performance curve segments were done subjectively, and therefore there is no statistical evidence to support the validity of this classification. However by comparing all the measures for an individual participant we can get a good sense of the general trends experienced in the system.

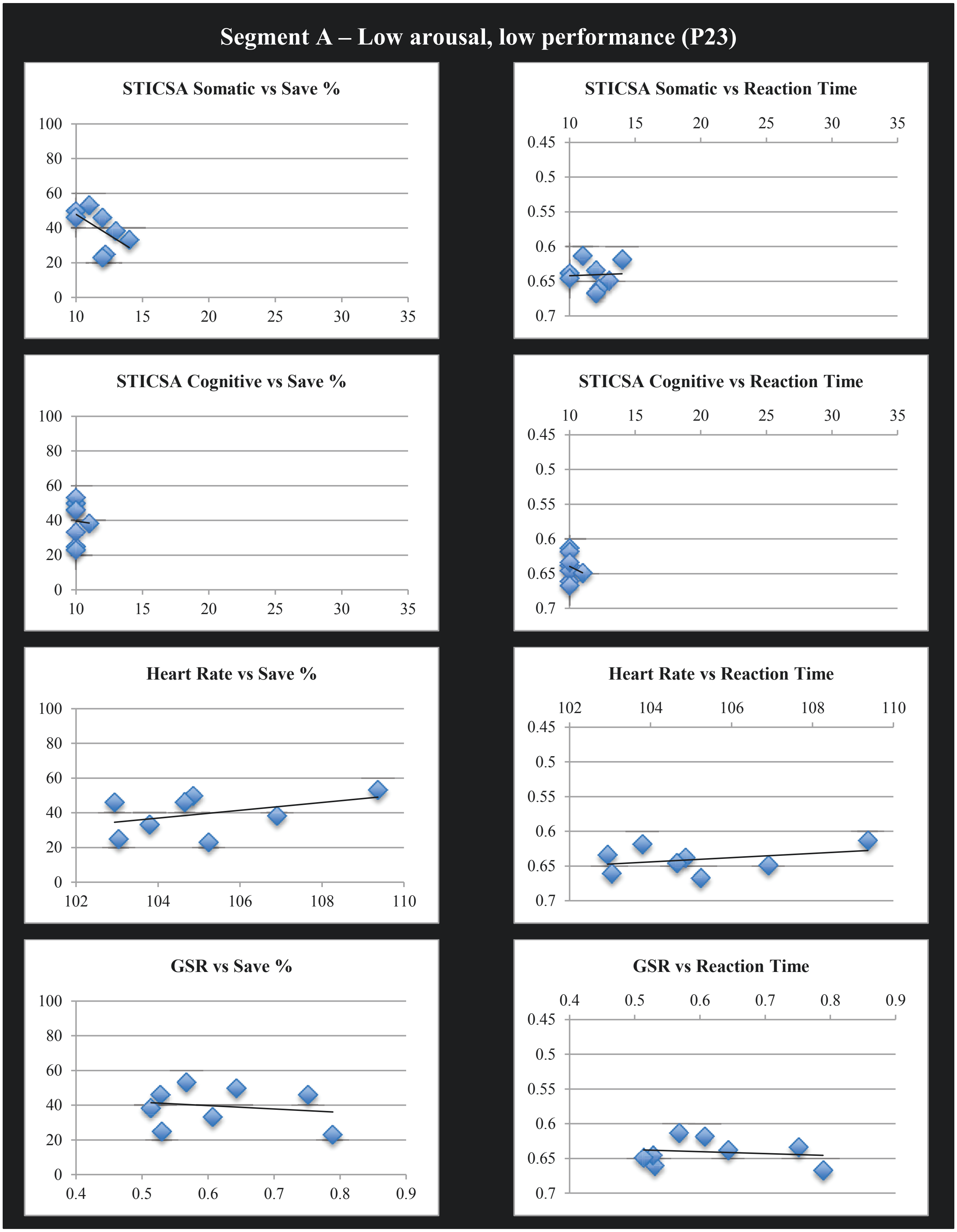


Figure 4.31: Anxiety vs. performance (Segment A) curves for a participant #23.

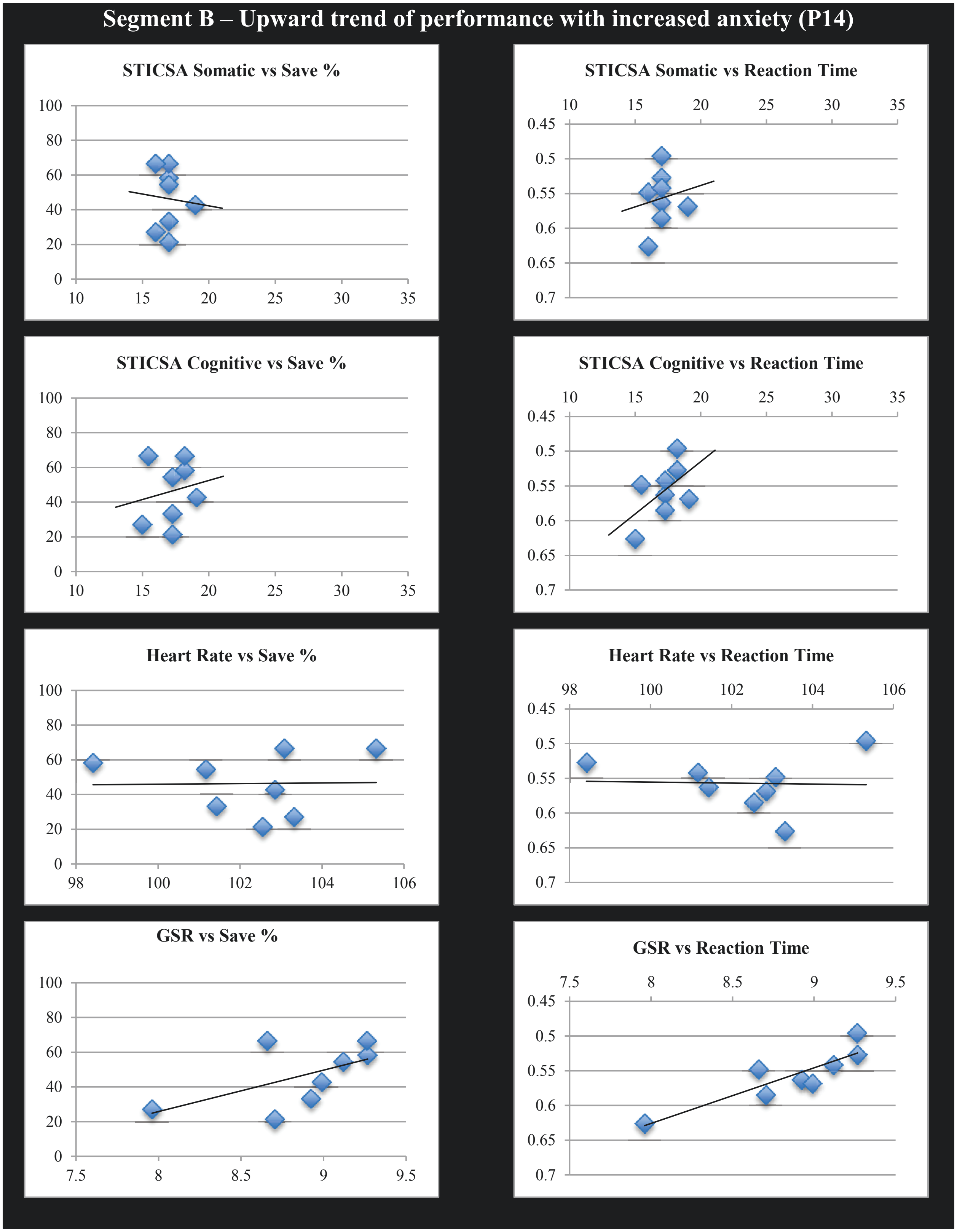


Figure 4.32: Anxiety vs. performance (Segment B) curves for a participant #14.

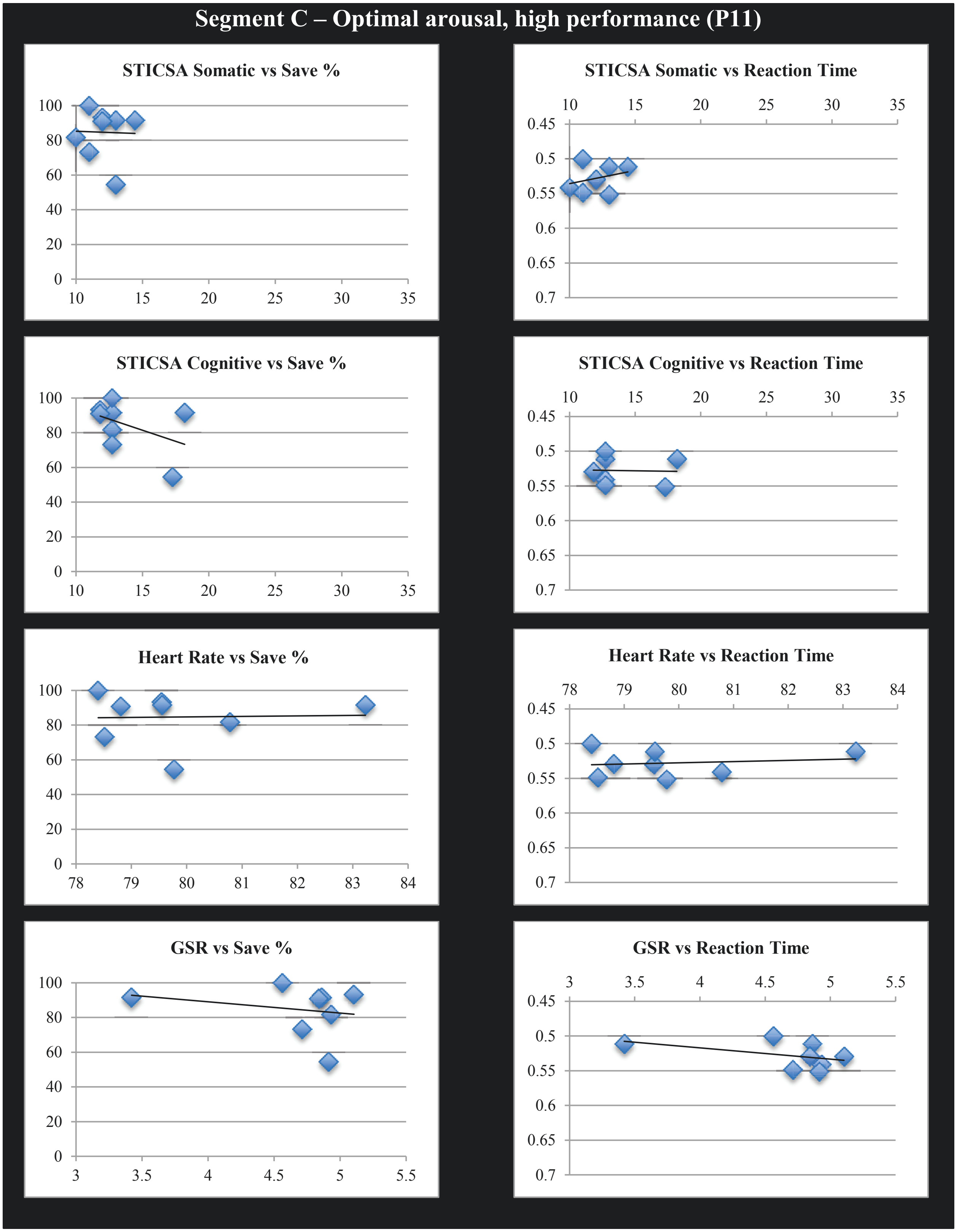
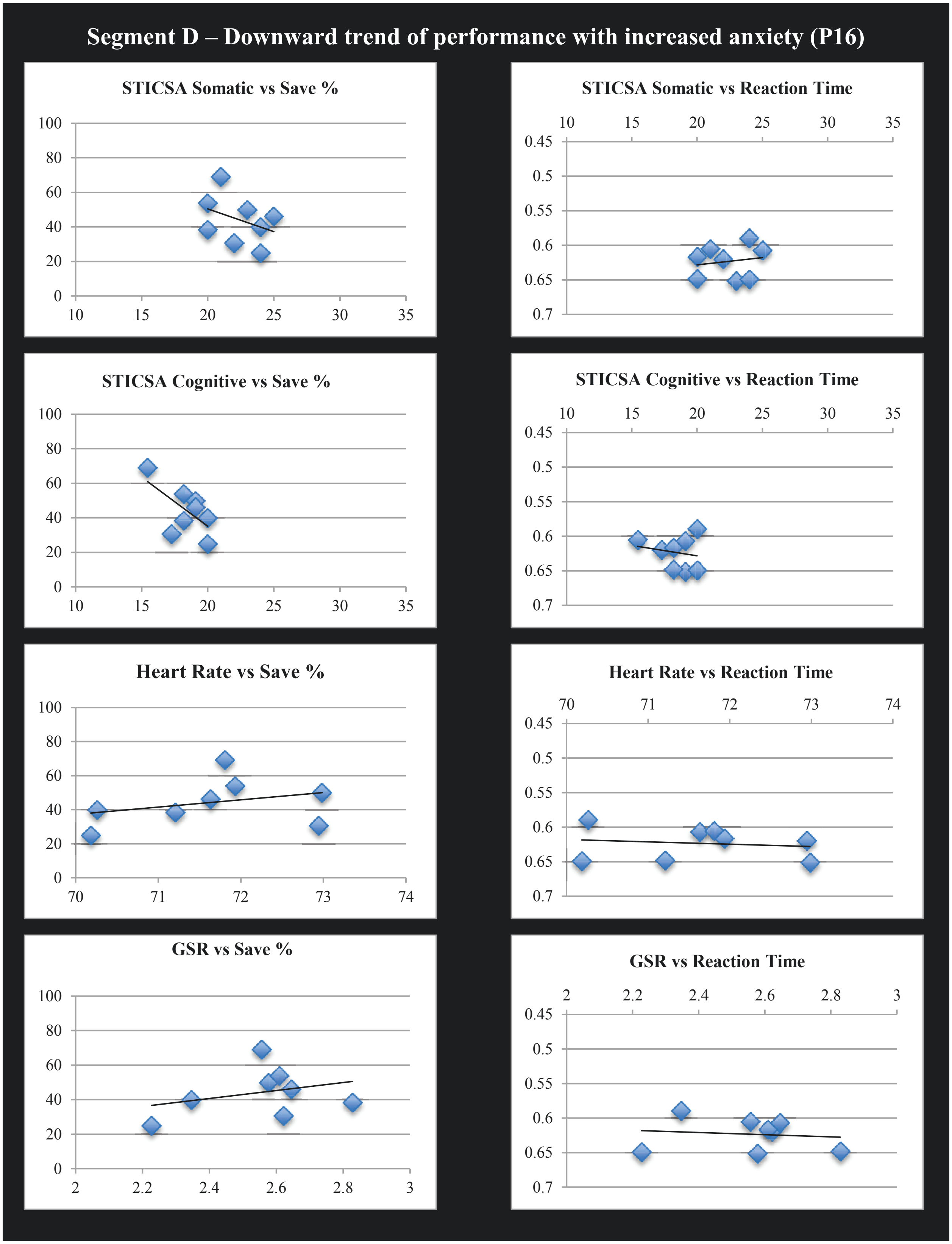


Figure 4.33: Anxiety vs. performance (Segment C) curves for a participant #11.


Segment D – Downward trend of performance with increased anxiety (P16)

STICSA Somatic vs Save %

STICSA Somatic vs Reaction Time

STICSA Cognitive vs Save %

STICSA Cognitive vs Reaction Time

Heart Rate vs Save %

Heart Rate vs Reaction Time

GSR vs Save %

GSR vs Reaction Time

Figure 4.34: Anxiety vs. performance (Segment D) curves for a participant #16.

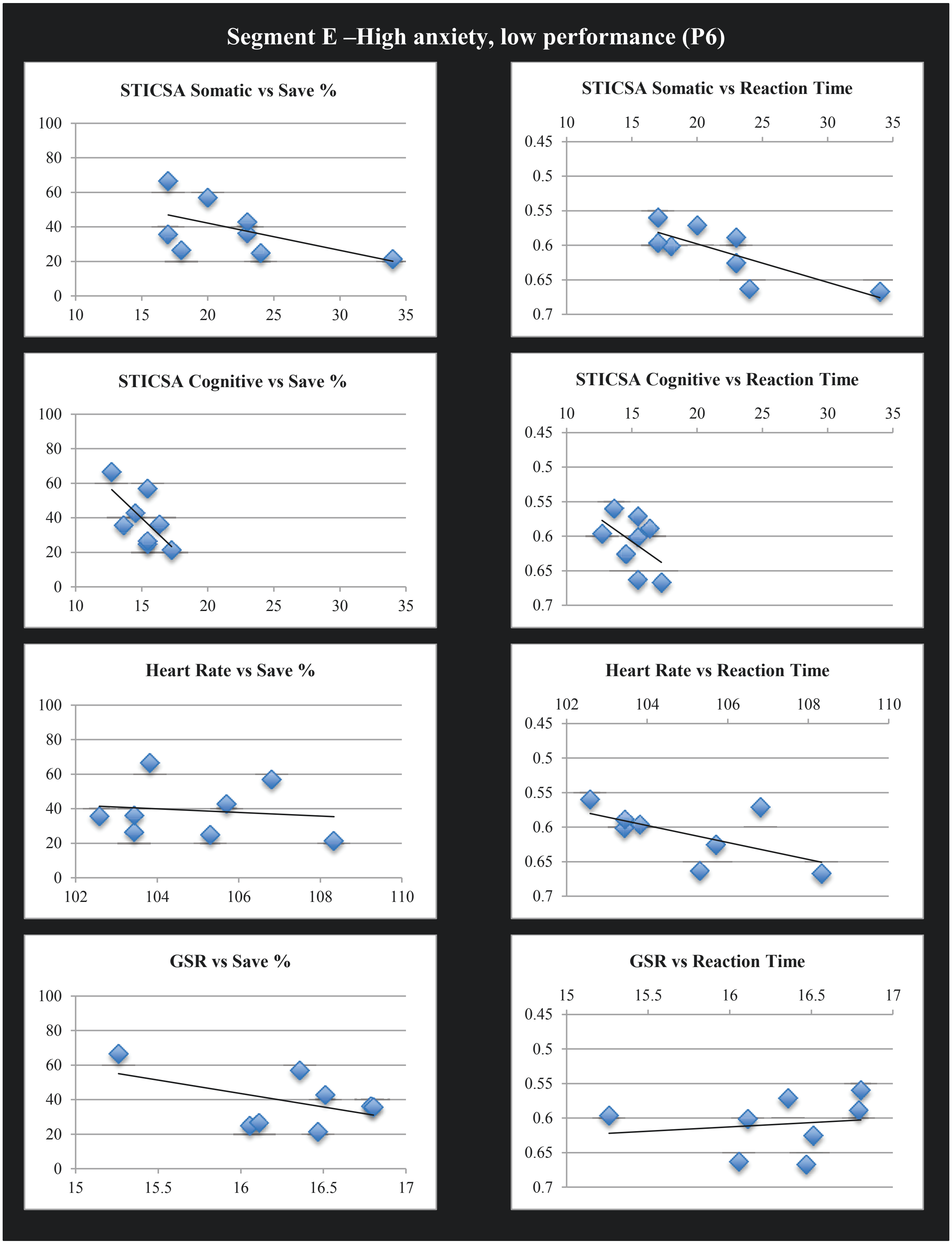


Figure 4.35: Anxiety vs. performance (Segment E) curves for a participant #6.

