# Cognitive Load and Motor Adjustment Under Virtual Defensive Pressure in Mixed Reality Sports Training

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Abstract: Defensive pressure experienced during competition exerts a significant impact on athletes' psychological states and motor behaviors; however, reproducing such pressure in training environments remains a persistent challenge. This study developed a Mixed Reality (MR)-based training system that enables athletes to experience realistic defensive pressure during actual physical movements, using virtual avatars that perform closeout actions. By integrating motion capture technology with an optical see-through head-mounted display, we constructed an environment where the perceived intensity of defensive pressure could be modulated by manipulating avatar height. Experiments involving nine skilled male basketball players compared three defensive conditions—Free (no defender), Human defender, and Virtual defender (180 cm)—and further examined the effects of avatar height variations (160 cm vs. 200 cm). Results indicated that virtual defenders, despite the absence of physical contact, induced psychological load comparable to that of human defenders, as measured by NASA-TLX scores and ball-holding duration. Notably, taller avatars elicited greater perceived pressure and accelerated shot preparation, although no significant differences in shooting accuracy were observed. These findings suggest that MR-based training systems offer an effective means to systematically scale perceived difficulty without compromising performance. Furthermore, the observed dissociation between subjective workload and final outcomes highlights the importance of incorporating multisensory feedback to enhance ecological validity in future system designs.

## 1 INTRODUCTION

In athletic performance, the execution of motor skills is closely related to the pressure perceived by athletes. This pressure can take various forms, including social evaluative stress caused by environmental factors such as attention from spectators and media, as well as spatial and physical constraints uniquely imposed by defenders in team sports(Endo et al., 2023). Among the various forms of pressure, particular attention has been paid to spatial pressure from defenders, which directly affects athletes' physical control. In fact, numerous studies have demonstrated that the performance of offensive athletes is significantly influenced by the pressure exerted by opposing defenders, based on data collected during actual matches across various sports(Sampaio et al., 2016; Leander et al., 2024; Griffin et al., 2017). Traditionally, interventions to prevent the decline of executive functions under psychological pressure—particularly stress caused by environmental factors—have relied on Virtual Reality Exposure Therapy (VRET)(Gerardi et al., 2010; Gerardi et al., 2020). This method aims to reduce real-world stress responses by allowing individuals to experience anticipated stress-inducing scenarios in a virtual environment beforehand. However, in sports contexts, the ability to control physical movements under pressure is critically important, and psychological habituation alone offers limited effectiveness. Because VR environments make it difficult for athletes to engage in training that involves actual body movements, in-



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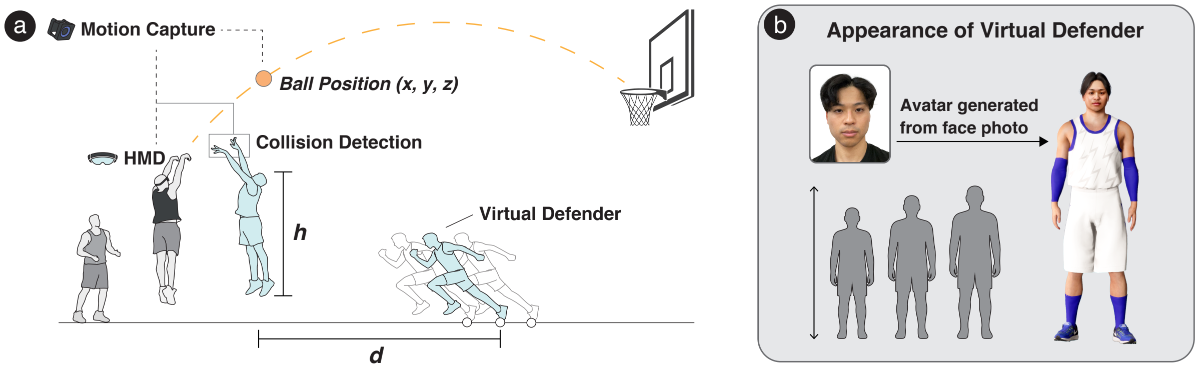


Figure 1: Overview of the proposed system and virtual defender. (a) Real-time motion capture and collision detection for simulating defensive pressure in MR. (b) Virtual defender appearance generated from facial photo with adjustable body attributes.

creasing attention has been given in recent years to reproducing realistic match scenarios using AR (Augmented Reality) and MR (Mixed Reality) technologies(Cheng et al., 2024; Wen et al., 2024). Nevertheless, very few studies have examined the psychological and physical effects that occur when athletes perform real-world movements under pressure from virtual defenders.

