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Effects of Visual Biofeedback on Competition Performance Using an Immersive Mixed Reality System

Maxwell Kennard
School of Integrative and Global Majors
University of Tsukuba
Tsukuba, Japan
max@ai.iit.tsukuba.ac.jp

Haihan Zhang
School of Integrative and Global Majors
University of Tsukuba
Tsukuba, Japan
zhang.haihan@image.iit.tsukuba.ac.jp

Yuki Akimoto
School of Integrative and Global Majors
University of Tsukuba
Tsukuba, Japan
yuki@ai.iit.tsukuba.ac.jp

Masakazu Hirokawa
Faculty of Engineering, Information and Systems
University of Tsukuba
Tsukuba, Japan
hirokawa_m@ieee.org

Kenji Suzuki
Faculty of Engineering, Information and Systems
University of Tsukuba
Tsukuba, Japan
kenji@ieee.org

***Abstract*—This paper investigates the effects of real time visual biofeedback for improving sports performance using a large scale immersive mixed reality system in which users are able to play a simulated game of curling. The users slide custom curling stones across the floor onto a projected target whose size is dictated by the user's stress-related physiological measure; heart rate (HR). The higher HR the player has, the smaller the target will be, and vice-versa. In the experiment participants were asked to compete in three different conditions: baseline, with and without the proposed biofeedback. The results show that when providing a visual representation of the player's HR or "choking" in competition, it helped the player understand their condition and improve competition performance (P-value of 0.0391).**

***Index Terms*—Information Visualization, Virtual and Augmented Reality Systems, Team Performance and Training Systems**

I. Introduction

Athletic competitions are not just a test of a person's physical abilities, but also their mental fortitude. There are instances in a sporting event where an athlete may show a considerable decrease in performance when under increased pressure or anxiety [1]. This pressure is often due to the fact that the player is not able to match their own self-expected standards or that of their teammates. This phenomenon is casually known as "choking" in sports competitions.

To create a biofeedback system for improving performance during competition and preventing choking, it is important that the system is able to accurately measure the user's mental stress. However, measuring the perceived stress of an individual can prove to be a challenging task. One such method of measuring stress is correlating it to a person's heart rate. In a study conducted by Oudejans and Pijpers, it was shown that although heart rate is not fully indicative of physiological anxiety, the heart rate can provide some indication of it [2]. Furthermore, their study had participants performing dart throwing during low, mild, and high anxiety situations. The results showed that increased anxiety levels correlated to an elevation in heart rate as well as deterioration in performance. From this study we concluded that using a heart rate sensor could be an effective means of monitoring the user's stress levels in our experiments.

Our goal with this study is to better understand the psychological impact of competition and develop a new way to train athletes. The developed system allows the player to visualize their own HR in real time under pressure. Having this visualization can allow both the player and their teammates to have a better understanding or their psychological state. This promotes better communication and understanding as they decide how best to deal with the stress and competition. Through this, we aim to show that this method of biofeedback support can promote a more efficient performance from the athletes.

There have been previous approaches for utilizing a virtual reality environment to improve sports training, but they all have their limitations. Most of these approaches do not allow players to play in a realistic setting. They are often constrained by a mechanism due to space limitations or burdened by head mounted displays [3] [4] [5]. These approaches also typically focus on an individual and therefore cannot accommodate competing against another human player [6]. Instead, in this study we use a mixed reality system with a large scale immersive environment, which allows players to perform in a setting more similar to the real world and can be inclusive of interactions with teammates or opponents.