4.5 Discussion

In the following subsections we will discuss the results in terms of the hypotheses. Before discussing the results independently, it is important to note an overall observation on the subjective anxiety measures in our study. In designing this study, we expected the participants to represent a broad range of trait anxiety. However, when we compare the trait anxiety scores in our study (see Table 4.11) to those of similar anxiety studies using the STICSA (Gros, Antony et al. 2007, Van Dam, Earleywine et al. 2012), it is apparent that we do not have a good representation of participants with high trait anxiety. We are therefore cautious of overgeneralizing our results, as further study is necessary to determine if our results are generalizable across a more typical population.

4.5.1 H1: Use of the system (in any condition) will raise anxiety over baseline levels.

We clearly demonstrated in this study that anxiety could be induced in a VR sport application (see Table 4.3, Figure 4.6, Figure 4.7, Figure 4.8, Figure 4.9, Figure 4.10, Figure 4.11). There was a significant difference between the means of the baseline and in-condition measures. We saw significance in both the subjective and physiological dependent variables; however, it is unclear to what extent the physiological changes were due to the physical activity in the in-condition means. It is also relevant to note that while there was a statistically significant increase in anxiety in the conditions, the levels of anxiety reported by participants were still relatively low in an absolute sense (see Table 4.11). This is not surprising if we consider the previous research regarding VRET (see Section 2.1.4.1). VRET applications are designed to target users with phobic reactions to specific stimuli. The end goal of using a VR sport psychology-oriented application would be to treat athletes suffering from competitive anxiety, not all athletes. However in our study we did not control for athletic background or competitive anxiety predisposition. Perhaps to see large increases in anxiety within the conditions, the users would need to be athletes suffering from competitive anxiety. Further research is needed to investigate this hypothesis.

4.5.2 H2: All three independent variables (known anxiety triggers, FOR, and SF) will have a direct relationship to anxiety.

We also saw a number of main effects and interactions among our three independent variables. Known anxiety triggers had the highest number of significant effects in regards to our dependent variables, evidenced by increases in anxiety in both the STICSA (see Figure 4.12, Figure 4.13) and CSAI-2R (see Figure 4.14, Figure 4.15) measures. This supports our hypothesis that known anxiety has a direct relationship to anxiety.

There was a main effect of FOR on both CSAI-2R Cognitive (see Figure 4.16) and CSAI-2R Confidence (see Figure 4.17) suggesting that the low FOR condition causes more anxiety than the high FOR condition. A reasonable explanation for this result is that the low FOR condition simulates the decrease in visual periphery (tunnel vision) that many individuals experience in high-pressure situations. It is also possible that not having peripheral elements as a frame of reference impacts the ability of participants to focus on the task. It is also relevant to note that the STICSA Cognitive scores showed the opposite trend. This contradicts our hypothesis, as we expected to see increased anxiety for the high FOR conditions. Our results demonstrate the opposite effect; that increasing the FOR decreases anxiety in a VR sport psychology system.

There was also a main effect of SF on CSAI-2R Somatic (see Figure 4.18). Participants experienced greater levels of somatic anxiety in the high SF conditions over the low SF conditions. We believe that the additional visual and auditory elements included in the high SF condition triggered physiological sensations in the participants. Perhaps these elements reminded participants of past competitive experiences. This concept is supported anecdotally by the post-experiment interviews; in which several participants noted that seeing additional characters and hearing crowd sounds reminded them of past competitive experiences. This supports our hypothesis that SF has a direct relationship to anxiety.

While there were several main effects on both the STICSA and CSAI-2R measures, there were no significant physiological changes between the conditions. This is possibly due to the within-subjects design of the experiment; in that physiological reactions could take time to manifest, and could permeate multiple conditions. A reasonable explanation for this result is that the physical involvement in the conditions muted the physiological changes that may have been occurring, or that certain individuals respond differently in a physiological sense to the various conditions.

We also observed several interactions between the independent variables. There was a significant interaction between FOR and SF on CSAI-2R Confidence (see Figure 4.19). The lowest CSAI-2R Confidence scores were seen in the low FOR/low SF condition, and the highest in the high FOR/low SF condition. It appears that when SF is high, FOR does not have any impact on confidence; however when SF is low, there is a direct relationship between FOR and confidence. We believe that the visual and auditory elements in the high SF condition provide a stabilizing effect on confidence that negates the impact of FOR on confidence. However without the high SF elements, the low FOR decreases a participant's confidence in themselves and their ability to perform. There was also a significant interaction between FOR and SF on save percentage (see Figure 4.20). The combination of high FOR/high SF resulted in the lowest save percentage scores, whereas the high FOR/low SF combination led to the best save percentage results. It seems that having a high FOR improves performance, but only if SF is low. This could be due to the total amount of visual distractors present in the condition, since in the low FOR/high SF condition the blank screens hide many of the visual elements. It therefore could be that having peripheral awareness is helpful, but only if the periphery does not include a large number of distracting elements.

There was also a significant interaction between known anxiety triggers, FOR, and SF on STICSA Cognitive (see Figure 4.21). Our analysis revealed that adding known anxiety triggers to both the low FOR/high SF and high FOR/low SF conditions significantly increases anxiety. However the effect of known anxiety triggers is not significant for the low FOR/low SF and high FOR/high SF conditions. A reasonable explanation for this result is that the low FOR/low SF conditions are too dissimilar from reality for known anxiety triggers to have a noticeable effect. It is also possible that the high FOR/high SF condition is similar enough to reality that when anxiety-inducing elements are added they do not become as big a focus as in other conditions. Whereas the low FOR/high SF and high FOR/low SF conditions only partially resemble reality, so the added anxiety-inducing elements could become a bigger focus hence increasing the total anxiety.

There was also a significant interaction between known anxiety triggers, FOR, and SF on CSAI-2R Confidence (see Figure 4.22). Confidence scores are significantly higher for all combinations of low vs. high known anxiety triggers. This is not surprising, since in all the high anxiety conditions, the displayed results were very poor. The low ANX/high SF conditions showed no significant differences between the two FOR options; however FOR is significant for all other combinations. It appears that high FOR increases confidence in all cases except when SF is high and ANX is low. A reasonable explanation for this result is that the low ANX/high FOR/high SF combination is the closest to a real life scenario, and memories of previous competitive situations are influential. There is also a significant difference between the low ANX/low FOR and SF pairings. It appears that adding high SF to the low ANX/low FOR increases confidence, but adding to all other combinations decreases confidence. This could be because the low ANX/low FOR/high SF condition is the only condition where there is neither distracting elements in the environment, nor are the performance results manufactured. So this is the only condition where the participant would hear lots of positive crowd noise without visual distractors in the periphery. Therefore we believe that there is an important interaction between visual and auditory stimuli. Further research would be needed to investigate this hypothesis.

In summary, we found main effects for all three of our independent variables. Known anxiety triggers and SF both supported our hypothesis, and increased levels of anxiety were seen in the high conditions. The results for FOR contradicted our hypothesis, demonstrating that increasing the FOR actually decreases the anxiety experienced in the system. All three of these findings are important considerations for the future work. We included known anxiety triggers as a control in our experiment, in order to make some initial conclusions about the feasibility of VR-based systems over real-life training. Since known anxiety triggers can be leveraged in real-life sport training, our results regarding known anxiety triggers do not hold much relevance for future system design. The results regarding FOR and SF are however very relevant. Future work can leverage highly realistic environments and accurate scenario simulations to induce feelings of anxiety in participants. However since we demonstrated that high levels of FOR decreases anxiety, it is advisable to use lower FOR displays to deliver the training for general populations (see Section 4.5.4 for a discussion on FOR for experienced goalkeepers). It should be noted that our low FOR condition still featured a fairly high FOR (90°). Future work should investigate if this result is generalizable to FOR displays lower than 90°.

4.5.3 H3: There will be a direct relationship between trait anxiety and anxiety experienced in the system.

Our analysis indicates that participants with high trait cognitive anxiety (according to our classifications) experience higher anxiety within the conditions than participants with low trait cognitive anxiety (see Figure 4.12, Figure 4.13). However participants with high trait somatic anxiety (according to our classifications) do not experience significantly greater anxiety than participants with low trait somatic anxiety. Interestingly, participants with high trait somatic anxiety experienced a significant decrease in anxiety between the baseline STATE version of the STICSA and the in-condition mean. There was no significant difference for participants with high trait cognitive anxiety between the baseline STATE version of the STICSA and the in-condition means. This suggests that participants with high trait somatic anxiety experience the highest levels of anxiety before the experiment begins. Therefore, it seems that trait somatic anxious individuals are highly influenced by the newness of the experiment.

The findings support our hypothesis to a limited extent. High trait cognitive anxiety participants experienced significantly higher levels of cognitive anxiety in the system; however high trait somatic anxiety participants did not experience a significant difference in somatic anxiety in the system. Conversely, the high trait somatic anxiety group experienced a significant decrease in somatic anxiety once the conditions started.

Overall, the participants in our experiment reported relatively low trait anxiety values. Therefore we are unable to make any strong conclusions about the impact of trait anxiety on anxiety experienced in the system. This line of research is also targeting athletes who struggle with competitive anxiety – therefore it is possible that merely looking at trait anxiety is not enough. Perhaps it is necessary to look at a population of athletes and control for competitive anxiety predisposition to get clear sense of how trait anxiety impacts the extent of anxiety experienced in a VR sport-oriented application.

4.5.4 H4: There will be a direct relationship between goalkeeper experience and anxiety experienced in the high FOR and high SF conditions.

Our analysis revealed a significant interaction between SF and goalkeeper experience for STICSA Cognitive (see Figure 4.25). The only significant pairing was for the low experience grouping between the low and high SF conditions. It seems that only the low experience grouping experiences a significant increase in anxiety in the high SF conditions. This is contrary to our hypothesis, as we expected individuals with past goalkeeper experience to demonstrate higher levels of anxiety in the high SF conditions. We believe that having past experience dulls the impact of SF, since the simulation still does not approach reality. Conversely, we believe that individuals with no experience find the simulation more believable. It is possible we simply did not have enough goalkeepers in our participant pool to truly investigate this hypothesis. Running a study that controls for goalkeeping experience may reveal different results.

There was also a significant interaction between known anxiety triggers, FOR, and goalkeeper experience on CSAI-2R Confidence (see Figure 4.26). Adding known anxiety triggers always significantly decreased the confidence scores in the low experience grouping, but the pattern was different for the high experience group. We saw a significant decrease in confidence for the experienced group when there were known anxiety triggers and FOR was high, but not when FOR was low. This suggests that high FOR is important for triggering anxiety in experienced goalkeepers. It could be that the low FOR/high ANX conditions resonate more as a video game for experienced goalkeepers, whereas the high FOR/high ANX conditions trigger memories of past failures.

There were also two significant interactions involving HR: an interaction between known anxiety triggers and goalkeeper experience (see Figure 4.27), and an interaction between FOR, SF, and goalkeeper experience (see Figure 4.28). However there were only three participants in the high goalkeeper experience group with usable HR data. Therefore the results are likely skewed based on the order each of the three participants faced the various conditions. The highest HR values were typically witnessed in the first experimental condition. In order to investigate whether goalkeeper experience truly has an impact on HR we would need to control for goalkeeper experience in our experimental design.

Our results only partially supported our hypothesis. Participants with past goalkeeper experience reported decreased confidence scores when known anxiety triggers were present and FOR was high. However experienced goalkeepers were less influenced by the high SF conditions than those without. Comments during the interviews with the experienced goalkeepers revealed that the high SF conditions did not feel very realistic compared to past competitive experiences. Future work is needed to further investigate the effects of both FOR and SF on experienced goalkeepers. However from our limited findings, we believe that VR for sport psychology systems should leverage high FOR and high SF to support experienced goalkeepers.

4.5.5 H5: The relationship between anxiety and performance will resemble an inverted-U shaped curve.

When we analyzed the combined anxiety vs. performance data for all participants we did not see any clearly defined patterns. However by looking at each participant individually we were able to discern some patterns of how anxiety impacted performance in the system. We see that different individuals experience anxiety in different ways. Some participants experience a decline in performance corresponding to subjective measures, some corresponding to physiological measures, and some corresponding to both. Occasionally there are even contrasts between the various measures. For instance, a participant might exhibit a trend of improved performance with increased cognitive anxiety and also an inverse trend between performance and GSR. We believe that the impact of anxiety on performance is not only individualized, but also multidimensional. The implication of this hypothesis is that there is no single measure that can be used to easily model the relationship between anxiety and performance. Rather, a combination of measures is needed to truly capture an individual's state of anxiety and the effects on performance.

In our analysis, we classified individual participants into specific zones of the Hebbian version of the Yerkes/Dodson law of arousal vs. performance curve (Diamond, Campbell et al. 2007) by visually analyzing the various anxiety measures. We divided the curve into five segments: (1) A – low arousal/poor performance, (2) B - energizing effect of arousal, (3) C – optimal arousal/peak performance, (4) D – negative impact of anxiety, and (5) E – high anxiety/poor performance. After classifying each participant, we ended up with a spread of representative cases in each segment. Segment C had the highest number of participants; where arousal is optimal and performance is high. We likely saw the highest number of participants in this segment due to the design of the experiment. These participants likely maintained an ideal level of arousal since there was a monetary incentive to perform well, but did not experience much anxiety when confronted with the various experimental conditions. The next greatest spread of participants was in the B and D segments. In these participants we tend to see a linear trend (either positive or negative) of performance as anxiety increased. For the B segment, it is likely that the participants were not heavily motivated by money, and tended to lose interest or motivation as the experiment progressed. Another possibility is that these participants began with a low level of arousal, and the anxiety-inducing nature of the system triggered an increase in arousal contributing to better focus and performance. For segment D, it is likely that participants began with an optimal level of arousal, but experienced increased anxiety within specific conditions that contributed to a decrease in performance. There are only two participants classified into segment A, and two into segment E. This is not surprising, since we would not expect participants to sign up for the study without at least a minor motivation to perform well.

We also would not expect to see a large number of participants experience extreme levels of anxiety when using the system.

The classification of participants into separate segments of the Hebbian version of the Yerkes/Dobson law (Diamond, Campbell et al. 2007) was done by visually analyzing the results, and is not supported with any statistical evidence. Further work is needed to determine the relationship between anxiety and performance, and validate our classifications of the data. Overall we expected to see larger variances of anxiety and performance between the various conditions. While we do see individual trends, we expected that the range of anxiety and performance would be much greater for individual participants. We expected to see a clear point where the performance began to decrease for each participant; however, our results did not demonstrate such a relationship. It is likely that the levels between our independent variables (particularly known anxiety triggers and simulation fidelity) were not great enough to cause large reactions in the participants. Comments from the participants during the post-experiment interviews suggest that more personal feedback in the conditions would have caused more anxiety (i.e. the experimenter providing the negative feedback instead of the system, or the teammates/coaches in the high SF conditions interacting personally with the participant).

4.6 Conclusions and Future Work

Our controlled experiment investigating the potential of VR for treating sport-induced anxiety yielded very positive results. There was a significant increase in anxiety between the baseline and in-condition means for both subjective (STICSA, CSAI-2R) and physiological (GSR, HR, HRV) measures. We also saw a number of main effects and interactions in regards to the three independent variables: known anxiety triggers, FOR, and SF. All three independent variables appear to impact subjective measures of anxiety; however there were no significant differences in terms of physiological measures.

Our study demonstrated a direct relationship between trait cognitive anxiety and anxiety experienced in the system. The study also demonstrated that high trait somatic anxiety individuals experience the highest levels of somatic anxiety near the beginning of the experiment. This implies that VR sport psychology training systems should employ short, frequent sessions to maximize the anxiety effect.

Our results indicate that experienced goalkeepers do not experience significantly higher levels of anxiety in the high FOR and high SF conditions. However, participants with no goalkeeper experience do experience significantly higher levels of anxiety in the high SF conditions. It is possible that experienced goalkeepers need even higher levels of SF in order to see a significant increase in anxiety. It is also possible that the experienced goalkeepers in our study did not have the appropriate backgrounds to elicit such results. Since ultimately we would like to use VR to support sport psychology training, athletes who are pre-disposed to anxiety would be our ideal target users. Further research controlling for goalkeeper experience and psychological disposition would be needed to effectively investigate this hypothesis.

Looking at the overall anxiety vs. performance results did not reveal any significant trends. However when we looked at participants individually we could see trends to indicate various relationships between anxiety and performance. Different participants experienced different patterns, suggesting that sport anxiety is multidimensional, and multiple anxiety measures are needed to get a good sense of the impact anxiety has an on individual’s performance. We were able to replicate the Hebbian version of the Yerkes/Dodson law of arousal vs. performance (Diamond, Campbell et al. 2007) by visually analyzing and classifying each participant into various segments of the curve.

It is clear that using a VR sport application can induce anxiety in participants, and a general estimation of the relationship between anxiety and performance can be determined by visually assessing participant data. Future research is needed to determine if sport psychology training in a VR environment can lead to long-term reduction in sport-induced anxiety.