In this study, defensive pressure is defined as the actions taken by defenders to apply spatial pressure on offensive players to restrict their movements and prevent them from scoring. The role of a defender is to read the opponent's movements, quickly move to the appropriate position, and block the opponent's passes or shots. The stronger the defensive pressure, the more difficult it becomes for the offensive athletes to fully utilize their motor skills. To counteract defensive pressure, athletes need to undergo appropriate training(Sarah et al., 2020). It is important to refine movements and decision-making under pressure by training while actually experiencing defensive pressure through scenarios that may occur in matches.

Traditional training methods that athletes have adopted to improve performance under pressure can be broadly categorized into individual practice and group practice. In individual practice, athletes often recreate critical in-game scenarios through mental imagery or practice using static objects that simulate defenders(Lindsay et al., 2023). In contrast, group practice involves training with teammates or partners, enabling the development of practical skills such as decision-making and shooting under defensive pressure(Wellington et al., 2023; Seyfi et al., 2018). However, both training approaches present certain limitations. In individual practice, the recreation of pressure situations heavily relies on the athlete's imaginative ability, while group practice is constrained in terms of the intensity and quality of defensive pressure it can realistically simulate. In actual matches, athletes often face defenders with greater physical size and ability than their teammates, making it difficult for conventional group training to reproduce the high-intensity pressure that they may have never experienced before. Therefore, there is a growing need for new training methods that allow athletes to physically experience defensive pressure in real time and flexibly adjust its intensity.

## 2 RELATED WORKS

### 2.1 Virtual Reality Exposure Therapy

In sports, performing exercises under defensive pressure from the practice stage to become accustomed to the defensive pressure expected in games is a commonly used training method. This shares similarities with exposure therapy, which is primarily used to treat anxiety disorders, phobias, and PTSD (Post-Traumatic Stress Disorder) (Richards and Rose, 1991). As a development of exposure therapy, many studies have been conducted on VRET (Virtual Reality Exposure Therapy), a treatment method that aims to recreate anxiety-inducing situations in a VR environment and gradually accustom individuals to these situations (Gerardi et al., 2010; Gerardi et al., 2020). Freeman et al. investigated the effectiveness of automatic cognitive intervention for acrophobia guided by an avatar virtual coach. The results indicated that participants in the VR treatment group experienced a significant reduction in acrophobia at the end of the treatment and during follow-up, suggesting that automated psychotherapy by a VR coach has effects equal to or greater than traditional treatment methods (Freeman et al., 2018). In this way, using VR for treatment to alleviate specific anxieties and fears has been proven effective in numerous studies. Therefore, if external pressure can be deliberately reproduced in a virtual environment and users can be gradually acclimated to it, the approach could be applied as a form of training aimed at enhancing resilience to external stressors encountered during actual competition.

### 2.2 Presence of Virtual Avatars

To effectively convey the spatial pressure of defense, it is necessary to consider the sense of presence people feel towards virtual avatars. The sense of presence in virtual avatars has been extensively studied, particularly in the field of social communication(Tianqi et al., 2024; Yoon et al., 2016; Christos and Michael-Grigoriou, 2022). In the study by Yoon et al., the impact of avatar body part visibility and character style on social presence was compared. The results showed that realistic full-body avatars generated a higher sense of social presence than any other conditions(Yoon et al., 2019). Furthermore, Yoon et al. also investigated the differences in presence caused by varying levels of avatar transparency(Yoon et al., 2023). Their study revealed that as transparency increased, social presence decreased. Based on these findings, it is suggested that to make people feel a strong sense of presence towards AR-displayed defense, it is necessary to use avatars with a realistic appearance and full-body visibility within the system, and to employ devices capable of projecting AR objects with low transparency.

One phenomenon to be cautious of when using realistic avatars is the Uncanny Valley(Mori, 1970). Previous research has shown that when virtual avatars are made to look realistic but exhibit unnatural movements, it can cause users of the system to feel a sense of eeriness(Angela et al., 2010). Therefore, in this study, to avoid unintentionally causing discomfort to athletes using the system, careful attention must be paid to the movements of the avatars.