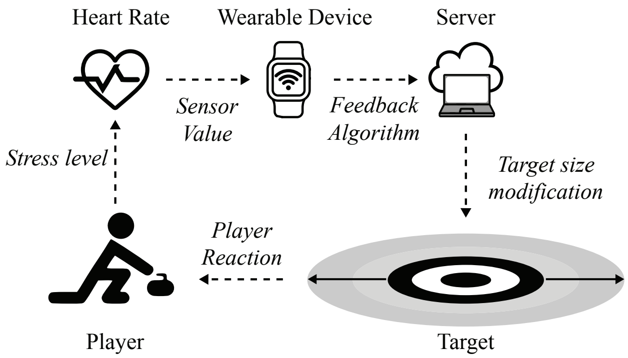

Fig. 1. Overview of the system

II. Methodology

A. Real-time Biofeedback using Immersive Display

The system is designed to provide feedback to the player based on their current mental stress state, measured by their heart rate. This feedback is presented in the form of a changing target size. The size of the target is calibrated to the player's individual baseline heart rate. If the player is more stressed than normal, shown by an elevated heart rate, the size of the target will shrink. If the player is more relaxed than normal, the size of the target will grow. To prevent the possible rapid changing of the target size to be a distraction and give the system adequate time to measure the heart rate, the size of the target is set to update every 5 seconds. This algorithm may seem unusual at first due to the fact that it seems likely that the player may get trapped in a negative feedback loop. For example, if the player is stressed the target will shrink. With a smaller target, the player may perform worse and continue to be stressed. This has the possibility for the target to always remain small and challenging. It may make sense for some to have the target get larger when the player is stressed so that they feel more relaxed. However, the point of this biofeedback mixed reality system is not to simply help players relax. Instead, we want the players to be forced to confront this negative feedback loop and have to internally figure out how to relax and overcome it. This method would better train athletes for a real competition where they do not have such a system at their disposal. It is one thing to design a system that makes it easier to perform when using the system, but it is much more beneficial to design a system that has the potential for real world improvements outside of the system. To summarize, this biofeedback algorithm is meant to improve player performance, not simply assist during the competition. An overview of the system diagram can be seen in Fig. 1.

B. Large Scale Immersive MR Space - "Large Space"

Our mixed reality (MR) application utilizes a large scale immersive display that is located at the University of Tsukuba. This system consists of a large all-around screen, 12 projectors, 20 motion capture cameras, and a dedicated server room. Images can be projected on the walls and floor of this space and allows users to freely move within it. The dimensions of the space are 25m long, 15m wide, and 7.7m high. This immersive display, called the "Large Space", provides a unique opportunity for users to experience a variety of training simulations, augmented reality sports, and interactive art [7]. It is for this reason we chose the Large Space to develop our biofeedback system and conduct our experiments.

The MR application was built in the Unity development environment and used scripts written in C#. The Unity application is the master program on the server and coordinates communication between the motion tracking system and the wearable heart rate sensor. The MR application projects the playing field and background onto the floor and walls, respectively, of the Large Space (Fig. 2). The playing field consists of three main components; a red target, a green target, and a starting line. The red target is the goal that players aim for when throwing their stones across the floor. The red target will also grow and shrink in size when the player's heart rate is either relaxed or stressed compared to their initial calibration. A point is scored for each successful stone that lands on the target. A curling stone can be placed on the green target to reset the score and give another player an opportunity to play. The starting line will pause the growth of the red target when a curling stone is thrown across it. This prevents players from being able to change the size of the target after having already thrown their stone, potentially scoring a point for a previously missed stone. The background consists of a scoreboard and images of cheering fans to simulate a competitive environment.

There are two ways the game can be played. The first way is for a single player game. The player will alternate between attempting to control their heart rate, with breathing exercises or alternative methods, to try to achieve a desired target size, and then sliding one of their stones across the floor. This method was chosen because the psychological and biological effects of deep breathing exercises have been previously studied [8] [9]. The second way is to play against another player. In this mode each player has three stones, but only one player can score points and control the size of the target. The other player's goal is to throw their stones into a position that makes it difficult for the first player to be able to score a point. After all the stones

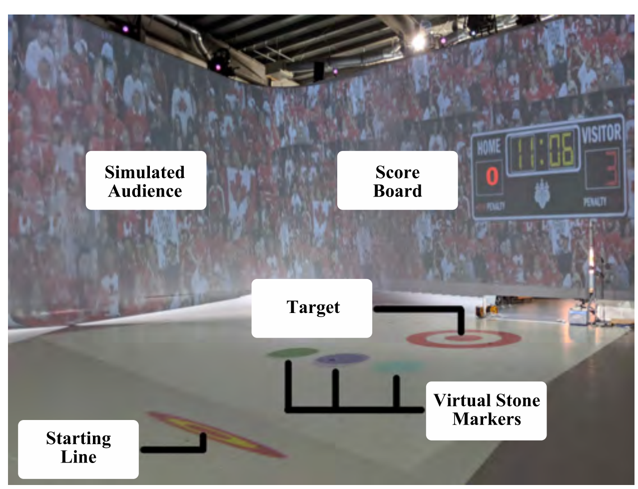

Fig. 2. Game projection in the Large Space

have been thrown, the players can reset the game and change who is in a scoring position. This mode gives a more realistic and stressful experience of competition.