5 Case study: Extreme Jump Trainer

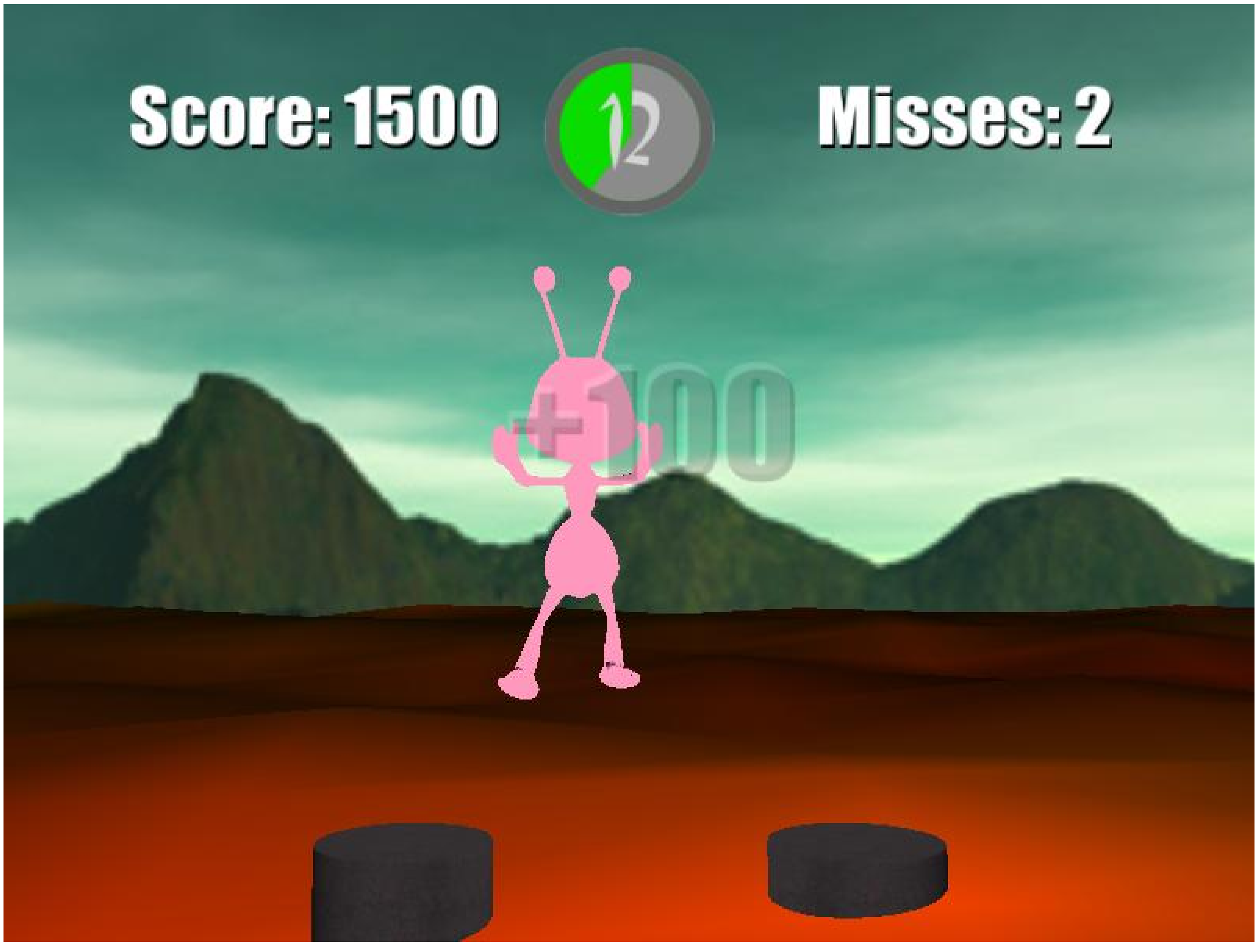


Figure 5.1: Screenshot of the *Extreme Jump Trainer* system.

5.1 Introduction

The previous two chapters of this thesis focused on the potential of using virtual reality (VR) to treat competitive anxiety. In this chapter we will investigate the feasibility of using VR to support another sport domain – biomechanics.

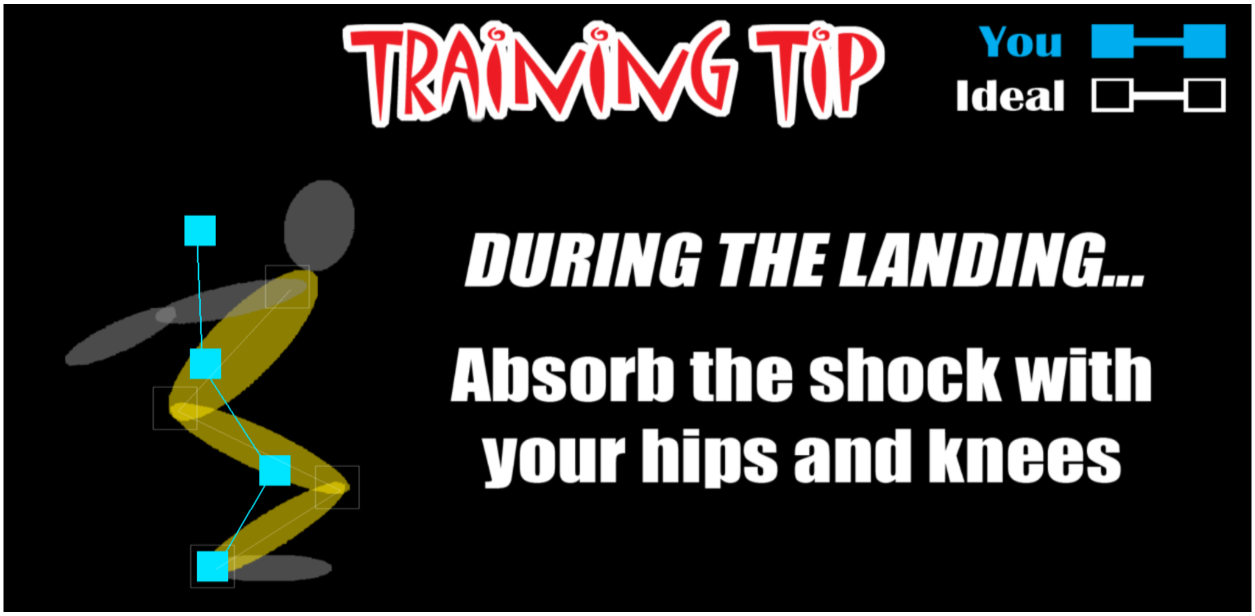
In this section we will present a jump training system we developed called *Extreme Jump Trainer*. The system is aimed at adolescents aged 5-12 who are looking to improve their jumping ability. The *Extreme Jump Trainer* system uses the Microsoft Kinect to provide real-time, full-body tracking to turn a common plyometric exercise (continuous lateral jumping) into a challenging video game. In the game, the user's movements control a cartoon avatar, and they must jump back-and-forth between two rocks floating in a sea of lava (see Figure 5.1). The goal of the exercise is to achieve as many jumps as possible in a period of 30 seconds. Jumping too slow, or not far enough, causes the character to sink into the pit of lava. After the exercise is over, users are presented with a series of images depicting their biomechanical performance. The performance at three key stages of the jump (DROP, DRIVE, and LANDING) are presented one at time, with the user's joint angles overlaid on an ideal representation of the jumping phase (see

Figure 5.2). The information presented is intended to improve a user's biomechanical technique. The purpose of the biomechanical analysis is twofold: (1) to improve the user's jumping ability, and (2) to reduce the risk of injuries associated with poor jumping technique.

The *Extreme Jump Trainer* system was developed to begin exploring the potential for VR to support sport biomechanical training. Two key research questions were addressed:

1. Can an effective VR biomechanical training system be achieved using standard computer equipment and commodity tracking devices?
2. How can we design the user experience of a sport training system to effectively deliver biomechanical principles?

The *Extreme Jump Trainer* system was demonstrated at an Open House event at Virginia Tech's Center for Human Computer Interaction (CHCI) in May of 2012. The response to the system was very positive and encouraging, and several users wanted to repeat the exercise multiple times in order to improve their biomechanical performance. The *Extreme Jump Trainer* project demonstrated anecdotally that an effective short-term VR biomechanical training system is achievable using standard computer equipment and commodity tracking devices. A controlled study would need to be conducted to validate these observations, and to determine the long-term benefits of the *Extreme Jump Trainer* system. The design, development and testing of the *Extreme Jump Trainer* system also revealed the importance of the user experience for delivering biomechanical principles to a broad audience of users. Most users were motivated primarily by the competitive nature of the application, and focused on maximizing the number of points earned in each round rather than on improving jumping biomechanics. From the limited data acquired at the project demo, it appears necessary to infuse the biomechanical training into the game play itself (i.e., the score is directly correlated to a user's adherence to the training tips) in order to encourage biomechanical improvement across a broad population of users.



DURING THE LANDING...

Absorb the shock with your hips and knees

Figure 5.2: An example of the biomechanical feedback provided to a user after the exercise is over. The yellow ovals represent the 'ideal' jumping model, and the blue squares are the user's actual performance.

5.2 Background and Motivation

Using VR for sports biomechanical training is an intriguing possibility, since it could combine both real-time analysis of an athlete's biomechanics and an engaging training environment. This would far exceed current training regimens, which generally occur in a gym without much technical intervention. Coaches provide most of the biomechanical feedback an athlete receives, relying on their own experience and perceptive abilities. At the higher levels of athletics (college and professional levels mainly) video is often used to analyze sport performance, but this is limited since it cannot be done in real-time, and provides only a single angle for performance analysis. Using VR for sport biomechanical training could represent a new paradigm in athletic development. It could lead to improved performance, faster development of athletes, reduced injuries, and faster recovery from serious injuries.

VR has proven itself very effective for a large set of training tasks, especially in the medical and military domains (see Chapter 2). Since VR training systems have been so successful in other domains, it seems plausible to infer that they would also be useful for real-time sports biomechanical training. However there are some fundamental differences between sport biomechanical training and other forms of training that make such an inference faulty. A few of the key differences include:

- **Sport actions often involve the whole body**
  Even the simplest of sport actions such as running and jumping require the activation and coordination of almost all the major muscle groups in the human body. This is much different than other VR training domains where only portions of the body need to be tracked for successful training scenarios (e.g., surgical training, flight simulator training).
- **Sport actions often require a lot of space**
  Most sport actions often require a lot of space to be performed (e.g., sprinting, pole vaulting, dunking a basketball). Training systems that require such space will need to include different design considerations than training scenarios involving relatively static scenarios (e.g., surgical training).
- **Sport actions often involve change in orientation**
  Many sport actions involve spinning, twisting, and moving between different orientations. This poses challenges for both tracking and displaying information to the user.
- **Sport actions often occur quickly**
  Many sport actions are dynamic, and occur at fast speeds. For instance the angular velocity of the arm of top-level pitchers is estimated to be between 300,000 and 500,000 degrees/second. Designing training systems to support such actions will require greater accuracy and precision than current training domains require.

It is clear that VR for sports biomechanical training is fundamentally different than other training domains. By studying the field, we can determine if existing tracking and display technologies are sufficient to support sport biomechanically training, and if so, to investigate how to design the user experience to maximize the training effectiveness.

An early exploratory study by Chua et al. looked at using VR for Tai Chi training (Chua, Crivella et al. 2003). At the time of these studies, tracking and display technology was limited, and both these systems featured low refresh rates and high latency. These technical limitations could explain the lack of performance improvement. Now that hardware has improved, we are seeing a few researchers re-examine the domain. Eaves et al. have recently looked at how best to train a dance task, and found that limiting the number of data points on the display helped users perform the task better (Eaves, Breslin et al. 2011). However, the system was only used to train static athletic postures, and did not support dynamic athletic actions. Kelly et al. looked at using extensive biomechanical analysis of users' golf swings, however the analyses were not in real-time (Kelly, Healy et al. 2010). Data was acquired using a VICON motion tracking system, and then analyzed post-hoc. While such a system can still lead to performance improvements, it is possible that a real-time training system could be an even more effective tool.

Why are there so few studies? There are several possible reasons to explain why VR for sport biomechanics training has not been investigated extensively:

- **Hardware/software limitations:** Until recently, even the highest-end full-body tracking systems had an upper limit of around 240 frames per second (fps). This can be limiting when being used for high-speed, dynamic sport actions.
- **Lack of portability of tracking systems:** A major issue with almost all high-end tracking systems is their lack of portability. Most systems need to be calibrated carefully, and are permanently installed inside laboratories. This severely limits the types of sport actions that can be studied. Often sports activities require extensive space or specialized equipment, and cannot be studied well in a lab.
- **Cost of tracking systems:** Another major issue with high-end tracking systems is their cost. Most high-end tracking systems are owned by research labs or academic institutions, and are not easily accessible by local sports teams. The cost of software is also an issue, since every sport has different athletic motions that need to be analyzed and interpreted in specialized ways.
- **Lack of sport biomechanical guidelines:** Even if all the other limitations could be overcome, there is currently very little conclusive research on what ideal sport actions look like. Interestingly this is largely due to the same limitations listed above, so it is likely that more knowledge on correct biomechanical principles will come to light over the next few years. Currently the standard practice is to compare a user's actions to an expert's (or a library of many experts) actions (Kelly, Healy et al. 2010). This has had success in improving the performance of many novice users, but is not very useful for users that are already experts in their sport.

Over the last few years several commodity tracking devices, such as the Microsoft Kinect, Nintendo Wii, and Playstation Move, have entered the market. The low cost and portability of these devices could help address several of the issues listed above. However the limitations on these devices in terms of space, speed and precision are still unclear, and we do not know if they can support a VR sport biomechanical system.

The Microsoft Kinect uses an RGB camera and a depth sensor to provide full-body, marker-free tracking (see Figure 5.3). The flexibility offered by such commodity devices is a great feature when considering VR sport biomechanics systems. Without being restricted to a lab, a lot more sport actions can be supported – and the low cost and widespread availability allows a broader audience to be reached.

Figure 5.3: Microsoft Kinect.

5.3 Goals of the Project

VR for sport biomechanical training is a largely unexplored field, and there are still many research questions to be addressed. In this exploratory project we developed an application called *Extreme Jump Trainer* in order to address the following two research questions:

1. Can an effective VR biomechanical training system be achieved using standard computer equipment and commodity tracking devices?
2. How can we design the user experience of a sport training system to effectively deliver biomechanical principles?

Being able to develop VR sport biomechanical training systems using commodity devices would be very useful. It would allow a greater number of sport scenarios to be supported; as such applications would no longer be dependent on expensive, non-portable tracking systems. It would also increase the accessibility of such applications, and open up possibilities for at-home training. This would greatly benefit rural and low-income families, who otherwise do not have access to high-level sport training. Therefore a goal of this project is to determine whether it is possible to develop effective VR sport biomechanical training systems using commodity devices.

Another question we intend to explore is how the user experience of such systems should be designed. The ultimate objective of such systems is to train athletes; therefore we want to design scenarios that will be engaging and motivating. Traditional sport training occurs in a gym with teammates, coaches, and crowds to encourage and motivate. VR training systems must offer something above and beyond what is possible in traditional training scenarios. Therefore a goal of this project is to explore possible design strategies to make some initial conclusions about how such systems should be implemented.

5.4 Development Process

The Extreme Jump Trainer application was developed during a class focused on innovative 3D applications, and throughout the semester we went through several stages of design. In the following sections we will outline how this project evolved from an initial concept into a fully functional jump training application.

5.4.1 Brainstorming

Initial Idea

The initial idea for this project came from a literature review we did in fall of 2011 for a Musculoskeletal Biomechanics class. It was a literature review investigating existing VR sport biomechanics applications, in which we discovered that there are currently very few VR tools for sport biomechanical training in real-time.

Our initial idea was to develop an application that used a VICON motion capture system to track an elite athlete performing a complex athletic task. The athlete's performance would be projected in stereo onto a large screen in real-time, superimposed on an ideal representation of the athletic task. The system would feature the ability to display the movements from various angles to target specific training goals based on the sport action. An additional consideration was to use a force platform to gain further biomechanical information to allow for more in-depth analyses. Possible sport actions for this idea were jumping, dance, yoga, squats, and volleyball block/pass/dig.

Refined Idea

After further research into the initial idea, we discovered that biomechanical knowledge about sport actions is still very limited. There are few solid guidelines regarding correct biomechanical technique; rather, most biomechanical training systems simply rely on a compilation of data from expert users. The timeline for the project was tight, and we did not have time to acquire such data. So we decided to switch our focus from expert athletes to novice athletes. Instead of a developing a system that would provide precise, biomechanical training our refined idea was to focus instead on generalized training principles. We decided to focus on a jumping task, since it is a relatively simple sport action that is well understood biomechanically, and because jumping is central to performance in many sports. One of the project members also had extensive playing and coaching experience in volleyball, and had the expertise needed to implement appropriate jump training protocols.

Since the new idea was targeting a broader audience, we felt it would be beneficial to include game-like elements in the application to teach the jumping principles in a fun way. We still wanted the biomechanical training to be the focus of the application, so our idea was to develop an application that featured a series of tutorials. Each tutorial would target one of the four jumping phases (see Figure 5.4) (Linthorne 2001), and would include the following:

- **Instruction/active learning**
  During the instruction, the system would demonstrate the correct postures for the involved jumping phase. Then during the active learning section users would practice the postures and see their body position superimposed on an ideal representation of the jumping phase.
- **Game-like challenge**
  During the game-like challenge, users would try to perform the appropriate action correctly in real-time, and depending on the result an animated character would do something cool like dunk a basketball or jump from one building to another.
- **Performance replays**
  After the challenge, replays would be shown. The replays would target the relevant stage of the jump and provide feedback on the users' performance.