### 2.3 Sports Training with Virtual Avatar

Recent advances in immersive technologies have drawn attention to the use of virtual agents in tactical training for team sports. Cheng et al. developed a Mixed Reality (MR) system designed to bridge the gap between tactical understanding and execution in basketball(Cheng et al., 2024). By enabling athletes to coordinate and confront virtual teammates and opponents, the system enhances spatial and situational awareness, allowing for repeated practice of complex tactics that are often difficult to achieve in conventional training environments.

The application of virtual avatars has also progressed in the context of coaching. Wen et al. proposed the Augmented Coach, which integrates 3D volumetric video and spatial annotations to deliver real-time visual feedback on posture and timing(Wen et al., 2024). This approach enables personalized remote coaching by projecting expert guidance directly into the athlete's environment.

In addition, studies have explored the psychological dimensions of immersive sports training. Stinson used a CAVE-based VR system to recreate penalty kick scenarios in soccer and investigated athletes' psychological responses under environmental pressure(Stinson and Bowman, 2014). Their findings demonstrated that both physiological and subjective stress responses were significantly induced even in virtual settings, suggesting the potential of VR-based resilience training.

While these studies have contributed valuable insights into environmental simulation, remote instruction, and psychological stress, there remains a lack of research that reproduces and modulates interpersonal pressure—specifically, the spatial and tactical pressure exerted by opposing players—in virtual environments. Furthermore, many existing studies target novice participants or lack realistic situational setups, highlighting the need for training systems that more closely replicate actual competition settings.

This study aims to design and evaluate a training environment grounded in real-game contexts by introducing virtual defenders into MR spaces that impose interpersonal pressure. Through both quantitative and qualitative analysis, we focus on the cognitive and behavioral demands induced by the presence of opponents—an aspect insufficiently addressed in prior work—and propose a novel framework for sport-specific MR training support.

## 3 PURPOSE

The objective of this study is to investigate how visually represented defensive pressure within a mixed reality (MR) environment affects athletes' preparatory behavior and perceived cognitive load during actual physical movement.

We hypothesize that realistic defensive actions performed by virtual avatars can induce a level of pressure comparable to that triggered by real human defenders. Accordingly, this study examines how skilled athletes respond—both cognitively and behaviorally—when facing defensive pressure from either a human or a virtual MR-based defender. Furthermore, we assess whether manipulating simple visual features of the virtual defender (e.g., height) can systematically modulate athletes' perceived threat and preparatory behavior.

The contributions of this study are fourfold:

- **Empirical validation that virtual defenders can induce cognitive pressure responses**—demonstrating perceived workload levels comparable to those induced by real human defenders.
- **Behavioral analysis of preparatory actions under different defender types**—revealing qualitative differences in how athletes manage perceived pressure when facing human versus virtual opponents.
- **Demonstration of scalable pressure modulation**—showing that simple visual manipulations, such as avatar height, can effectively tune perceived defensive pressure.
- **Proposal of a methodological framework**—enabling the investigation of dissociation between perception (subjective pressure), preparation (ball-holding duration), and performance (shooting accuracy) in ecologically valid MR-based sports scenarios.

# 4 PROPOSED METHOD

## 4.1 Generation of Defensive Pressure by Virtual Player

In this system, a virtual player with collision detection for the ball performs defensive actions against a user wearing a see-through HMD (Head-Mounted Display), thereby inducing pressure on the user. Figure 1 shows an overview of the proposed method. The virtual player performs defensive actions against a user performing specific offensive actions. The success of the virtual player's defensive interference is calculated based on the real-time measured position of the ball and the position of the virtual player in the system. When the ball makes contact with the virtual player, immediate feedback is provided to the user. This requires the user to recognize the virtual player as a defender, similar to a real human, and move in a way that prevents their offensive actions from being obstructed. By implementing collision detection for the virtual player and minimizing the differences from the real world, the system allows the user to feel pressure from the virtual player. This system is not limited to specific scenes or sports and can be applied to various training scenarios by intentionally inducing pressure in interpersonal sports.

## 4.2 Collision Detection Between the Ball and the Virtual Player

In this system, the moment when the constantly tracked ball and the virtual player in the system come into contact is detected. The entire surface of the virtual player's body is specified as a range capable of detecting contact with any object, and based on the position and size of the ball, feedback can be provided to the user. The physical characteristics and movement speed of the virtual player can be arbitrarily modified, allowing for the adjustment of pressure. For instance, by increasing the height of the virtual player to simulate a real-world match, or by setting a higher movement speed to enhance the agility of the defense, the pressure can be adjusted accordingly.