C. Curling Stones

The curling stones used for this system are modified versions of a children's toy. Each stone weighs 400 grams and is 10 centimeters tall (not including the handle) with an 18 centimeter diameter. The toy stones were each equipped with three round ball caster wheels and three motion tracking markers. Each stone has the motion tracking markers placed in a unique configuration to be easily identified by the motion tracking system, OptiTrack. An example of one of the stones with markers attached is shown in Fig. 3. As these stones are moved around the Large Space, motion tracking cameras recognize the location of the stone in the room and send the position information to a Unity script. From there, Unity will provide this position information to a color coded, digital circle which is projected onto the floor of the Large Space and follows the curling stone.

D. Wearable Device for Monitoring Heart Rate

A wearable device was also designed for this system. The device is constructed from three main parts; a MAX30102 heart rate sensor, NodeMCU Microcontroller, and an ESP8266 Wi-Fi module. All of these components are mounted on the outside of a fingerless glove; Fig. 4. The MAX30102 sensor uses a noninvasive photo-diode to measure the heart rate. This process works because oxygenated and deoxygenated hemoglobin in the blood absorb different amounts of both red light and infrared light. Additionally, the blood volume in the arteries is constantly changing with each heartbeat. Comparing the ratio between the absorbed light in the hemoglobin and the blood volume in the arteries, it is possible to calculate a heart rate [10]. During the experiment, the sensor is placed on the wearer's finger due to the fact that previous studies have shown it to be the most accurate location for measuring heart rate and blood oxygen saturation (SpO_2) [11].

The data recorded by the sensor is transmitted directly to the NodeMCU. This microcontroller was programmed in the Arduino IDE and is responsible for processing and filtering the signal from the heart rate sensor. In our program, the heart rate is responsible for determining the size of the target the

Fig. 3. Curling stone with motion trackers

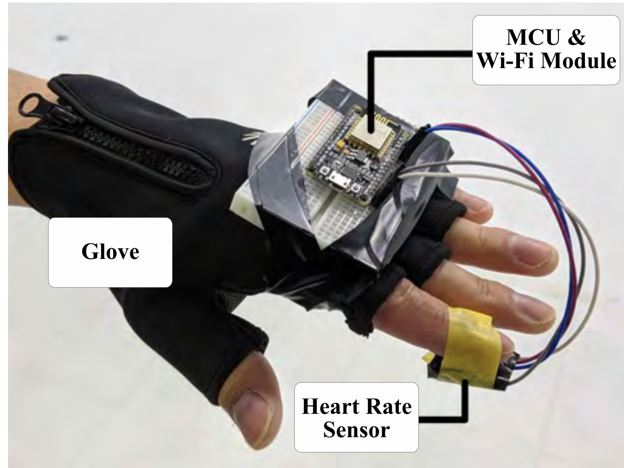

Fig. 4. Wearable heart rate sensor

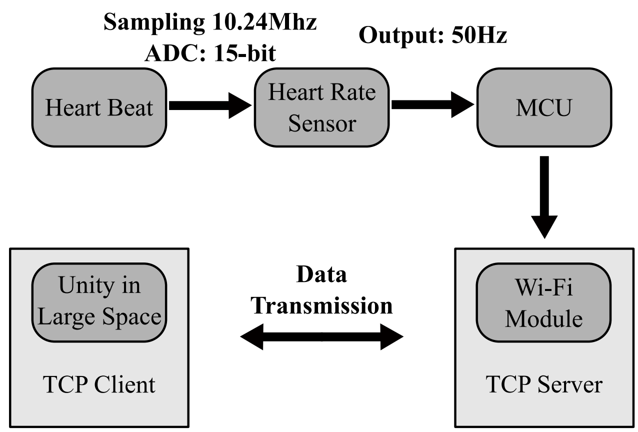

Fig. 5. Network diagram of the wearable device

player is aiming for with the curling stones. After the heart rate is calculated from the sensor, the value is scaled into an appropriate target size relative to the user's resting heart rate which is measured during calibration. This target size is then sent over Wi-Fi to the servers where the Unity program is running. Unity receives the desired target size information and then changes the target projected onto the floor of the Large Space accordingly. The network diagram is shown in Fig. 5.

III. Experiment

The experiment was modeled after a study conducted by Gucciardi and Dimmock [12]. In their study a group of experienced golfers' putting accuracy was measured under different levels of anxiety. Similarly, in our study we took a group of 8 healthy, male university students and measured their accuracy of hitting the target with a curling stone under three different conditions.