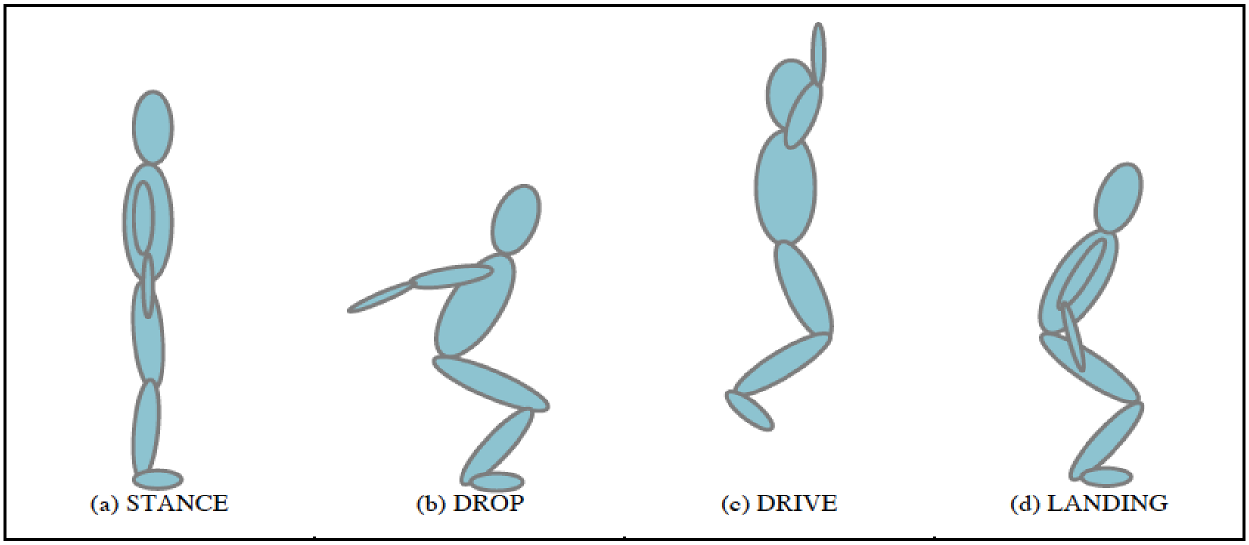

(a) STANCE (b) DROP (c) DRIVE (d) LANDING

Figure 5.4: Depiction of the four jumping phases.

Since we were now planning on targeting novice users instead of elite athletes, we started to consider using a Microsoft Kinect to support the application instead of a VICON tracking system. Teaching general jumping principles would not require the same level of accuracy in tracking as a system developed for elite athletes. Therefore it was possible that using the Microsoft Kinect would satisfy our purposes. Using a commodity device would also expand the flexibility of the training system. Instead of requiring a research lab with high-end equipment, the system could be leveraged by any user with a PC and a Microsoft Kinect device.

5.4.2 Sketches

At this phase in the project design, we were still undecided between two potential setups: (1) VICON motion tracking system, forceplate, and projection display and (2) Microsoft Kinect, and a large-screen TV. We drew a sketch for each of the potential setups to present during a class discussion (see Figure 5.5).

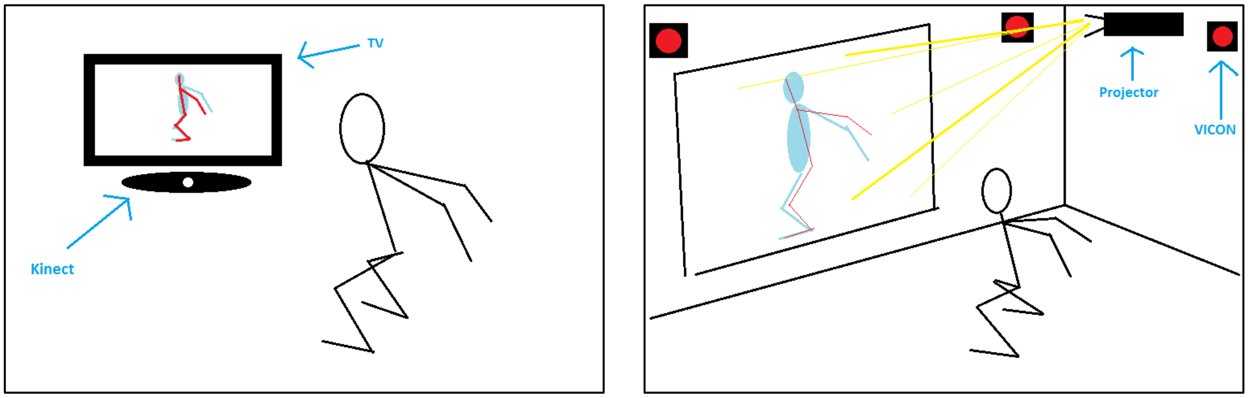


Figure 5.5: Initial sketches of the potential jumping application.

During the class discussion, the Microsoft Kinect option was much preferred. Our classmates expressed that the Microsoft Kinect setup was desirable because of its flexibility. Any user with a PC and Microsoft Kinect could use the system in their own home, and would not be restricted to a lab. After this discussion we chose to pursue the Microsoft Kinect option.

5.4.3 Visual Prototypes

In order to demonstrate to the class our concept for the application we put together a series of visual prototypes (see Figure 5.6). At this point we were planning on making the tutorials the main part of the application, and having the game-like challenge be a secondary element. Therefore the visual prototypes were developed to demonstrate the flow of the tutorials. Our concept was to develop a tutorial for each phase of the jump (see Figure 5.4). Each tutorial would begin with an instruction section, where the correct biomechanical postures for that phase would be demonstrated through a series of visualizations. The tutorial would then move to an active-learning section, where the user would try to achieve the correct posture limb-by-limb and hold it for a set length of time.

After presenting the visual prototypes to the class, we had an extended discussion about the direction of the project. People thought the instruction section would be mundane, and would not keep the attention of the users. We discussed how our perceptions were likely not a good representation of the population we were trying to design for. Our extensive playing and coaching background is evidence that we have a deep intrinsic motivation for athletic improvement. But it is unrealistic to expect that a broad audience would share this same motivation. Rather, it was important for us to design the system in the way that would inspire an average user to improve. So we decided to change the direction of the project, focus more on the fun elements of a challenging game, and infuse the biomechanical training into the game itself. We decided to structure the system similar to standard plyometric jump training exercises. Users would perform a jumping activity for a set period of time (in this case 30 seconds) and then take a break. We would leverage these break periods to provide biomechanical feedback in the form of ‘training tips’.

5.5 Final Design

Through the extensive design process, the purpose of the system evolved. The final design was to develop a VR biomechanical jump training system that would:

- Use standard computer equipment and commodity tracking devices.
- Focus on targeting a broad audience of users with varied athletic backgrounds.
- Involve a challenging game-scenario, where user enjoyment and motivation was of prime importance.
- Provide biomechanical feedback during break periods, to be used in subsequent training rounds.

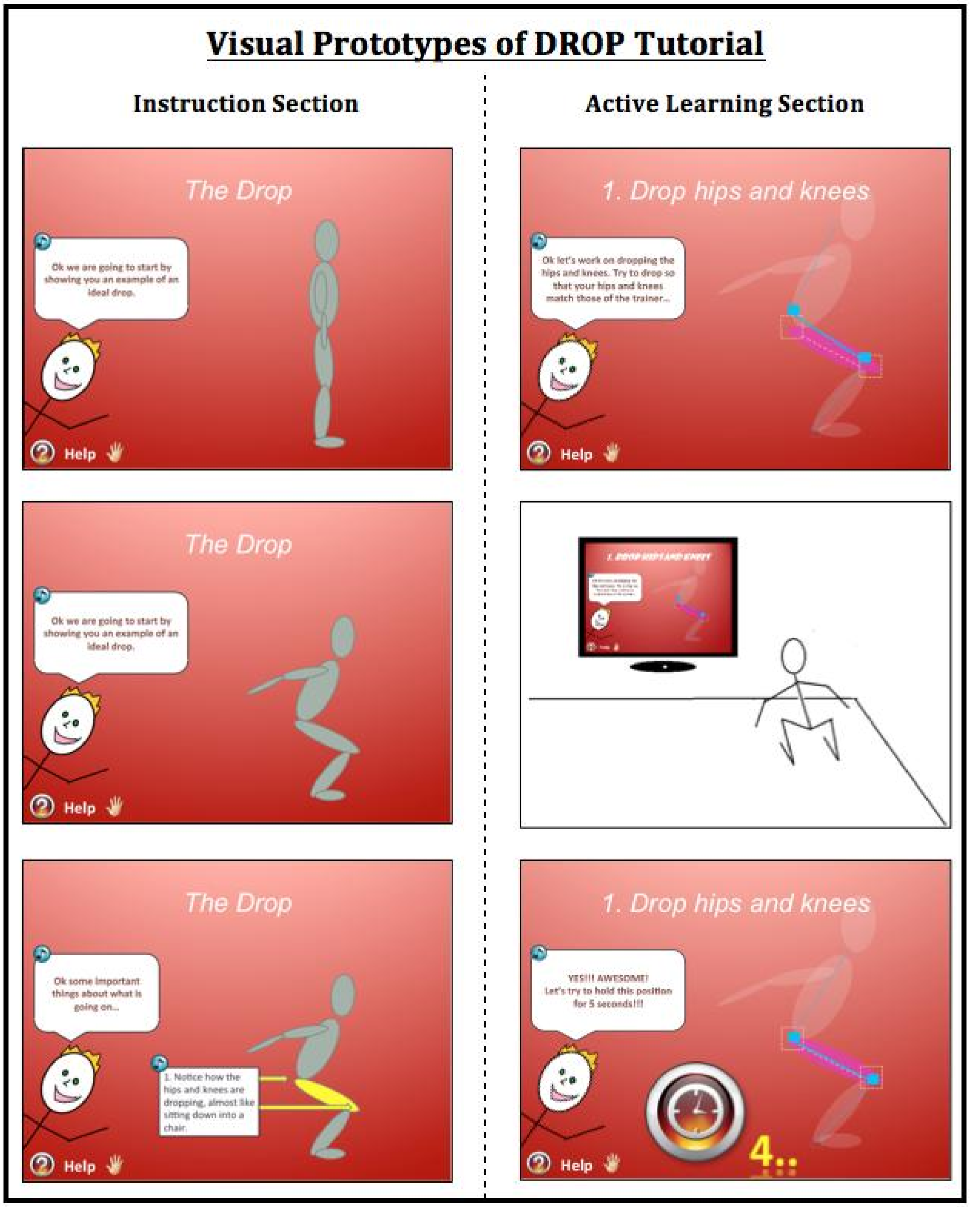


Figure 5.6: Prototypes *Instruction* (left) and *Active Learning* (right) sections for the THIGH potion of the DROP phase.

We wanted to choose a plyometric jumping activity that was both practical for biomechanical training, and could easily be infused into a game scenario. Plyometric exercises refer to a classification of exercises based around having muscles exert maximal force in as short a time as possible, with the goal of increasing both speed and power (Chu 1992). We choose to use *continuous lateral jumping*, since it met both the criteria. *Continuous lateral jumping* is a very common plyometric exercise that promotes jumping ability, coordination, speed, and proprioceptive control. We also immediately thought of a gaming scenario to fit the exercise – jumping from rock to rock in a sea of flowing lava.

We put a lot of thought into what biomechanical jumping principles we wanted to include in the system. We decided to include one training tip for each of the active phases of the jump (DROP, DRIVE, and LANDING). The STANCE phase is a static posture that does not hold much importance for novice athletes, so we chose to exclude it from the feedback. We knew users were only going to have a short period of time to interact with the system during the demo, so we chose training tips that could have immediate impact. The training tips we chose for the system and their justifications are as follows:

1. **DROP (ARMS)**
   Driving the arms back during the DROP phase provides a lot of momentum to propel the athlete upwards during the jump. From our expert knowledge, we knew that this element is often lacking in novice athletes. It is an easy element to train, and can often improve an individual's jump significantly.
2. **DRIVE (ARMS)**
   Same as in the DROP phase, driving the arms high into the air during the jump can significantly improve an individual's vertical. Many young athletes only use their arms minimally, if at all.
3. **LANDING (CORE)**
   Improper landing biomechanics can put excessive stress on the ankle and knee joints, increasing the potential for serious injury. Landing improperly also slows an athlete down, since their body is not balanced and ready to make another athletic move. Teaching proper landing biomechanics can greatly improve an athlete's speed and quickness, and increase their athletic longevity.

5.5.1 Apparatus

The *Extreme Jump Trainer* system uses a standard desktop computer (Windows 7 64-bit, NVidia GeForce GTS 250 512MB graphics card) and a Microsoft Kinect to run the application. Any standard display can be used, but for the project demo we used a 42" LCD TV. Sound was supported using a pair of external speakers. In order to achieve full-body tracking throughout the entire exercise, the user was told to stand approximately 10 feet (3m) away from the display.

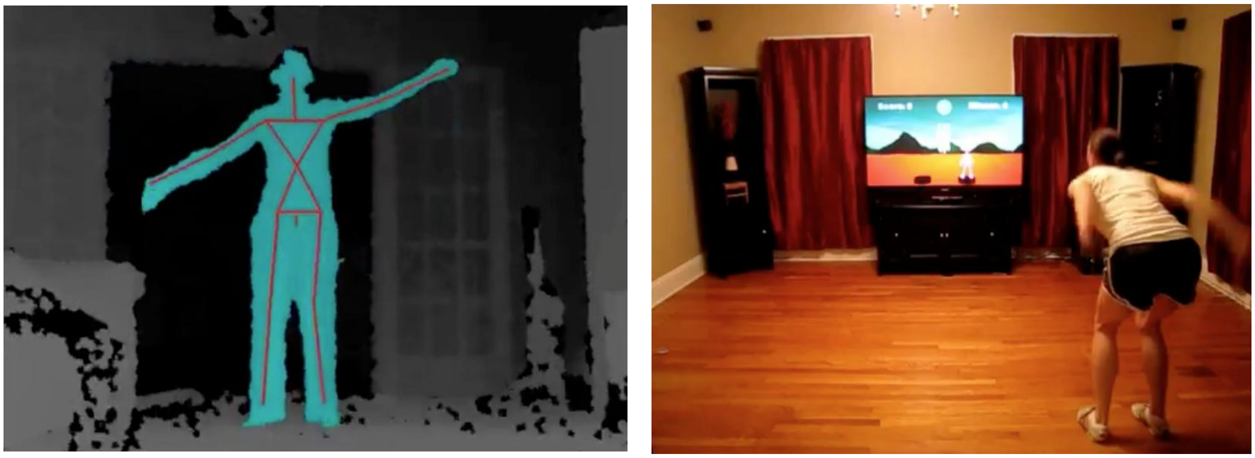


Figure 5.7: (L) Screenshot of the Flexible Action and Articulated Skeleton Toolkit (FAAST). (R) Image of the *Extreme Jump Trainer* system setup.

The *Extreme Jump Trainer* application was developed using the WorldViz Vizard VR Software Toolkit. The Kinect motion tracking data was acquired and streamed to Vizard over a VRPN server using the Flexible Action and Articulated Skeleton Toolkit (FAAST) (see Figure 5.7 (L)). The environment and avatar for the application were modeled using Google Sketchup, and then imported in 3D Studio Max (3DS Max). The avatar animations were created using the Biped Tool in 3DS Max. The flowing lava effect was achieved using a Mesh Modifier and the OSG Sequence Helper feature of the OSG Exporter plugin. All 3DS models and animations were exported to Vizard using the OSG Exporter plugin.

5.5.2 Environment

The basic environment for the *Extreme Jump Trainer* system features an animated character jumping between two rocks floating in a sea of lava (see Figure 5.8). The top panel of the environment displays the overall score, the countdown timer, and the number of missed jumps (both too slow and too short). The user earns 100 points for every successful jump, and loses 50 points (limited to 0) if they either take too long to jump or do not jump a far enough distance. Every time a user earns or loses points, the amount (+100 or -50) is flashed shortly in the middle of the display. The system features a variety of sounds including a springy jump sound, the sound of a coin every time points are earned, shouts/cries when a jump is missed, and background music.

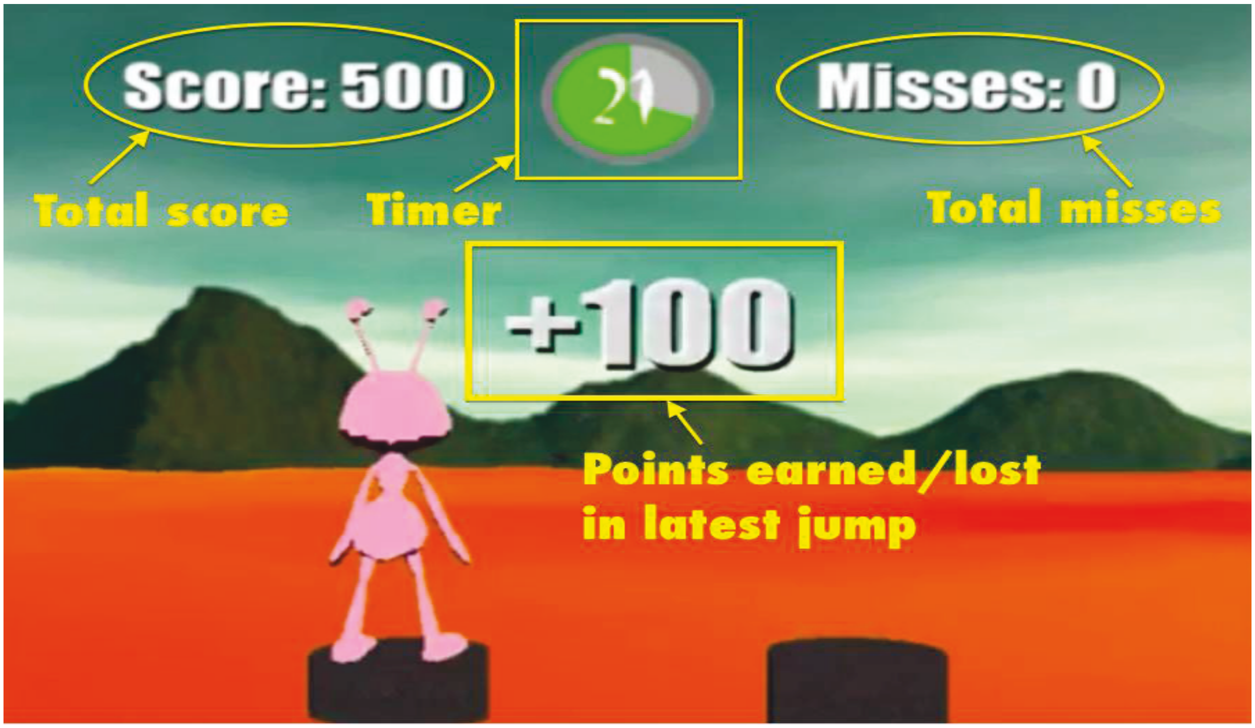


Figure 5.8: Screenshot of the application with details about the environmental elements.