# 5 SYSTEM CONFIGURATION

## 5.1 Virtual Player

In this study, it is necessary to pay attention to the physical characteristics of the avatars to investigate the differences in pressure exerted by virtual players versus real human defenders. If the appearance of the avatars significantly differs from that of the human defenders, the players taking the shots might perceive the defense differently, potentially affecting the evaluation of the pressure (Wang et al., 2013). Therefore, in this study, we used an AI called Avaturn, which can create 3D avatars from photographs, to generate 3D models of the human defenders for use in the experiments (Avaturn, 2025). The height of the avatars was adjusted on the platform used to create the system to match that of the human defenders. Additionally, the defensive movements are a critical aspect that greatly affects the pressure. Therefore, during the experiments, we measured the movements of the human defenders using Optitrack motion capture system and configured the system to minimize any discrepancies.

## 5.2 Motion Capture System

The position data of the ball was measured using the Optitrack motion capture system. The motion capture cameras were set to a sampling rate of 120 Hz. An octagonal basketball (Wilson) was used in the experiment, with a total of 42 markers placed along the edges of each face. Additionally, during the experiments, participants wore motion capture suits (Optitrack) to measure their body movements. A skeleton model was created for each participant, allowing the system to automatically estimate the position of occluded markers from other visible markers, even when markers were obscured by the ball or the participant's body.

## 5.3 Head Mounted Display

For dynamic sports like basketball, a standalone HMD is desirable. Considering the importance of weight and field of view (FOV) for physical activities, the Magic Leap 2 (Magic Leap) was used. This device is lightweight at 260g and provides an adequate FOV of 70 degrees (horizontal: 45 degrees, vertical: 55 degrees), ensuring sufficient visibility for movement. Additionally, as an optical see-through HMD, it minimizes latency and discomfort when interacting with the real world. The device also features a dimming function for AR content, allowing it to display immersive content to the user without transparency, maintaining a sense of immersion (Yoon et al., 2023).

## 5.4 Large Space

In this study, the experiments were conducted using "LargeSpace," a large-scale immersive display owned by the University of Tsukuba(Takatori et al., 2016). "LargeSpace" consists of 12 projectors, 10 computers, and 20 motion capture cameras, allowing motion capture measurements in a spacious area of 25 meters in width, 7.7 meters in height, and 15 meters in depth. In this space, a half-court basketball court was created by laying polyline tape (molten) according to the specifications set by the FIBA (International Basketball Federation). Additionally, a freestanding basketball hoop (Spalding) was installed within the same space.

# 6 EXPERIMENT

## 6.1 Experimental Design

### 6.1.1 Participant and Collaborator

In this study, there were two types of individuals involved: experiment participants and an experiment collaborator. The experiment participants refer to the nine individuals who were measured in this study. All participants were male (age: M = 21.0, SD = 2.05; height: M = 173.5 cm, SD = 2.89; basketball experience: M = 11.8 years, SD = 2.04). To control for factors that could affect pressure evaluation, participants were required to have at least seven years of basketball experience under the guidance of a coach

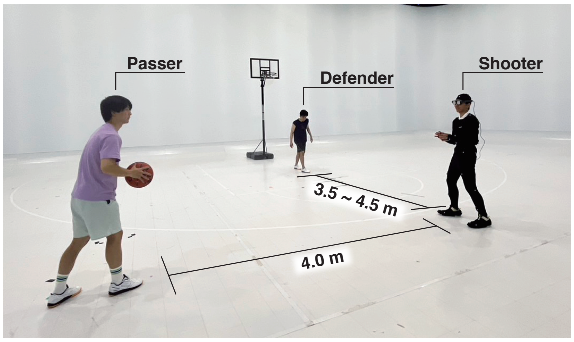


Figure 2: Shooting task setup with variable defensive pressure distances.

and a height between 170 cm and 180 cm. The experiment collaborator refers to the individual who played the role of the defender. All participants faced the same defender (male, age = 23, height = 180 cm, basketball experience = 14 years). This experiment was approved by the institutional ethics review board (Approval ID: 2024R892). All participants provided written informed consent prior to participation and received compensation after completing the experiment.