The experimental procedure was first clearly explained to each participant and they each gave their consent to participate. Each person completed the experiment with only the test administers present. The 8 participants were randomly split into two equal groups, A and B. Each group completed the same 3 trials, but the order in which they were completed changed.

The experiment began by having each participant place the wearable heart rate sensor on their non-dominant hand. The wearable device was tethered to a computer for data logging with a 3 meter USB cable. This cable also provided enough length that it did not interfere with the throwing motion of the participant. They were placed on one side of the room behind a starting line. On the other side of the room, 7 meters away, an ‘X’ shape was taped to the floor. In each trial the participant was first given 3 practice throws to get used to the movement of the curling stone. Afterwards, the participant was given 6 chances to slide the curling stone as close to the center of the target as they could. The distance between the stone and the target was recorded each time and then the stone was returned to the participant. The first trial for both groups was to establish a baseline of their performance and heart rate. They were told only to relax and just try their best.

Once the first trial was completed, the participant was then informed that they will compete in a “curling competition” amongst the other participants. The participants were also told that the winning player would receive a cash prize. Previous studies have shown that a monetary incentive is capable of inducing anxiety in participants [13]. Group A participants first competed using the biofeedback system. A target was projected onto the floor of the Large Space and they were informed that the size of it would change with their heart rate. If they were stressed the size would shrink, and if they were relaxed the size would grow. The target size updated every 5 seconds after averaging their heart rate during that time period and would change between 5 different sizes. These sizes ranged from 0.5 meters to 3 meters in diameter. The middle size reflected their baseline heart rate that was measured during the first trial. There were two smaller sizes and two larger sizes which were based on the heart rate ranges above or below the baseline, respectively. Although the size of the target changed, each participant was still informed to aim for the center of the target. They were told that the changing target size was to help them visualize their current stress levels. Group B participants competed without using the biofeedback system first. A target was projected onto the floor and the size did not change. Once again each person was allowed 3 practice throws and then 6 tries to get as close to the center of the target as possible. After the second trial, both groups were given a 5 minute break to sit down and relax. When the break was over, they were informed they would have one last chance to try to compete for the cash prize. Group A then competed without the biofeedback and Group B competed with the biofeedback.

The aim of the experiment was to compare the results of the two competitions and see if the participants were able to minimize their distance to the target and perform better when they had the ability to visualize their stress levels. Lastly, each participant was given a survey which included questions using a 7 point Likert scale to gauge their own perception of their stress levels throughout the experiment.

IV. Results

The first thing we looked at after the experiment was the distance that each participant's stones landed from the target.

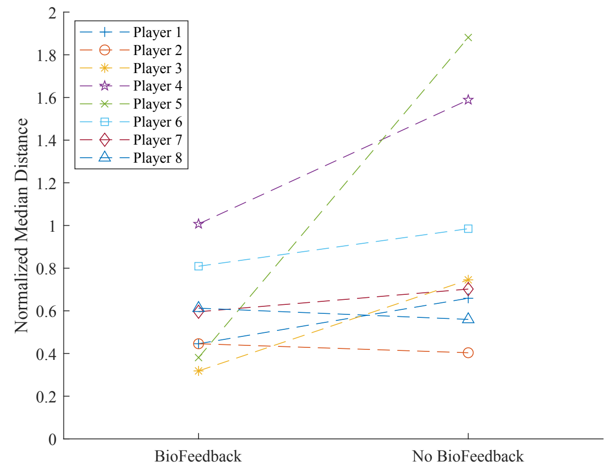

Fig. 6. Median of the stones distance from the target normalized to the player's baseline.

After the initial 3 practice throws, the median distance the stone landed from the target was calculated for the remaining 6 stones from each of the three trials; baseline, biofeedback, and no biofeedback. The median distance was chosen due to the small sample size and filtering of extreme scores. The median distance was normalized to each player's individual baseline and plotted in Fig. 6. It is worth reminding the reader that, like golf, the lower score is desirable in this situation as it means the player was more accurate and closer to the target. Overall, 6 out of the 8 participants showed an improvement in their score when competing with the biofeedback when compared to the competition without the biofeedback.

This improvement is further highlighted when looking at the groups median distance as a whole, Fig. 7. A Wilcoxon signed-rank test was performed to show the statistical significance of the data. When comparing the biofeedback condition with the baseline using this method, the P-value was 0.0156. Additionally, when comparing the biofeedback and no biofeedback conditions, the P-value was 0.0391.