5.5.3 Task

The task of the *Extreme Jump Trainer* system is to jump from side-to-side as many times as possible in a period of 30 seconds (see Figure 5.9). The goal is to maximize the distance of each jump, and to jump back and forth in a continuous manner (land and right away continue into the next jump). If the user successfully jumps from one side to the other passing the distance threshold (correlated to their height), the avatar successfully jumps from one rock to the other and the user is awarded 100 points (see Figure 5.10). If the user takes too long in between jumps (more than 0.5 seconds), the avatar spins, sinks into the lava, and fades away and the user is deducted 50 points and awarded 1 miss (see Figure 5.11). If the user does not jump past the distance threshold, the avatar lands in the lava and fades away and the user is deducted 50 points and awarded 1 miss (see Figure 5.12). In both failure cases, a new avatar immediately appears to allow the user to continue the exercise without delay.

Figure 5.9: How the user interacts with the *Extreme Jump Trainer* system (Stinson_CA_T_2013_videos.mp4, 17 MB).

5.5.4 Animation Control

The avatar animations inside the *Extreme Jump Trainer* system are determined based on the motion tracking data from the user. Changes in animation state are determined based on the center of mass (COM) data point streamed by FAAST. In order to reduce noise in the data, the COM values are smoothed continually using a 5-point running average.

In total there are 12 different animation tracks within the application:

- STANCE LEFT: standing still on the left rock
- DROP LEFT: from standing to drop on the left rock
- DRIVE LEFT: from drop on the left rock up to the peak
- LAND LEFT: from peak to landing on the right rock
- MISS LEFT: from peak to landing in the lava on the right side
- SINK LEFT: from standing to spinning and sinking on the left side
- STANCE RIGHT: standing still on the right rock
- DROP RIGHT: from standing to drop on the right rock
- DRIVE RIGHT: from drop on the right rock up to the peak
- LAND RIGHT: from peak to landing on the left rock
- MISS RIGHT: from peak to landing in the lava on the left side
- SINK RIGHT: from standing to spinning and sinking on the right side

Figure 5.10: When the user jumps laterally past a distance threshold (correlated to their height) the avatar successfully jumps from one rock to the other.

Figure 5.11: If the user takes too long in between jumps (> 0.5 seconds) the avatar fades away and spins into the lava. A new avatar appears immediately so that the user can continue the exercise without delay.

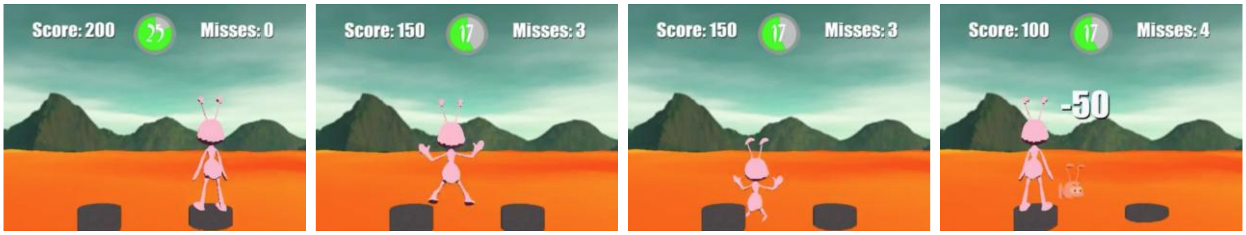


Figure 5.12: If the user does not jump past the distance threshold (correlated to their height), the avatar lands in the lava and fades away. A new avatar appears on the opposite rock so the user can continue the exercise without delay.

The avatar is controlled by keeping track of the user state, and looking for 5 key events: the user initiating a drop, the user initiating a drive (jump), the user reaching their peak, the user landing, and no user activity for 0.5 seconds. The events are triggered as follows:

1. **User initiates a DROP**
   The user must currently be in a STANCE state, and the current vertical COM value must be 6cm less than their base vertical COM value. At this point the state is changed to DROP, and the appropriate DROP animation is triggered.
2. **User initiates a DRIVE**
   The user must currently be in a DROP state, and their current COM value must be 3cm greater vertically than their base COM, and 5cm horizontally closer to the center than the COM value in the most recent LAND state. At this point the state is changed to DRIVE, and the appropriate DRIVE animation is triggered.

3. **User reaches their PEAK**
   The user must currently be in a DRIVE state, and the current vertical COM value must be less than the vertical COM value from the previous frame. If the user has surpassed the required distance threshold, the state is changed to LAND and the appropriate LAND animation is triggered. Otherwise the state is changed to MISS and the appropriate MISS animation is triggered.
4. **Users LANDS**
   The user must currently be in either a LAND or MISS state, and the current vertical COM value must be greater than the vertical COM value from the previous frame. At this point the state is changed to STANCE, and the appropriate STANCE animation is triggered.
5. **No user activity for 0.5 seconds**
   The user must currently be in either a STANCE or DROP state, and more than 0.5 seconds must have passed since they were last in a LAND state or since the last SINK animation was triggered. At this point the user remains in the same state so they can still initiate a jump at any time, but the appropriate SINK animation is triggered.

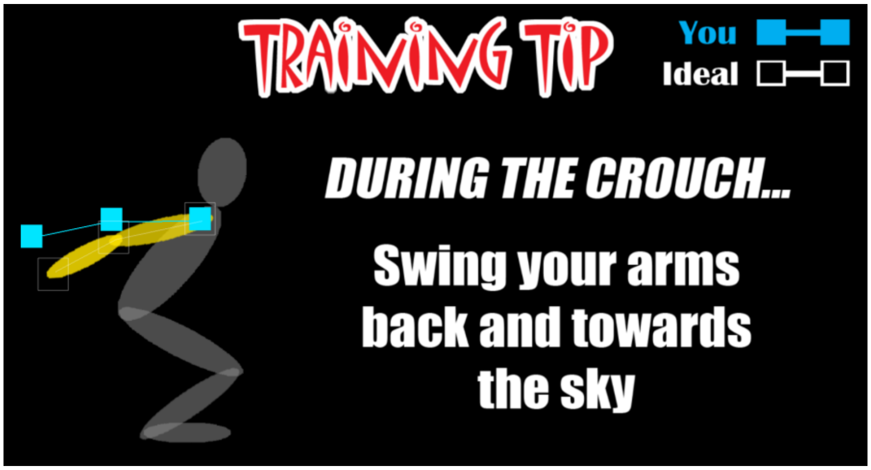
5.5.5 Biomechanical Feedback

After each round, biomechanical feedback is provided to the users through training tips. A training tip is provided for each of the three active phases of the jump (DROP, DRIVE, LANDING). The training tips are displayed as static images, and superimpose the user's performance on a representation of the ideal posture for that jumping phase (see Figure 5.13, Figure 5.14, Figure 5.15). The yellow ovals, white lines and boxes represent the ideal joint angles and limb positions. The blue lines and boxes represent the user's performance.

The user's performance is determined by calculating the mean joint angles at key moments of the jump for every jump completed during the round. These key moments are determined as follows:

- **DROP (ARMS)** – The system looks for the position of the arms at the moment when the wrist joints are the furthest behind the user's body during the DROP phase (see Figure 5.13).
- **DRIVE (ARMS)** – The system looks for the position of the arms at the peak height of the jump (see Figure 5.14).
- **LANDING (CORE)** – The system looks for the position of the core when the user's COM is lowest during the LAND phase (see Figure 5.15).

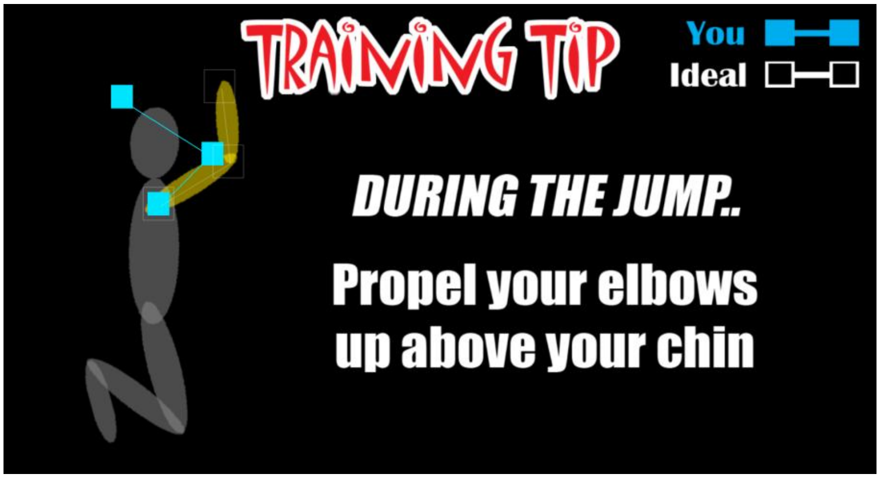
The purpose of displaying the training tips is to allow the user the opportunity to improve their biomechanical technique in the following round. By seeing how their performance varies from the ideal, they can adjust their posture during the different jump phases to achieve a more biomechanically sound jumping technique (see Figure 5.16).



DURING THE CROUCH...

Swing your arms back and towards the sky

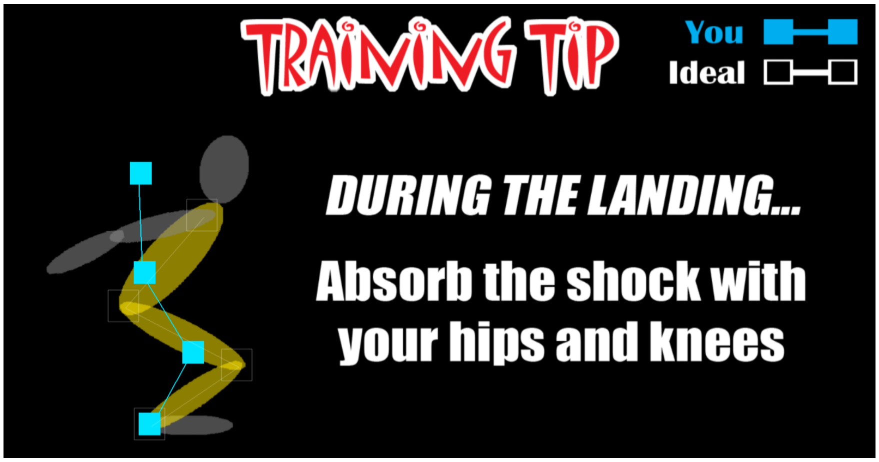
Figure 5.13: Biomechanical feedback for the crouch phase. In this example, the user is very close to the optimal arm position, with the blue squares (user) very nearly aligned with the yellow ovals (ideal).



DURING THE JUMP..

Propel your elbows up above your chin

Figure 5.14: Biomechanical feedback for the jump phase. The user is driving their arms up nice and high, however the hands are going a bit too far back horizontally.



DURING THE LANDING...

Absorb the shock with your hips and knees

Figure 5.15: Biomechanical feedback for the landing phase. In this figure we see that the user is not absorbing the jump much at all, leading to potential injury risks.

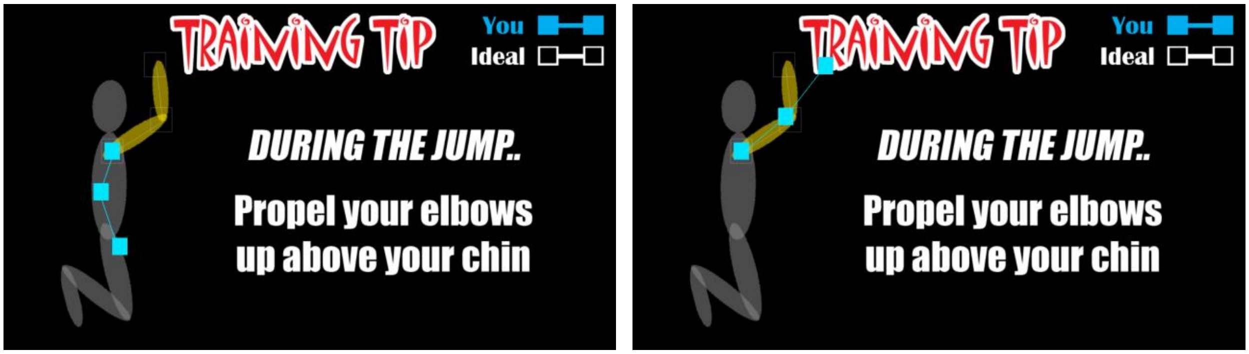


Figure 5.16: With repeated training, users can develop improved biomechanical jumping technique. An example is depicted in the above images with (L) representing a user that is not using their arms during the jump phase, and (R) depicting an improved performance.

5.6 Discussion

The *Extreme Jump Trainer* system was developed to begin exploring the potential for VR to support sport biomechanical training. Two key research questions were addressed:

1. Can an effective VR biomechanical training system be achieved using standard computer equipment and commodity tracking devices?
2. How can we design the user experience of a sport training system to effectively deliver biomechanical principles?

The *Extreme Jump Trainer* system was demonstrated at an Open House event at Virginia Tech's Center for Human Computer Interaction (CHCI) in May of 2012. The response to the system was very positive and encouraging, and several users wanted to repeat the exercise multiple times in order to improve their biomechanical performance. Even though the system did have some inherent hardware and software limitations, it did not impact the bulk of users who tried the system. All users were tracked effectively, and only one user exceeded the application's jumping speed threshold. All users were motivated to perform well, and greatly enjoyed the game-like environment.

The *Extreme Jump Trainer* project demonstrated anecdotally that an effective short-term VR biomechanical training system is achievable using standard computer equipment and commodity tracking devices. Several dozen users from a variety of age groups and athletic backgrounds used the system, and only one exceeded the system's jumping speed threshold. Not all users who tried the system participated in multiple rounds, however those who did were able to make immediate improvements to their jumping biomechanics (based on the specific criteria being reported on in the training tips). A controlled study would need to be conducted to validate these observations, and to determine the long-term benefits of the *Extreme Jump Trainer* system.

Using the Microsoft Kinect for this activity revealed that sufficient tracking accuracy could be achieved using a commodity device. In the *Extreme Jump Trainer* system, the Microsoft Kinect was placed directly in front of the user. We chose this design since we needed accurate tracking of the participants' side-to-side movements. In this configuration, it was possible that important biomechanical information could be missed if the user moved in a way that occluded body parts from the Microsoft Kinect. For instance, there was potential for the shoulders or upper body to occlude the arms when the user crouched down and swung their arms backwards during the

DROP phase. This did not end up being an issue with the system, largely because the population of users that tested the application had limited jumping experience. Very few of the users moved their arms significantly during the task, and even fewer users crouched to a far enough point where occlusion would be an issue. The system was therefore capable of detecting the limited arm movement, and provided appropriate feedback. The fact that this did not present a limitation during the demo can even be viewed as supportive evidence for this type of training. It validated our thoughts that young athletes often do not employ appropriate biomechanical techniques, and could greatly benefit for this style of training. This may, however, be a major limitation for expert users, or for novices who use the system over an extended period of time. Experimenting with different angles, or leveraging multiple Microsoft Kinects are potential extensions of the application to address this concern.

The design, development and testing of the *Extreme Jump Trainer* system also revealed the importance of the user experience for delivering biomechanical principles to a broad audience of users. The fun, interactive nature of the system was appealing to users, especially children. Many of the users commented on how the sounds, animations, and the game scenario made them really enjoy the jumping exercise. However unless the user already had a high level of intrinsic motivation to improve their jumping biomechanics, they were likely to overlook the training tips. Most users were motivated primarily by the competitive nature of the application, and focused on maximizing the number of points earned in each round rather than on improving jumping biomechanics. From the limited data acquired at the project demo, it appears necessary to infuse the biomechanical training into the game play itself (i.e., the score is directly correlated to a user's adherence to the training tips) in order to encourage biomechanical improvement across a broad population of users.

5.7 Conclusions and Future Work

This project addressed two research questions:

1. Can an effective VR biomechanical training system be achieved using standard computer equipment and commodity tracking devices?
2. How can we design the user experience of a sport training system to effectively deliver biomechanical principles?

The *Extreme Jump Trainer* project demonstrated anecdotally that an effective short-term VR biomechanical training system is achievable using standard computer equipment and commodity tracking devices. A controlled study would need to be conducted to validate these observations, and to determine the long-term benefits of the *Extreme Jump Trainer* system. The design, development and testing of the *Extreme Jump Trainer* system also revealed the importance of the user experience for delivering biomechanical principles to a broad audience of users. Most users were motivated primarily by the competitive nature of the application, and focused on maximizing the number of points earned in each round rather than on improving jumping biomechanics. From the limited data acquired at the project demo, it appears necessary to infuse the biomechanical training into the game play itself (i.e., the score is directly correlated to a user's adherence to the training tips) in order to encourage biomechanical improvement across a broad population of users.

The findings from this exploratory project demonstrate great potential for VR sport biomechanical training. Users from a wide variety of ages and athletic backgrounds enjoyed the *Extreme Jump Trainer* system, and several users were encouraged to improve their biomechanical technique based on the training tips. It would also be interesting to expand the project into a full-fledged jump training system with multiple levels and jumping exercises. The system could then be administered as a long-term jumping training program, and compared to traditional jump training regimens. This would further our understanding around the usefulness of using a VR platform for administering sport biomechanical training, and the feasibility of such systems over long-term use.

6 Conclusions and Future Work

This work investigated the potential of VR to support two separate domains of sport training: sport psychological training, and sport biomechanical training.

6.1 VR for Sport Psychology Training

This work addressed three research questions regarding VR for sport psychological training:

1. Can VR systems induce feelings of anxiety or stress in sport-oriented applications?
2. How does the anxiety experienced in VR systems impact performance?
3. How do the various aspects of the VR system design influence the extent of anxiety experienced? Do we need fully immersive VR?

We conducted a preliminary case study using a VR goalkeeper system to begin investigating these questions. Three elite soccer goalkeepers were recruited for the study, and participated in two separate experimental sessions. Results from the study provided anecdotal evidence that VR could be a useful platform for sport psychological training, but there were no conclusive findings. Interviews with the participants after the study highlighted several key considerations for refining the goalkeeper system to make it a more ecologically valid simulation of a penalty kick shootout. Their insights also suggested that targeting elite athletes might have limited our attempts to induce anxiety. All three of the participants reported very high confidence scores on the background questionnaires, suggesting that they were not predisposed to experience anxiety in a goalkeeping task.