### 6.1.2 Target Offensive Action

In this experiment, we evaluate the pressure felt by participants during shooting when faced with defense. Specifically, participants perform three-point shots in a scenario called "closeout" (Hopla, 2012). A "closeout" refers to a situation where the defender runs towards the offensive player who has just caught the ball, requiring the offensive player to execute a quick shooting motion compared to a free state without any defense. The actual experimental setting is shown in Figure 2. In the condition with defense, an audible signal is given before each shot, and simultaneously, the experimenter passes the ball to the participant. At the same time, the defensive collaborator starts running from a designated position and attempts to block the shot, applying pressure on the shooting participant. To prevent the shooting participant from becoming accustomed to the defender's actions, the defensive collaborator randomly starts from three different positions with varying distances. The running distances are Hard: 3.5m, Medium: 4m, and Easy: 4.5m from the shooter. To ensure consistent running speeds, the defensive collaborator practiced the closeout 30 times from each position prior to the experiment and subsequently measured the time for 15 trials from the signal to reaching 1m in front of the three-point line. The results showed that for the Hard distance, the average time was 1.2522 s with a standard deviation of 0.0864 s; for the Medium distance, the average time was 1.4748 s with a standard deviation of 0.1062 s; and for the Easy distance, the average time was 1.6042 s with a standard deviation of 0.0775 s. For the virtual player's closeout action, we applied the animation that most closely matched the average running time for each difficulty level and set it to randomly vary the speed within the standard deviation. Lastly, in the condition without defense, an audible signal is given before each shot, the experimenter passes the ball to the participant, and the participant takes the shot.

#### 6.1.3 Evaluation Criteria

Across the two experiments conducted in this study, we evaluated three primary aspects to assess the psychological and behavioral effects of defensive pressure: ball-holding duration, NASA-TLX, and shooting performance.

**Ball-holding duration** was used as a behavioral indicator of hesitation or caution under pressure. It was computed based on the 3D distance between the ball marker and the nearest hand marker. Specifically, holding was defined as the period starting when the ball first entered within 24.5 cm of the hand marker and ending when it first moved beyond 24.5 cm. The threshold of 24.5 cm was chosen to correspond to the official diameter of a basketball. Longer holding durations were interpreted as increased cognitive load or decision-making latency, particularly in the presence of a defender.

**NASA-TLX** was used to assess subjective mental workload. After each condition, participants completed the validated Japanese version of the NASA-TLX(Hart and Staveland, 1988; Haga and Mizukami, 1996), which consists of six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration. Each item was rated on a scale from 0 to 100. To calculate the overall workload score, we used the original weighted NASA-TLX method, in which participants first performed pairwise comparisons to assign relative weights to the subscales. The final score was then computed as a weighted average of the six subscale ratings. This measure captured participants' internal states, such as mental demand and frustration, which are not always externally observable through behavior.

**Shooting performance** served as an outcome-based measure reflecting task success. Each shot was scored using a 4-point system based on established methods in prior studies(Fazel et al., 2018). A score of 3 was given for a successful shot that did not touch the rim, 2 for a successful shot that hit the rim, 1 for a missed shot that hit the rim, and 0 for a missed shot that did not touch the rim. The total score across all shooting attempts in each condition was used as the final performance measure.

Together, these three indicators—behavioral delay, perceived mental load, and motor performance—were used to comprehensively assess the influence of defensive pressure under both real and virtual conditions. Comparisons were made not only between defense and no-defense conditions, but also between human and virtual defenders, allowing us to examine whether virtual agents can elicit responses similar to real human opponents.

### 6.2 Pressure Comparison Between Human and Virtual Defenders

The objective of this experiment was to evaluate the differences in psychological and behavioral pressure exerted by human and virtual defenders during shooting actions. To this end, we conducted an experiment with nine skilled basketball players under three different conditions.

#### 6.2.1 Procedure

Prior to the start of the experiment, participants completed 30 practice three-point shots. They were then instructed on how to use the mixed reality (MR) system and were shown how the "Blocked" feedback would be displayed when a shot was blocked. Thereafter, following the experimental setup described in Section 6.1, each participant performed fifteen three-point shots under the following three conditions:

- **Free:** No defender was present. Participants were allowed to shoot without any obstruction.
- **Human:** A real human defender with a height of 180 cm performed a closeout to contest the shot.
- **Virtual (V-180):** A virtual defender with the same height, appearance, and motion as the Human condition contested the shot within a mixed reality environment.

The order of the three conditions was randomized for each participant to control for order effects.

Data corresponding to the three evaluation criteria—ball-holding duration, subjective workload (NASA-TLX), and shooting performance—were collected and analyzed after each condition. These data served as the basis for assessing the psychological and behavioral effects of defensive pressure.