The heart rate data was also measured throughout the experiment for each participant. The data was split into the three conditions and normalized to each participant's individual baseline. The plotted results are shown in Fig. 8. Exactly half of the participants had a higher heart rate during the biofeedback condition when compared with the condition without it. To confirm, a Wilcoxon signed-rank test was once again performed on the data set. It showed that there was no significant difference between the measured heart rates of the conditions with and without biofeedback.

Though there is no significant difference between the heart rate of the participants, it is interesting to look at the participants' heart rate during the experiment. More specifically, the user's heart rate at the moment the participant decides to throw the stone. For this we selected one of the participant's data which best highlights the potential benefits of the proposed system. Fig. 9 shows the data for Participant 8 (P8) during

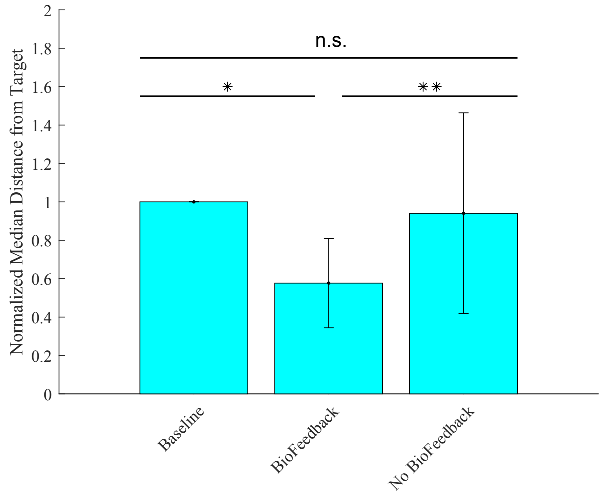

Fig. 7. Normalized median distance of the group

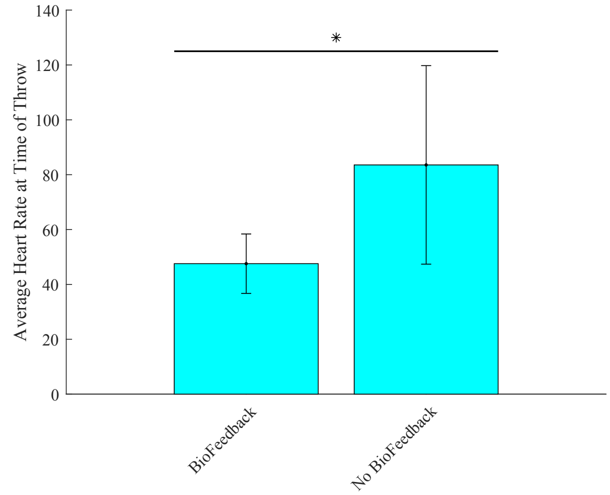

Fig. 9. Example of a participant's average heart rate corresponding to the times that they threw the stone.