We refactored the application to better simulate a soccer penalty kick situation, and designed a controlled study to investigate its impact on a broader population. Twenty-five participants were recruited to participate in the study, representing a wide variety of athletic and anxiety backgrounds. Results from the study demonstrate that anxiety can in fact be triggered in a VR sport application. We observed significant variances in physiological measures of heart rate, heart rate variability, and galvanic skin response and in qualitative measurements of cognitive anxiety and confidence. All the variances indicated a direct relationship between using the system and increased anxiety.

The results also demonstrated that participants with high trait anxiety (both cognitive and somatic) experienced greater levels of anxiety in the system than participants with low trait anxiety. This suggests that athletes struggling with sport-induced anxiety would experience greater levels of anxiety in the system than athletes without. However a study that controls for athletes of specific anxiety characteristics is needed to confirm this conjecture.

Several participants reported previous competitive goalkeeper experience, so we compared the two groups in our analysis to determine if there were any variances. The results suggest that there is an inverse relationship between anxiety and goalkeeper experience, contrary to our predictions. Having goalkeeper experience actually reduces the amount of anxiety experienced in the high simulation fidelity conditions. It could be that experienced goalkeepers need highly realistic simulations to effectively trigger anxiety, or that only goalkeepers who suffer from sport-induced anxiety will be impacted by such system characteristics.

The experiment also demonstrated that anxiety is expressed differently for every individual in the VR goalkeeper system. When we analyzed the impact of anxiety on performance, we observed no general trends across all participants. However, when we looked at each participant individually, we could see clear relationships between specific anxiety measures and performance in the system. Some participants experienced strong trends corresponding to qualitative measures of anxiety, some to physiological measure of anxiety, and some to a combination of both. By considering all measures together, we could get a good sense of how anxiety was impacting their performance, and project their relative zone on the Hebbian version of the Yerkes/Dodson law curve (Diamond, Campbell, Park, Halonen, & Zoladz, 2007).

In terms of our independent variables, known anxiety triggers were the most influential in triggering anxiety in participants. There were significant increases in both somatic and cognitive anxiety, and significant decreases in confidence. This suggests that including anxiety triggers such as negative feedback, lack of control, and unpredictability can be leveraged in a VR sport psychology system to effectively induce anxiety in most participants. SF was also a factor for inducing anxiety, demonstrated by significant increases in somatic anxiety in the high SF conditions. This indicates that in a sport-oriented application, including a highly realistic simulation can trigger physiological reactions in participants. Counter to our expectations, increasing the FOR significantly reduced the level of cognitive anxiety and increased the confidence in participants. We believe this could be related to the decrease in visual periphery that many individuals experience in high-pressure situations. There were also many significant interactions between the independent variables, suggesting there is still a lot we do not fully understand about how the combination of known anxiety triggers, FOR, and SF impact anxiety. Our results suggest that performance is influenced by the amount of visual distractors surrounding the users, and that confidence is related to the combination of visual distractors and positive auditory stimuli.

This experiment also provided insight about the usefulness and practicality of the various anxiety measures. The STICSA (Ree, MacLeod, French, & Locke, 2000) and the CSAI-2R (Cox, Martens, & Russell, 2003) were certainly the most useful measures in terms of statistical significance, and are also easy to administer and analyze. The STICSA is advantageous because it provides a measure of an individual's trait anxiety, whereas the CSAI-2R provides an additional measure of confidence – both of which held a lot of statistical significance in our experiment. Physiological measures of HR, HRV, and GSR were useful for analyzing overall variances between baseline and in-condition means, but did not provide any statistical significance when analyzing the main effects and interactions of our independent variables. Performance measures provided some statistical significance between the independent variables, but were confounded slightly by system performance. Since athletic actions occur very quickly, it is important to ensure low system latency to achieve accurate performance results. The combination of all measures was very useful in our work for analyzing the relationship between anxiety and performance for individual participants. Therefore we suggest that any research investigating the relationship between anxiety and performance in a VR context should leverage a combination of subjective, physiological, and performance measures.

There is extensive potential for future work in the area of VR for sport psychology. Now that we have determined that anxiety can be induced across a broad population of participants, future work can investigate how athletic populations react to the system. Do we need to improve the ecological validity of the simulation even further to trigger anxiety in elite athletes? Can similar results be seen in low fidelity VR systems?

Topic	Guideline
Athletes to target	- Athletes with high trait anxiety - Athletes suffering from competitive anxiety
Main objective of the VR training system	- The training system should induce enough anxiety to cause the athlete to be on the right-hand side of the anxiety vs. performance inverted-U shaped curve (where anxiety begins to have a negative impact on performance) (see Figure 2.1). - As anxiety increases, there should be a decrease in performance. The performance decrease can be represented by failure to perform the appropriate sport action (i.e., a miss in a goalkeeper application) or as an increase in the reaction time needed to perform the action.
Design considerations	- **High ecological validity:** Athletes should interact with the system the same way they do in real-life. Whenever possible, athletes should use their own bodies to interact with the system. - **High simulation fidelity:** The scenarios used in the VR training system should involve a high-level of detail, and invoke an emotional connection with the user. Accurate representations of the stadiums, sounds, coaches, teammates, and opponents should be employed whenever possible. Extreme detail should be included in the primary characters in the simulation. Motion capture data, as well as fine details (i.e. eye contact, celebrations, etc.) should be varied, and mimic typical real-life scenarios. - **Incentives & repercussions:** The athlete should feel a strong motivation to perform well in the VR training system. Some athletes may have an intrinsic motivation to perform well, while others may need additional incentives and repercussions. Having a coach present is an easy way to increase the motivation in most athletes. Other possibilities include using rewards (monetary or other) and positive/negative reinforcement. - **Multiple measures of anxiety:** Since anxiety is expressed differently between individuals, it is important to include a variety of anxiety measures to accurately determine how the athlete is responding to the system. We recommend using a combination of physiological (HR, HRV or GSR) and subjective (STICSA or CSAI-2R) measures.
Type of intervention	- Based on VRET and sport psychology research, we recommend that the primary intervention should be short sessions over a long period of time (i.e. 2/week for 3 months). Repeated exposure to the situations that cause anxiety will lessen the effect, and allow improved performance in real-life sport scenarios. - The sessions should aim to create positive experiences in the athlete (that they can perform successfully in high-pressure situations). The system should challenge the athlete (shouldn't be too easy), but should also adapt to the athlete if performance begins to drop (shouldn't be too hard). - We also recommend that a coach or sport psychologist oversee the athlete while using the system. The coach/sport psychologist should provide guidance to the athlete, and suggest cognitive processes for controlling the anxiety. Coaches/sport psychologists should also be prepared to end the sessions early, or suggests breaks if the athlete gets too frustrated or upset.

Table 6.1: Guidelines for the development of VR sport psychology training systems.

A future study could also refine the application into a full-fledged sport psychology training system. The application could be used along with sport psychology protocols, and studied to see if any long-term benefits are associated with use of the system, and whether the training transfers to in-vivo competitive situations. Our guidelines for the development of VR sport psychology training systems are presented in Table 6.1.

There is also potential to use the application to conduct sport psychology research. Environmental elements can be controlled, and different athletic populations studied to better understand the factors influencing competitive anxiety, and the best methods to treat the condition.

6.2 VR for Sport Biomechanical Training

This work also addressed two research questions regarding VR for sport biomechanical training:

1. Can an effective VR biomechanical training system be achieved using standard computer equipment and commodity tracking devices?
2. How can we design the user experience of a sport training system to effectively deliver biomechanical principles?

A VR jump training application was developed to begin investigating these questions. The application uses a Microsoft Kinect and a desktop computer to achieve full-body tracking, and infuses a common jump training exercise into a fun, challenging game. At the end of each round, a series of images are displayed to the user with tips for improving their biomechanical technique in future rounds.

The system was tested by a broad population of users, and was successfully used by all participants. The application demonstrated anecdotally that an effective biomechanical training system could be achieved using standard computer equipment and commodity tracking devices.

Insights from the development and testing of the application also revealed the importance of the user experience for delivering biomechanical training to a broad audience. Most users were excited by the game-like nature of the system, and thoroughly enjoyed the training task. The system effectively turned a common jumping exercise into a challenging, enjoyable task. However only a few of the users paid attention to the biomechanical training tips. We observed that it is important to infuse the training principles into the task, to encourage users to focus on the biomechanical training.

This project demonstrated the potential for VR sport biomechanical training systems, but did not study the system in a controlled manner. Future work could further develop the application into a full-fledged training system with multiple levels, tasks, and training modules. The system could then be compared to standard jump training regimens to determine the short- and long-term benefits of training in a VR sport biomechanical system.

6.3 Final Thoughts

The work presented in this thesis demonstrates the potential of VR to support both sport psychology and sport biomechanical training. The two sport domains were researched separately, and addressed distinct research goals. However it would be interesting to fuse the two areas together to further support both domains.

For instance, commodity devices could be leveraged to acquire biomechanically accurate motion capture data from a wide variety of athletes and then used to improve the ecological validity of sport psychology-based VR systems. VR sport psychology systems could also be developed using standard computer equipment and commodity devices to access and study broader populations of athletes.

It would also be interesting to use our findings from the VR sport psychology research to improve VR-based biomechanical training systems. The systems could leverage qualitative, physiological, and performance measures to monitor and adapt to the athlete. The training methods, difficulty level, and types of feedback could be dynamically managed to engage users and maintain an optimal level of arousal for maximal training effects.

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Appendix A – Pre-Experiment Questionnaire (Case Study)

Pre-Experiment Questionnaire

1. Gender: Male Female
2. Age: ____________
3. Do you wear glasses or contact lenses? No Glasses Contact Lenses
4. Years of goalkeeper experience: __________
5. How many hours a week do you train in goalkeeper-specific drills? _____________________
6. How many hours a week do you train against penalty kicks? ____________________________
7. Do you feel you get **enough** training to perform at your best? Please explain.
8. Do you feel you get the **right** training to perform at your best?
9. Do you experience any of the following in pressure situations?
   a. Heart racing
   b. Increased perspiration
   c. Muscle tension
   d. Fear of failure
   e. Difficulty concentrating
   f. Other:
10. What elements of the game environment cause you to feel increased pressure to perform?
11. How do you currently prepare for high pressure situations? (Please describe any mental training techniques or exercises you currently use.)
12. On a scale of 1 to 7, how much confidence do you have in your abilities?
    1 2 3 4 5 6 7
    No confidence Very confident
13. On a scale of 1 to 7, how would you rate your overall goalkeeper ability?
    1 2 3 4 5 6 7
    Poor ability Stellar ability

14. On a scale of 1 to 7, how would you rate your goalkeeper ability in high pressure situations?

1 2 3 4 5 6 7

Poor ability Stellar ability

15. Do you have any experience with playing the Wii, Playstation Move, or any other video game that uses motion tracking?

Yes No

16. If yes, how many hours a week do you play on average?

Less than 1 1 to 5 5 to 10 10 to 15 15 to 20 20+

17. Do you have any experience with playing video games other than the ones described above?

Yes No

18. If yes, how many hours a week do you play on average?

Less than 1 1 to 5 5 to 10 10 to 15 15 to 20 20+

19. What type of games do you play: (check all that apply)

___ First person shooting games (Half Life, Quake, etc.)
___ Sports games (e.g. Need for Speed, Madden, etc.)
___ Massive multiplayer online games (e.g. World of Warcraft)
___ Real-time strategy games (e.g. Starcraft)
___ Mobile devices casual games (e.g. Iphone, Ipad, etc.)
___ Motion capture casual games (e.g. Wii Sports, Wii Ft)
___ Social games (e.g. Farmville, Mafia Wars)
___ Third-person action games (e.g. Grand Theft Auto, Gears of War)
___ Other:

20. Do you have any experience with virtual environments? (CAVE, head-mounted displays, etc.)? If yes, please describe.

Appendix B – Post-Stage Questionnaire (Case Study)

Post-Stage Questionnaire

1. Please rate your sense of being on the soccer field, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.
   I had a sense of "being there" on the soccer field.

   1 2 3 4 5 6 7
   Not at all Very much

2. To what extent were there times during the experience when the soccer field was the reality for you?
   There were times during the experience when the soccer field was the reality for me...

   1 2 3 4 5 6 7

   At no time Almost all the time

3. When you think back about your experience, do you think of the soccer field more as images that you saw, or more as somewhere that you visited?
   The soccer field seems to me to be more like...

   1 2 3 4 5 6 7
   Images that I saw Somewhere that I visited

4. During the time of the experience, which was strongest on the whole, your sense of being on the soccer field, or of being elsewhere?
   I had a stronger sense of...

   1 2 3 4 5 6 7

   Being elsewhere Being on the soccer field

5. Consider your memory of being on the soccer field. How similar in terms of the *structure of the memory* is this to the structure of the memory of other *places* you have been today? By 'structure of the memory' consider things like the extent to which you have a visual memory of the soccer field, whether that memory is in color, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such *structural* elements.
   I think of the soccer field as a place in a way similar to other places that I've been today...

   1 2 3 4 5 6 7

   Not at all Very much so

6. During the experience, did you often think to yourself that you were actually on the soccer field?
   During the experience I often thought that I was really standing on the soccer field...

   1 2 3 4 5 6 7

   Not very often Very much so

Appendix C – Post-Experiment Questionnaire (Case Study)

Post-Experiment Questionnaire

1. Do you think the conditions were ordered correctly to cause a gradual increase in intensity/pressure throughout the experiment? If no, please explain how you would have modified the structure.

2. Do you think the amount of intensity/pressure you felt in a given stage was affected by the results of earlier stages? Or did you begin each trial with a neutral perspective?

3. How did pushing a button to indicate your decision affect the intensity/pressure of the interaction? Do you think you would feel more intensity/pressure if the system required:
    a. Rapid gestures in the direction of the ball?

    b. Full body movements?

4. What criteria did you use to make your decision on what direction the ball was headed?

5. What criteria do you use in real-life penalty kick situations to decide what direction the ball is headed?

6. What caused you to feel more intensity/pressure? (circle one for each pair)

a.	Individual stages	Partner stages
b.	1-Screen stages	4-screen stages
c.	Practice-like stages	Game-like stages

7. Please rank the different conditions from 1-8 based on the intensity/pressure you felt during the interaction (with 1 being the most, and 8 being the least).

    ___ 1 Screen/Practice-like (Individual)

    ___ 4 Screens/Practice-like (Individual)

    ___ 1 Screen/Game-like (Individual)

    ___ 4 Screens/Game-like (Individual)

    ___ 1 Screen/Practice-like (Partner)

    ___ 4 Screens/Practice-like (Partner)

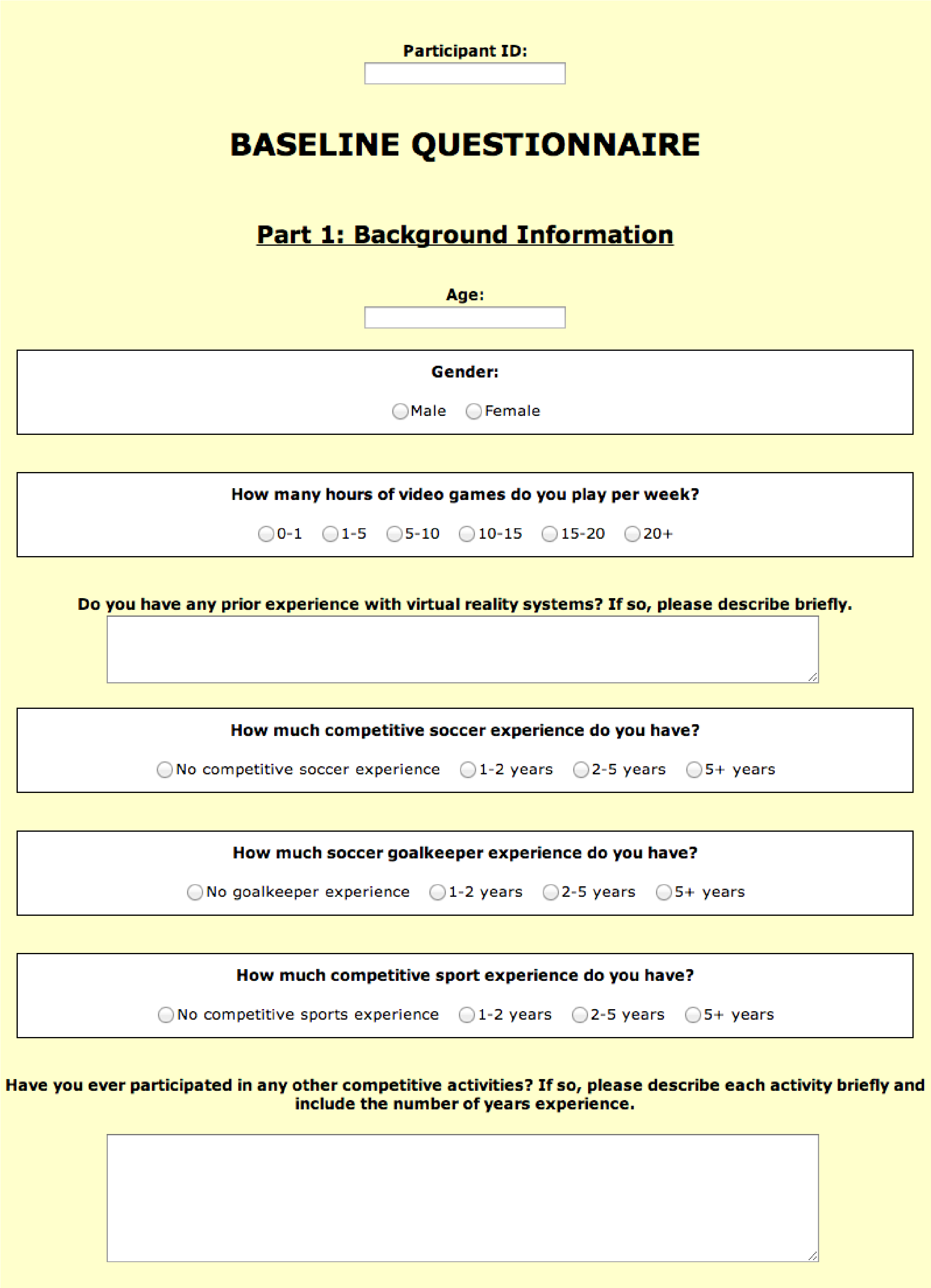
    ___ 1 Screen/Game-like (Partner)

    ___ 4 Screens/Game-like (Partner)

8. Do you think training in the condition you ranked #1 in the previous questions would be beneficial to you as an athlete?