#### 6.2.2 Result

The results demonstrated clear differences in both subjective and behavioral pressure across the three conditions (Free, Human, V-180). These results are visualized in Fig.4, and detailed data for the NASA-TLX subscales are summarized in Table1.

**Ball-Holding Duration:** A Friedman test revealed a significant effect of defender type on ball-holding duration ($\chi^2(2) = 9.56$, $p = 0.0084$). Participants held the ball significantly longer in the Free condition (1.08 ± 0.13 s) than in the Human (0.88 ± 0.07 s; $p = 0.0078$) and Virtual (0.98 ± 0.11 s; $p = 0.0273$) conditions. The Human condition also resulted in shorter durations than the Virtual condition ($p = 0.0117$).

**Subjective Mental Workload (NASA-TLX):** NASA-TLX scores differed significantly among the three conditions ($\chi^2(2) = 14.00$, $p = 0.0009$). The Free condition (37.56 ± 15.30) was rated significantly lower in mental workload than both the Human (63.44 ± 15.79; $p = 0.0039$) and Virtual (58.26 ± 16.16; $p = 0.0039$) conditions. No significant difference was found between the Human and Virtual conditions ($p = 0.3008$), suggesting comparable perceived pressure from both.

**Shooting Score:** No significant difference in shooting performance was found among the conditions ($\chi^2(2) = 3.00$, $p = 0.2231$). The average scores were 3.81 ± 0.50 for Free, 3.42 ± 0.69 for Human, and 3.40 ± 0.49 for Virtual. Although a Wilcoxon test revealed a marginally significant difference between Free and Virtual ($p = 0.0273$), no difference was observed between Free and Human ($p = 0.1275$) or Human and Virtual ($p = 0.7991$).


Figure 3: Virtual Defender Height Variations (160 cm vs. 200 cm).

## 6.3 Differences in Defensive Pressure by Adjusting Physical Features

In the second experiment, the effect of a virtual defender's physical characteristics—specifically height—on perceived and behavioral pressure was examined.

### 6.3.1 Procedure

The procedure was identical to that of the first experiment, except for the defender height conditions. As illustrated in Figure 3, each participant performed fifteen three-point shots under the following two conditions:

- **V-160:** A virtual defender with a height of 160 cm performed a closeout block motion in the mixed reality environment.
- **V-200:** A virtual defender with a height of 200 cm performed the same motion in the same environment.

All other aspects of the procedure, including the randomized order of conditions, motion capture recording, extraction of ball-holding duration, NASA-TLX evaluation, and 4-point shot scoring method, were consistent with the first experiment.

### 6.3.2 Result

The results of this experiment are visualized in Fig.4, and detailed data for the NASA-TLX subscales are summarized in Table1. Taller or human defenders were associated with higher perceived pressure and shorter preparation time, but did not lead to differences in actual scoring performance. In addition to the within-experiment comparison between V-160 and V-200, we conducted an exploratory cross-condition analysis involving Human, V-160, V-180, and V-200, as all participants experienced these conditions under a consistent protocol.

**Ball-Holding Duration:** A Friedman test showed a significant effect of defender type on ball-holding duration ($\chi^2(3) = 13.40$, $p = 0.0038$). Wilcoxon tests revealed that participants held the ball significantly longer in V-160 (0.97 ± 0.11 s) than in V-200 (0.85 ± 0.11 s; $p = 0.0039$), and also longer in V-160 compared to Human ($p = 0.0078$) and V-180 ($p = 0.6523$). Human and V-180 conditions both led to significantly shorter durations compared to V-160.

**Subjective Mental Workload (NASA-TLX):** A Friedman test found a significant difference among conditions ($\chi^2(3) = 8.60$, $p = 0.0351$). V-200 resulted in significantly higher workload scores (79.07 ± 9.56) compared to V-160 (53.30 ± 16.30; $p = 0.0078$), V-180 ($p = 0.0273$), and Human ($p = 0.0391$). No significant difference was observed between Human, V-160, and V-180.

**Shooting Score:** No significant difference in shot accuracy was found across the four conditions ($\chi^2(3) = 2.10$, $p = 0.5512$). All pairwise Wilcoxon tests returned non-significant results (all $p > 0.35$), indicating that increased pressure did not translate into lower scoring performance.