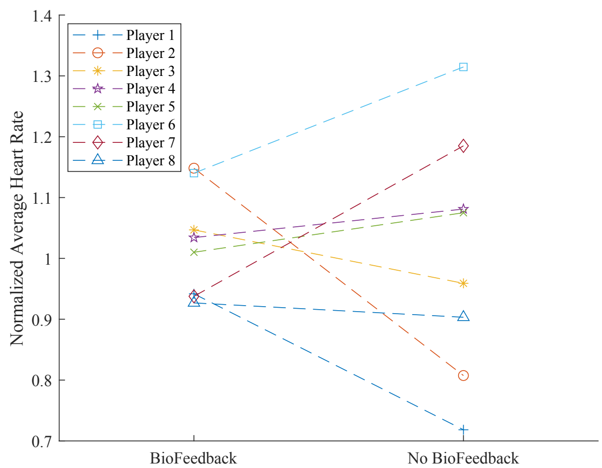

Fig. 8. Normalized average heart rate for participants during the experiment

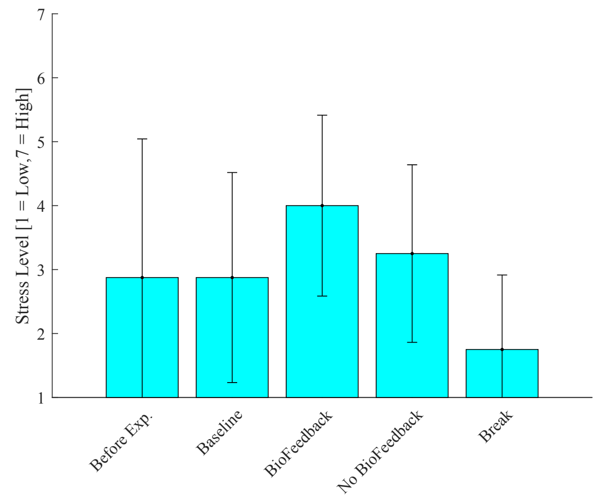

Fig. 10. Average group stress during the experiment

the experiment. It is easily seen by the standard deviation that this participant tried to only throw the stone when they were in a more relaxed state when using the biofeedback system. Without the use of the biofeedback system, there is no correlation between the heart rate and the time at which they decided to throw. Comparing the biofeedback and no biofeedback conditions, the P-value was 0.0313. We believe that this method led them and other participants to achieving a better overall score when using the biofeedback system.

Lastly, we considered the data received from the surveys that each participant was asked to submit upon completion of the experiment. The questions they were asked were to rank their levels of stress over the course of the experiment on a scale of 1 to 7; 1 being very relaxed and 7 being very stressed. The results are presented in Fig. 10. As expected, the "Before Experiment" and the "Baseline" conditions were relatively neutral for the participants. The largest recorded stress was due to the "Biofeedback" condition, with the "No Biofeedback" condition being less. The lowest recorded stress level was from the 5 minute break the participants received between the two competitions.

V. Discussion

A. Player Performance

Overall, mental stress is one of the many factors that affect a player's HR during competition. This experimental setup did not require much physical movement or long term performance. Therefore, the main factor which caused the change of HR recorded during the experiment is assumed to be the mental stress and anxiety experienced by the player.

Looking again at Fig. 10, it is shown that the participants recorded higher self evaluated levels of stress during the biofeedback competition than the competition without biofeedback. However this is not inherently a bad thing. We believe that this is due to the players simply being more aware of their own internal stress states. From the other data it was shown that the participants actually performed better with the biofeedback. Even though higher levels of stress were reported, this did not inhibit their performance. Instead, this shows that the players were able to recognize their own stress and still be able to successfully overcome it. Additionally in Fig. 8, it was shown that there was no significant difference between the recorded heart rates. It was only the user's perception of their stress that showed any difference. This illustrates the fact that a user's perceived stress is also important to consider during these experiments. Measuring HR alone would not have shown the full effects of mental stress experienced by the participants. This is possibly due to the fact that the participants had varying levels of competitive experience and reacted differently to the challenges presented in the experiment. The large error bars in this figure are due to 2 participants who mentioned higher than normal levels of stress prior to starting the experiment due to other outside influences.

Fig. 9 shows one participant's data for the correlation between their heart rate and timing of their stone throws. This participant did make the best use of the biofeedback system. All the participants were told that there was no time constraint during the experiment. They were free to take as long as they needed to perform their best. During the biofeedback competition, P8 would wait and take deep breaths until the target was at its largest size. Then, and only then, would he proceed to throw the stone. This worked well up until the final stone when he was having difficulty relaxing knowing it was his last chance to attempt to win the prize. P8 took an extra two and a half minutes to complete the trial when using the biofeedback. Not all participants used the biofeedback system to this same extent, but a significant number of them benefited from it.

B. Limitations

Though not explored in this paper, it was noted that there were minor differences in players' performance who had previous competitive experience. In a future study, it would be interesting to see if more experienced players would be able to take better advantage of the system. We would also want to see if frequent training with a biofeedback visualization system could have long term benefits to their other competitive pursuits. This would require much more participants and a longer time frame than was done for this initial pilot study.

We also considered designing experiments to evaluate the individual components of the system to see which has the greatest effect on performance. These components may include changing the speed at which the target size updates, changing the number of target sizes possible, and changing the amount of stress on the participant.

VI. Conclusion

We have shown that our system allows for real-time biofeedback visualization during competition and can help players improve their performance. Even though the players showed higher self evaluated levels of stress, the participants were able to perform better using the biofeedback mixed reality system. We attribute this to the visualization aspect of our system that allows the players to be more cognizant of their own mental stress and HR. Small levels of stress can be beneficial in competition and our goal was to never eliminate it entirely. Instead we want the players to be aware of their stress levels and find a way to still perform their best. From the feedback we received, we believe future improvements can be made to the system to make it even better for aiding player performance.

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