9. What improvements would you suggest to make the system more effective?

Appendix D – Baseline Questionnaire (Controlled Study)



Participant ID:

BASELINE QUESTIONNAIRE

Part 1: Background Information

Age:

Gender:

○Male ○Female

How many hours of video games do you play per week?

○0-1 ○1-5 ○5-10 ○10-15 ○15-20 ○20+

Do you have any prior experience with virtual reality systems? If so, please describe briefly.

How much competitive soccer experience do you have?

○No competitive soccer experience ○1-2 years ○2-5 years ○5+ years

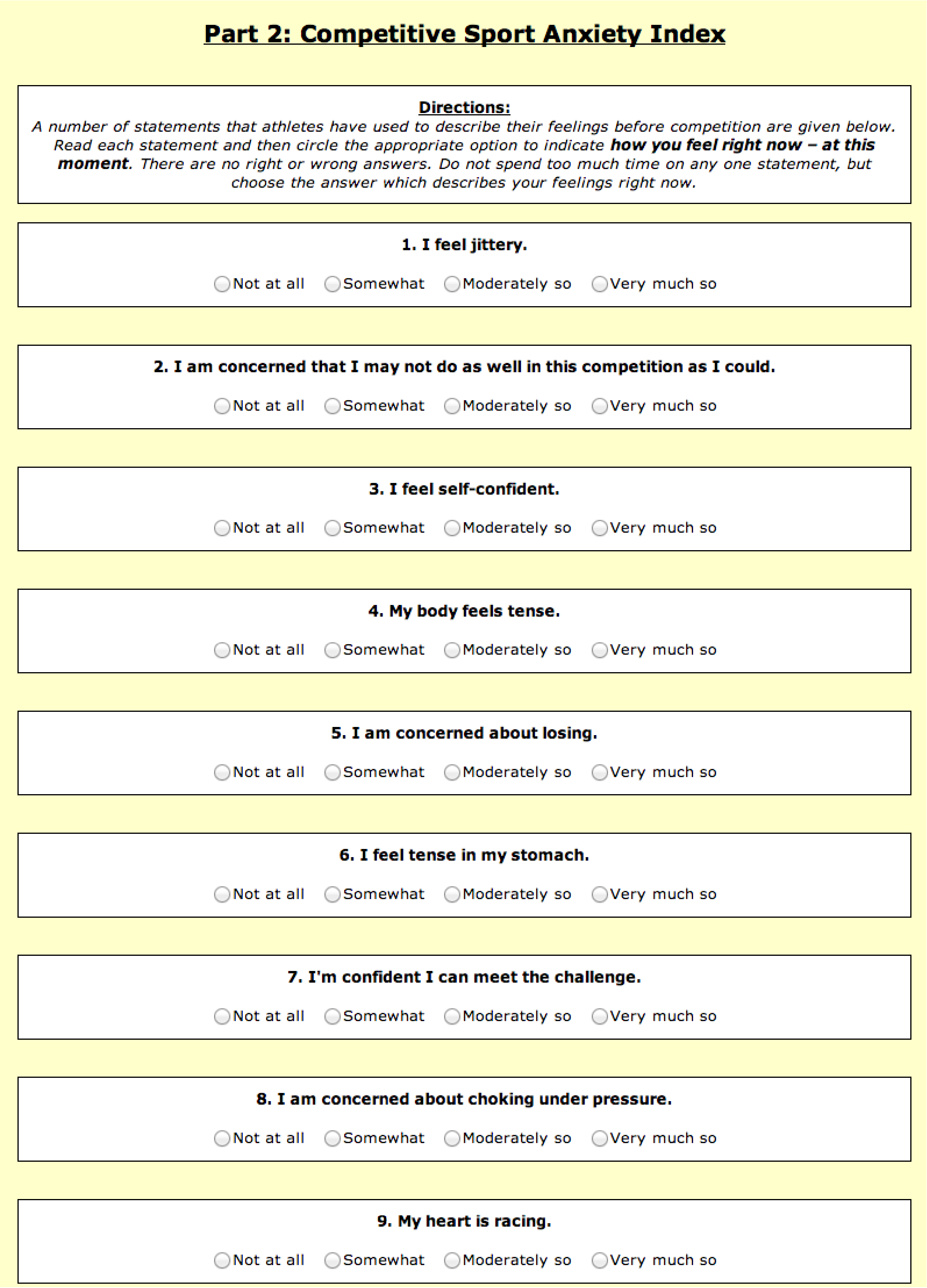
How much soccer goalkeeper experience do you have?

○No goalkeeper experience ○1-2 years ○2-5 years ○5+ years

How much competitive sport experience do you have?

○No competitive sports experience ○1-2 years ○2-5 years ○5+ years

Have you ever participated in any other competitive activities? If so, please describe each activity briefly and include the number of years experience.



Part 2: Competitive Sport Anxiety Index

Directions:
A number of statements that athletes have used to describe their feelings before competition are given below. Read each statement and then circle the appropriate option to indicate ***how you feel right now – at this moment****. There are no right or wrong answers. Do not spend too much time on any one statement, but choose the answer which describes your feelings right now.*

1. I feel jittery.

○Not at all ○Somewhat ○Moderately so ○Very much so

2. I am concerned that I may not do as well in this competition as I could.

○Not at all ○Somewhat ○Moderately so ○Very much so

3. I feel self-confident.

○Not at all ○Somewhat ○Moderately so ○Very much so

4. My body feels tense.

○Not at all ○Somewhat ○Moderately so ○Very much so

5. I am concerned about losing.

○Not at all ○Somewhat ○Moderately so ○Very much so

6. I feel tense in my stomach.

○Not at all ○Somewhat ○Moderately so ○Very much so

7. I'm confident I can meet the challenge.

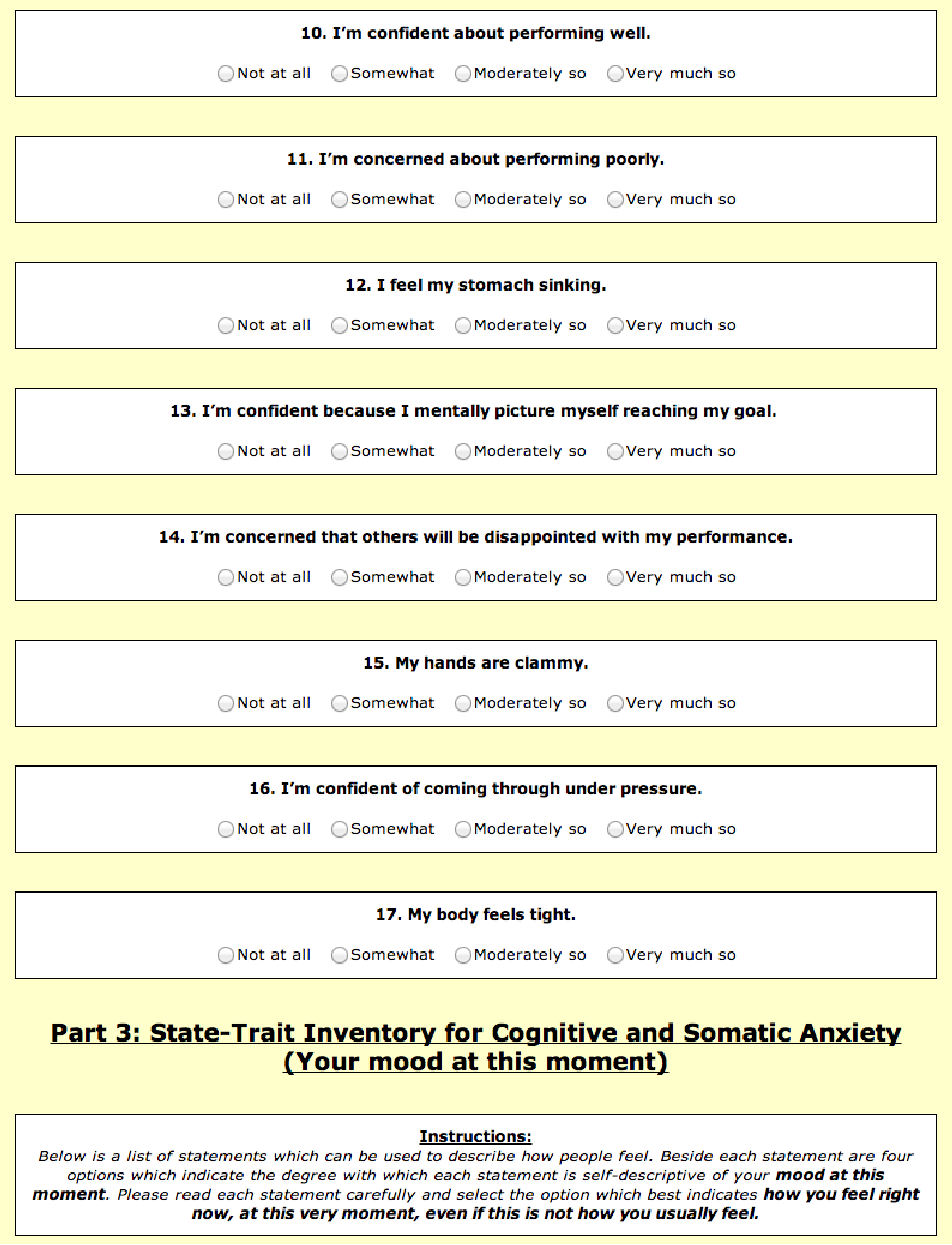
○Not at all ○Somewhat ○Moderately so ○Very much so

8. I am concerned about choking under pressure.

○Not at all ○Somewhat ○Moderately so ○Very much so

9. My heart is racing.

○Not at all ○Somewhat ○Moderately so ○Very much so



10. I'm confident about performing well.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

11. I'm concerned about performing poorly.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

12. I feel my stomach sinking.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

13. I'm confident because I mentally picture myself reaching my goal.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

14. I'm concerned that others will be disappointed with my performance.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

15. My hands are clammy.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

16. I'm confident of coming through under pressure.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

17. My body feels tight.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

Part 3: State-Trait Inventory for Cognitive and Somatic Anxiety (Your mood at this moment)

Instructions:

Below is a list of statements which can be used to describe how people feel. Beside each statement are four options which indicate the degree with which each statement is self-descriptive of your ***mood at this moment****. Please read each statement carefully and select the option which best indicates* ***how you feel right now, at this very moment, even if this is not how you usually feel.***

1. My heart beats fast.

○ Not at all ○ A little ○ Moderately ○ Very much so

2. My muscles are tense.

○ Not at all ○ A little ○ Moderately ○ Very much so

3. I feel agonized over my problems.

○ Not at all ○ A little ○ Moderately ○ Very much so

4. I think that others won't approve of me.

○ Not at all ○ A little ○ Moderately ○ Very much so

5. I feel like I'm missing out on things because I can't make up my mind soon enough.

○ Not at all ○ A little ○ Moderately ○ Very much so

6. I feel dizzy.

○ Not at all ○ A little ○ Moderately ○ Very much so

7. My muscles feel weak.

○ Not at all ○ A little ○ Moderately ○ Very much so

8. I feel trembly and shaky.

○ Not at all ○ A little ○ Moderately ○ Very much so

9. I picture some future misfortune.

○ Not at all ○ A little ○ Moderately ○ Very much so

10. I can't get some thought out of my mind.

○ Not at all ○ A little ○ Moderately ○ Very much so

11. I have trouble remembering things.

○Not at all ○A little ○Moderately ○Very much so

12. My face feels hot.

○Not at all ○A little ○Moderately ○Very much so

13. I think that the worst will happen.

○Not at all ○A little ○Moderately ○Very much so

14. My arms and legs feel stiff.

○Not at all ○A little ○Moderately ○Very much so

15. My throat feels dry.

○Not at all ○A little ○Moderately ○Very much so

16. I keep busy to avoid uncomfortable thoughts.

○Not at all ○A little ○Moderately ○Very much so

17. I cannot concentrate without irrelevant thoughts intruding.

○Not at all ○A little ○Moderately ○Very much so

18. My breathing is fast and shallow.

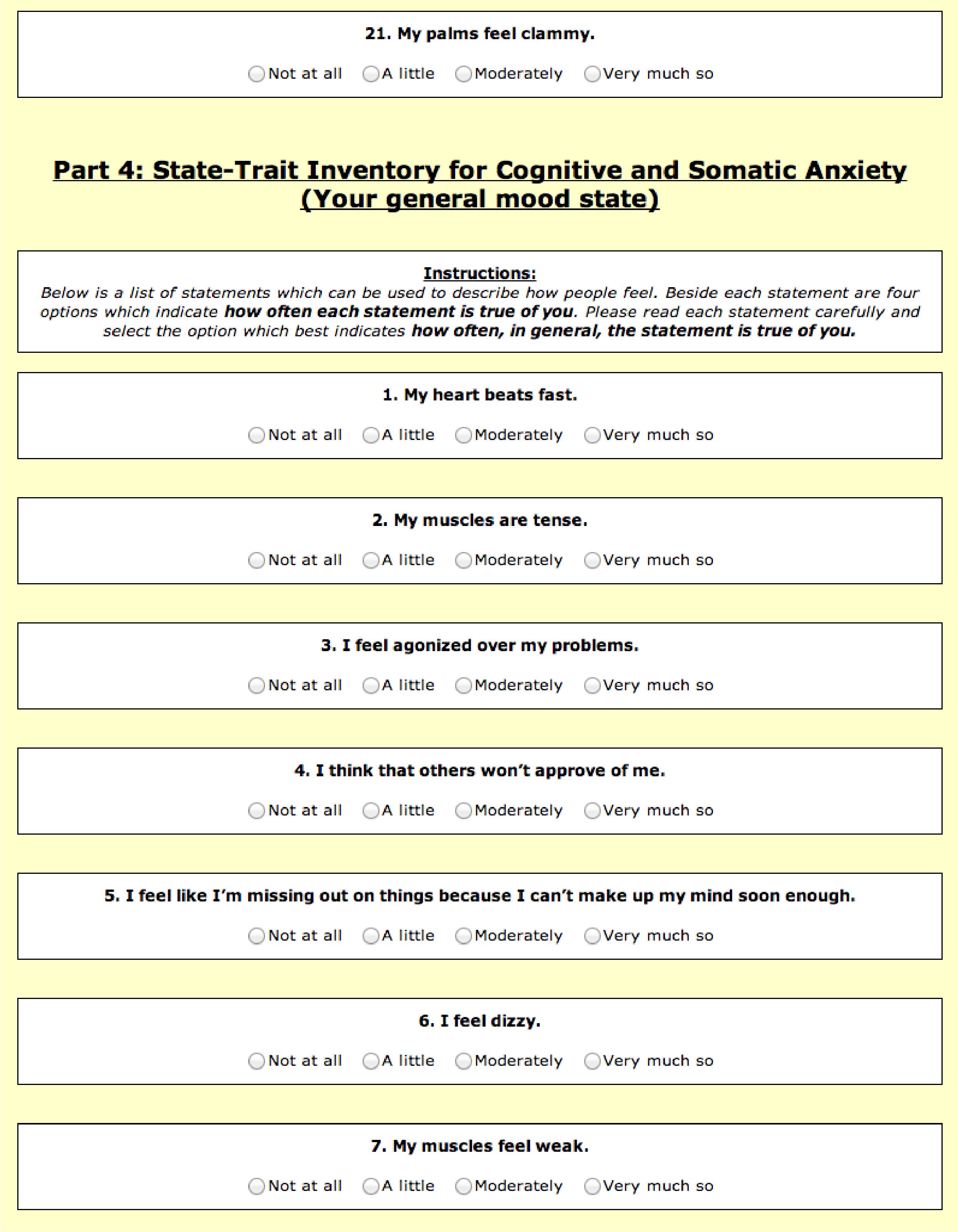
○Not at all ○A little ○Moderately ○Very much so

19. I worry that I cannot control my thoughts as well as I would like to.

○Not at all ○A little ○Moderately ○Very much so

20. I have butterflies in the stomach.

○Not at all ○A little ○Moderately ○Very much so



21. My palms feel clammy.

○Not at all ○A little ○Moderately ○Very much so

Part 4: State-Trait Inventory for Cognitive and Somatic Anxiety (Your general mood state)

Instructions:

*Below is a list of statements which can be used to describe how people feel. Beside each statement are four options which indicate **how often each statement is true of you**. Please read each statement carefully and select the option which best indicates **how often, in general, the statement is true of you.***