# 7 DISCUSSION

## 7.1 Reproducibility of Defensive Pressure in Mixed Reality

This study demonstrated that spatial pressure from virtual defenders in a mixed reality (MR) environment can induce a psychological burden on athletes equivalent to that caused by human defenders. This is supported by the finding that virtual defenders—designed to replicate the appearance, height, and movement of human counterparts—elicited no significant differences in subjective mental workload compared to real human defenders. This indicates that virtual characters can serve as cognitively demanding agents and suggests that MR can be expanded from merely replicating training environments to actively designing pressure conditions.

However, a significant difference in ball-holding duration during shooting was observed between the Virtual and Human defender conditions. Despite reporting comparable subjective pressure, participants tended to hold the ball slightly longer when facing virtual defenders. This suggests that subtle discrepancies in bodily sensation specific to MR environments—as well as missing or altered environmental cues such as auditory or tactile feedback—may have influenced motor behavior(Kilteni et al., 2012; Gonzalez-Franco and Lanier, 2017). For example, factors such as visual latency, depth misperception, or lack of material realism could have slightly delayed participants' decision-making and response timing, leading to longer preparation phases.

Additionally, analysis of the NASA-TLX subscales revealed that Frustration was reported to be higher under the virtual defender condition compared to the human defender condition. This suggests that even if the overall level of perceived spatial pressure was similar, emotional stress and feelings of incongruity may have been heightened in the virtual environment. Subtle discrepancies from real-world sensations and the lack of natural interactive responses may have unconsciously triggered irritation among the participants(Kilteni et al., 2012), which in turn could have influenced preparatory motor behavior, such as the observed prolongation of ball-holding duration.

This dissociation between subjective experience and observable behavior offers critical insights for improving the design of MR training systems. Even if visual representations of defensive actions convincingly recreate subjective pressure, athletes' timing and motor accuracy may not fully align with real-world responses. While one participant stated that "the pressure induced by the virtual defender felt almost the same as from a human defender," another participant noted, "In an actual game, if my shot is blocked, I fail. But in MR, I can still shoot even if the defender visually blocks me—so it felt unnatural to play against a virtual defender."

This comment highlights an important design consideration for current MR systems.: regardless of how visually realistic they appear, the absence of real consequences (e.g., losing possession) can reduce the athlete's sense of accountability for their actions, leading to responses that diverge from those observed in actual competitive contexts. Therefore, in addition to achieving visual and motor fidelity, MR systems must integrate sensory feedback and multisensory cues to bridge the gap between perception and action.

For example, Chelladurai et al. reported that the integration of haptic feedback and spatial audio enabled users to have a more natural and realistic experience(Chelladurai et al., 2024). Such multimodal system design is expected to bring MR experiences closer to the physicality of actual sports performance, thereby enhancing the fidelity and generalizability of training.

## 7.2 Scalable Cognitive Load via Visual Properties

In the second experiment, we examined how a single visual characteristic, specifically the height of the defender, influenced both cognitive and behavioral responses. The results revealed clear differences in NASA-TLX scores and ball-holding durations, suggesting that participants evaluated the physical threat posed by the defender based on visual information prior to physical interaction. This evaluation appears to influence the temporal aspects of decision-making. Similarly, prior research by Mousas et al. demonstrated that variations in the appearance and motion of virtual characters could modulate users' emotional reactivity, supporting the notion that visual features alone can systematically shape perceived pressure in immersive environments(Mousas et al., 2018).

In particular, the virtual defender with a height of 200 cm elicited significantly higher cognitive load compared to the 160 cm and 180 cm conditions, and also led to a significantly shorter ball-holding duration than the 160 cm condition. Although the height increase from 180 cm to 200 cm was the same 20 cm as that from 160 cm to 180 cm, clear changes

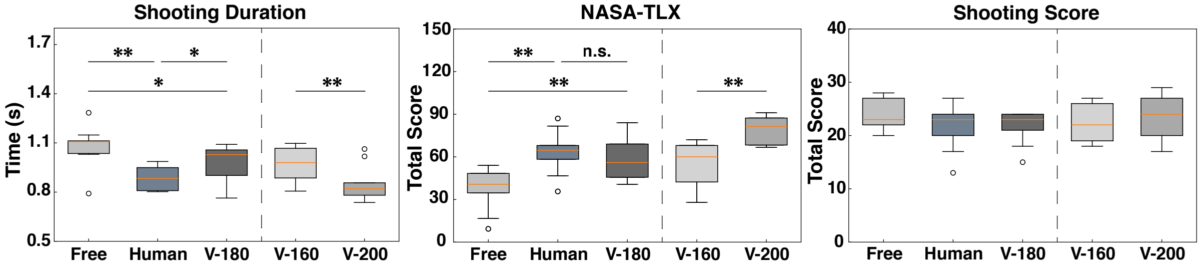


Figure 4: Comparative analysis of behavioral and cognitive metrics across all experimental conditions: shooting duration (s), NASA-TLX total score, and shooting score. (*$p < .05$, **$p < .01$; n.s. = not significant).