1. My heart beats fast.

○Not at all ○A little ○Moderately ○Very much so

2. My muscles are tense.

○Not at all ○A little ○Moderately ○Very much so

3. I feel agonized over my problems.

○Not at all ○A little ○Moderately ○Very much so

4. I think that others won't approve of me.

○Not at all ○A little ○Moderately ○Very much so

5. I feel like I'm missing out on things because I can't make up my mind soon enough.

○Not at all ○A little ○Moderately ○Very much so

6. I feel dizzy.

○Not at all ○A little ○Moderately ○Very much so

7. My muscles feel weak.

○Not at all ○A little ○Moderately ○Very much so

8. I feel trembly and shaky.

○Not at all ○A little ○Moderately ○Very much so

9. I picture some future misfortune.

○Not at all ○A little ○Moderately ○Very much so

10. I can't get some thought out of my mind.

○Not at all ○A little ○Moderately ○Very much so

11. I have trouble remembering things.

○Not at all ○A little ○Moderately ○Very much so

12. My face feels hot.

○Not at all ○A little ○Moderately ○Very much so

13. I think that the worst will happen.

○Not at all ○A little ○Moderately ○Very much so

14. My arms and legs feel stiff.

○Not at all ○A little ○Moderately ○Very much so

15. My throat feels dry.

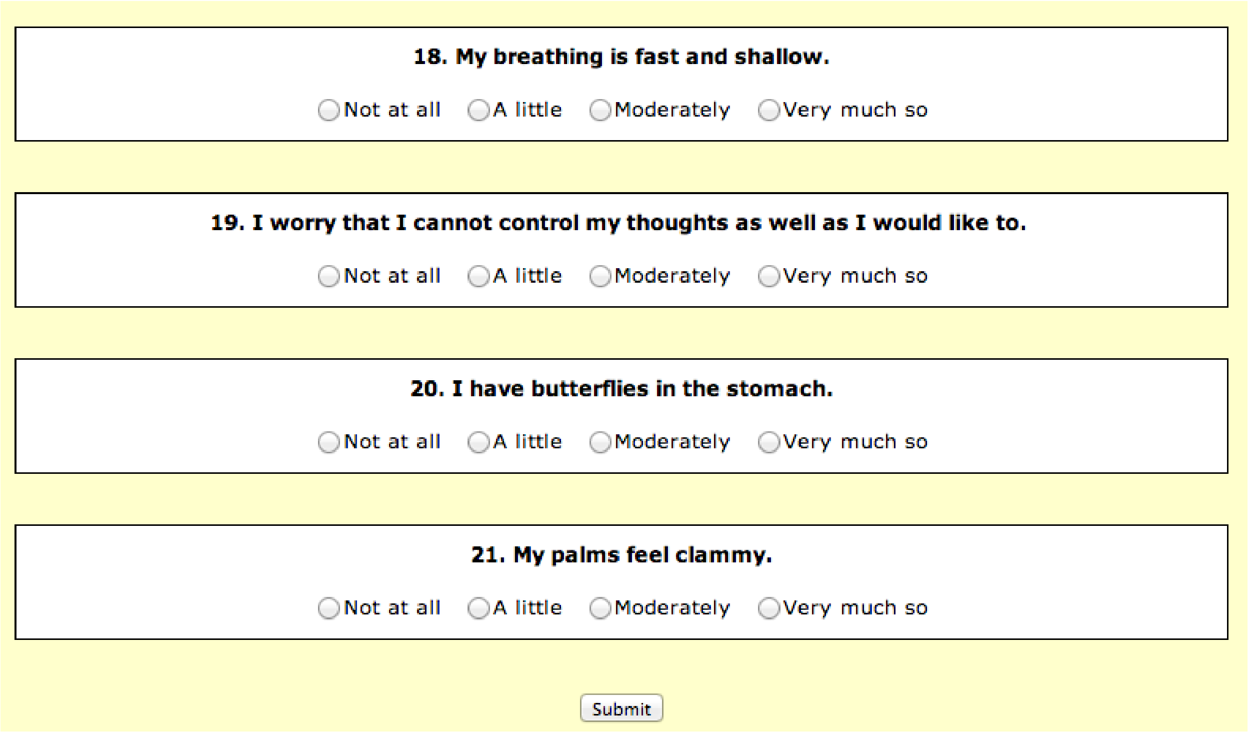
○Not at all ○A little ○Moderately ○Very much so

16. I keep busy to avoid uncomfortable thoughts.

○Not at all ○A little ○Moderately ○Very much so

17. I cannot concentrate without irrelevant thoughts intruding.

○Not at all ○A little ○Moderately ○Very much so



18. My breathing is fast and shallow.

○ Not at all ○ A little ○ Moderately ○ Very much so

19. I worry that I cannot control my thoughts as well as I would like to.

○ Not at all ○ A little ○ Moderately ○ Very much so

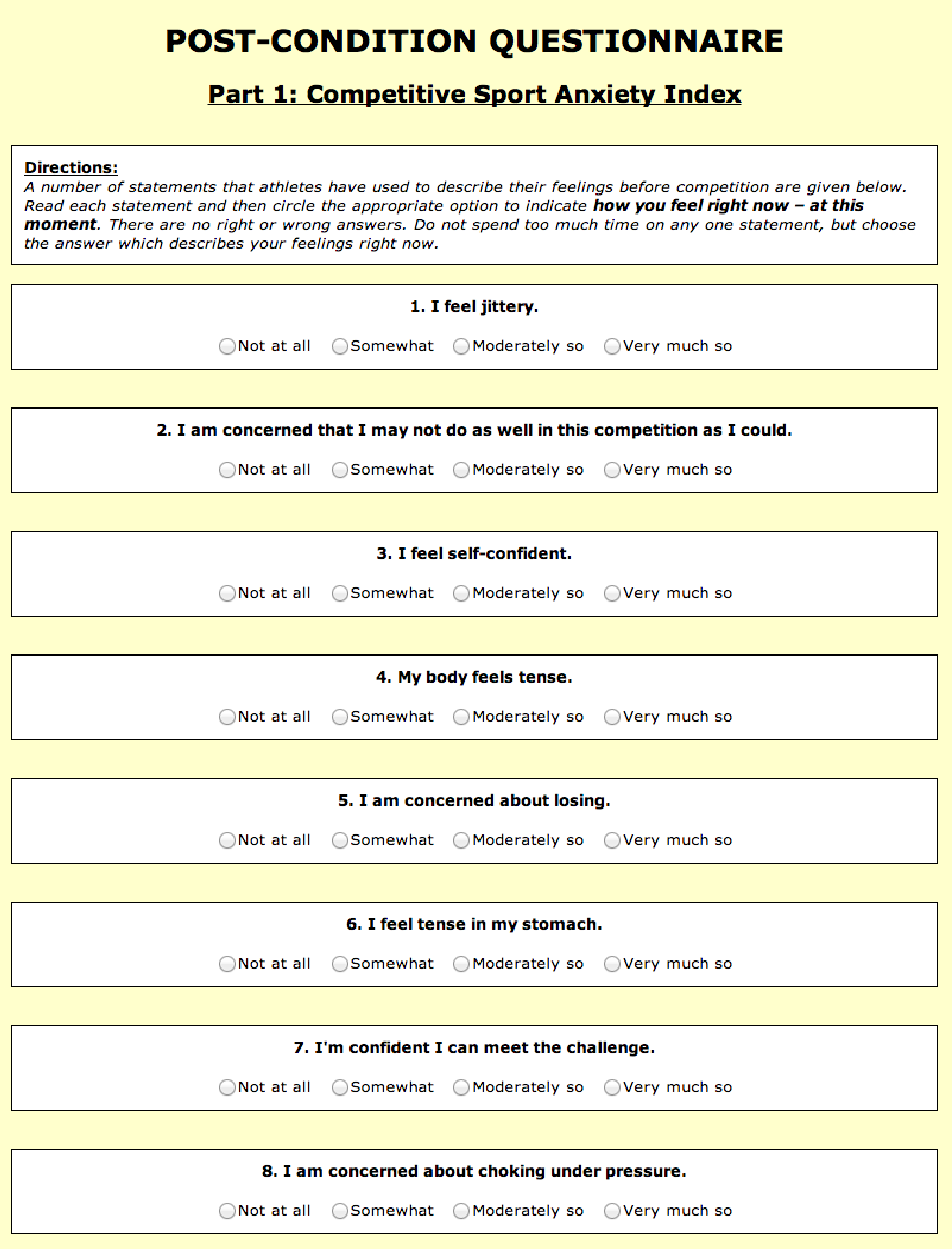
20. I have butterflies in the stomach.

○ Not at all ○ A little ○ Moderately ○ Very much so

21. My palms feel clammy.

○ Not at all ○ A little ○ Moderately ○ Very much so

Appendix E – Post-Condition Questionnaire (Controlled Study)



POST-CONDITION QUESTIONNAIRE

Part 1: Competitive Sport Anxiety Index

Directions:
A number of statements that athletes have used to describe their feelings before competition are given below. Read each statement and then circle the appropriate option to indicate ***how you feel right now – at this moment****. There are no right or wrong answers. Do not spend too much time on any one statement, but choose the answer which describes your feelings right now.*

1. I feel jittery.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

2. I am concerned that I may not do as well in this competition as I could.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

3. I feel self-confident.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

4. My body feels tense.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

5. I am concerned about losing.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

6. I feel tense in my stomach.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

7. I'm confident I can meet the challenge.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

8. I am concerned about choking under pressure.

○ Not at all ○ Somewhat ○ Moderately so ○ Very much so

9. My heart is racing.

○Not at all ○Somewhat ○Moderately so ○Very much so

10. I'm confident about performing well.

○Not at all ○Somewhat ○Moderately so ○Very much so

11. I'm concerned about performing poorly.

○Not at all ○Somewhat ○Moderately so ○Very much so

12. I feel my stomach sinking.

○Not at all ○Somewhat ○Moderately so ○Very much so

13. I'm confident because I mentally picture myself reaching my goal.

○Not at all ○Somewhat ○Moderately so ○Very much so

14. I'm concerned that others will be disappointed with my performance.

○Not at all ○Somewhat ○Moderately so ○Very much so

15. My hands are clammy.

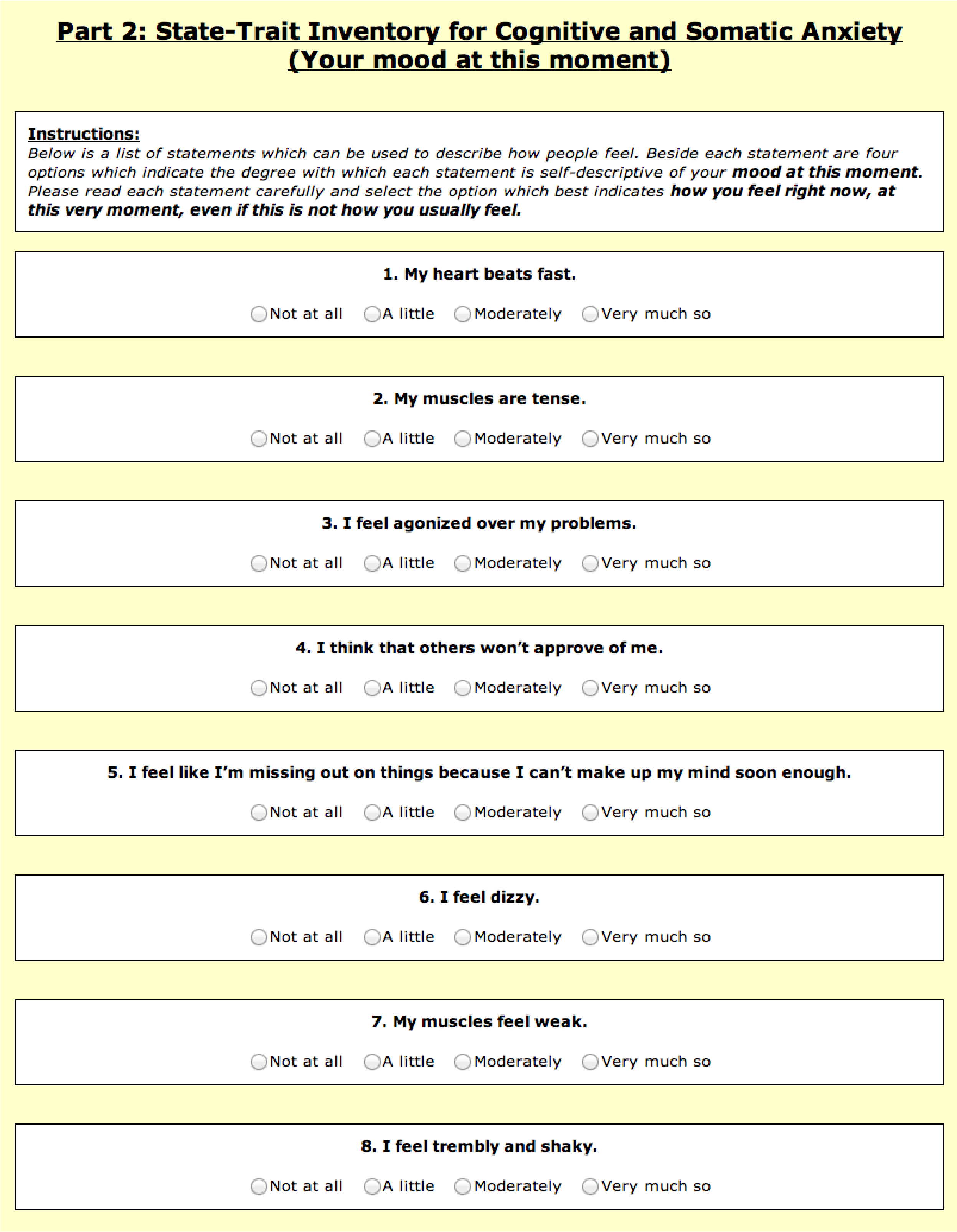
○Not at all ○Somewhat ○Moderately so ○Very much so

16. I'm confident of coming through under pressure.

○Not at all ○Somewhat ○Moderately so ○Very much so

17. My body feels tight.

○Not at all ○Somewhat ○Moderately so ○Very much so



Part 2: State-Trait Inventory for Cognitive and Somatic Anxiety (Your mood at this moment)

Instructions:
Below is a list of statements which can be used to describe how people feel. Beside each statement are four options which indicate the degree with which each statement is self-descriptive of your ***mood at this moment****. Please read each statement carefully and select the option which best indicates* ***how you feel right now, at this very moment, even if this is not how you usually feel.***

1. My heart beats fast.

○Not at all ○A little ○Moderately ○Very much so

2. My muscles are tense.

○Not at all ○A little ○Moderately ○Very much so

3. I feel agonized over my problems.

○Not at all ○A little ○Moderately ○Very much so

4. I think that others won't approve of me.

○Not at all ○A little ○Moderately ○Very much so

5. I feel like I'm missing out on things because I can't make up my mind soon enough.

○Not at all ○A little ○Moderately ○Very much so

6. I feel dizzy.

○Not at all ○A little ○Moderately ○Very much so

7. My muscles feel weak.

○Not at all ○A little ○Moderately ○Very much so

8. I feel trembly and shaky.

○Not at all ○A little ○Moderately ○Very much so

9. I picture some future misfortune.

○Not at all ○A little ○Moderately ○Very much so

10. I can’t get some thought out of my mind.

○Not at all ○A little ○Moderately ○Very much so

11. I have trouble remembering things.

○Not at all ○A little ○Moderately ○Very much so

12. My face feels hot.

○Not at all ○A little ○Moderately ○Very much so

13. I think that the worst will happen.

○Not at all ○A little ○Moderately ○Very much so

14. My arms and legs feel stiff.

○Not at all ○A little ○Moderately ○Very much so

15. My throat feels dry.

○Not at all ○A little ○Moderately ○Very much so

16. I keep busy to avoid uncomfortable thoughts.

○Not at all ○A little ○Moderately ○Very much so

17. I cannot concentrate without irrelevant thoughts intruding.

○Not at all ○A little ○Moderately ○Very much so

18. My breathing is fast and shallow.

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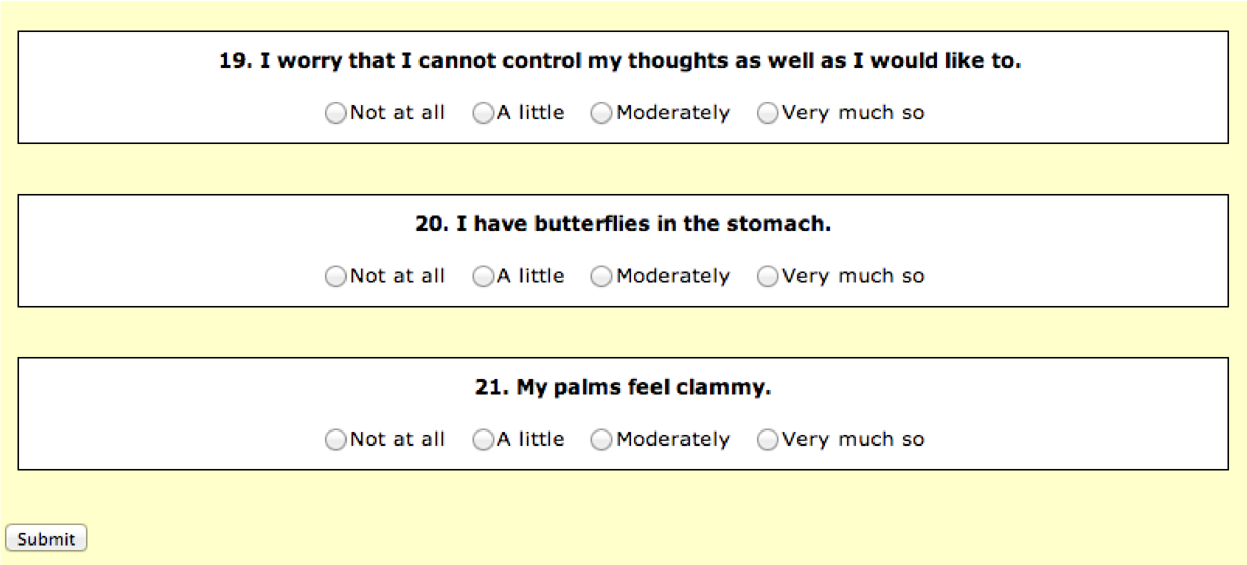

19. I worry that I cannot control my thoughts as well as I would like to.

○Not at all ○A little ○Moderately ○Very much so

20. I have butterflies in the stomach.

○Not at all ○A little ○Moderately ○Very much so

21. My palms feel clammy.

○Not at all ○A little ○Moderately ○Very much so

Appendix F – Citations for Copyrighted Work

Figure 2.1 **[Fair Use]**

Diamond, D. M., A. M. Campbell, C. R. Park, J. Halonen and P. R. Zoladz (2007). "The temporal dynamics model of emotional memory processing: a synthesis on the neurobiological basis of stress-induced amnesia, flashbulb and traumatic memories, and the Yerkes-Dodson law." Neural plasticity 2007.
http://upload.wikimedia.org/wikipedia/commons/5/5f/HebbianYerkesDodson.JPG
(Accessed May 16, 2013) Fair use determination attached.

Figure 2.2 **[Fair Use]**

Chua, P. T., R. Crivella, B. Daly, N. Hu, R. Schaaf, D. Ventura, T. Camill, J. Hodgins and R. Pausch (2003). Training for physical tasks in virtual environments: Tai chi. Virtual Reality, 2003. Proceedings. IEEE, IEEE.
http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=1191125
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Figure 2.3 **[Fair Use]**

Eaves, D. L., G. Breslin, P. Van Schaik, E. Robinson and I. R. Spears (2011). "The short-term effects of real-time virtual reality feedback on motor learning in dance." Presence: Teleoperators and Virtual Environments 20(1): 62-77.
http://www.mitpressjournals.org/doi/abs/10.1162/pres_a_00035
(Accessed May 16, 2013) Fair use determination attached.