Table 1: NASA-TLX Scores (Mean ± SD) by Condition and Subscale.

| Subscale | Free | Human | V-160 | V-180 | V-200 |
|---|---|---|---|---|---|
| Mental Demand | 22.78 ± 12.77 | 62.22 ± 22.10 | 45.00 ± 22.78 | 48.89 ± 21.76 | 76.67 ± 12.75 |
| Physical Demand | 25.00 ± 12.99 | 58.33 ± 24.24 | 41.67 ± 23.05 | 44.44 ± 19.44 | 83.33 ± 7.50 |
| Temporal Demand | 23.33 ± 13.46 | 61.67 ± 27.50 | 27.22 ± 20.48 | 50.00 ± 21.79 | 70.00 ± 28.61 |
| Performance | 48.33 ± 26.58 | 51.67 ± 28.39 | 58.33 ± 25.98 | 51.11 ± 23.15 | 55.00 ± 18.87 |
| Effort | 43.33 ± 30.00 | 61.11 ± 21.76 | 59.44 ± 19.91 | 55.00 ± 23.05 | 73.33 ± 18.37 |
| Frustration | 23.89 ± 23.42 | 66.67 ± 17.14 | 47.22 ± 30.83 | 61.67 ± 19.84 | 78.89 ± 20.58 |

in cognitive and behavioral responses were observed only in the former case. This suggests, as one participant noted—"I normally don't play against players who are 200 cm tall, so I felt strong pressure"—that it was not merely the visual size of the defender, but rather the surpassing of an internalized reference norm that acted as a qualitatively distinct threat stimulus. Indeed, Shen et al. demonstrated that in VR environments, increases in object size—quantified by omnidirectional field of view occupancy—were significantly associated with elevated anxiety levels and heart rate, supporting the idea that surpassing a certain size threshold may trigger qualitatively different cognitive responses(Shen et al., 2022).

Furthermore, detailed analysis of the NASA-TLX subscales revealed qualitative differences in the nature of cognitive load across conditions. For example, Temporal Demand remained particularly low under the 160 cm condition, whereas Effort and Frustration sharply increased under the 200 cm condition. This suggests that players, who normally rely on automatized shooting skills, had to exert more conscious control under stronger perceived pressure, increasing cognitive and emotional load.

Additionally, the response patterns for Effort and Frustration did not follow a linear progression, but instead exhibited a sharp increase specifically when moving from 180 cm to 200 cm. This suggests the presence of a threshold effect in the perception of virtual threat, wherein cognitive and emotional loads escalate nonlinearly once the defender's height or visual salience surpasses a certain perceptual boundary. Such nonlinear changes in cognitive and behavioral responses near the perceptual threshold are consistent with the findings by Tseng et al., who demonstrated that perceptual manipulations in VR environments can lead to abrupt behavioral changes once a sensory threshold is surpassed(Tseng et al., 2022). Their work showed that small undetected manipulations could accumulate and trigger nonlinear shifts in user behavior upon crossing a critical perceptual boundary, aligning with the present results.

On the other hand, no significant difference was observed between the V-160 and V-180 conditions. One possible explanation is that the height difference between these two avatars may have been relatively minor in the context of the participants' own heights, which were all within the 170 cm range. In contrast, the 200 cm avatar may have exceeded a perceptual threshold, thereby functioning as a qualitatively distinct stimulus that provoked a heightened sense of threat and a stronger cognitive-motor response.

These findings indicate that, within mixed reality training environments, it is possible to design not only motor difficulty but also the level of perceived pressure in a gradual and scalable manner by skillfully manipulating the visual features of virtual defenders.

## 7.3 Dissociation Between Perceptual Load and Final Performance Outcome

In this study, while significant differences were observed in subjective workload (NASA-TLX scores) and preparatory behavior (ball-holding duration), no substantial statistical differences were found in the final performance outcome, namely shooting accuracy. These results suggest that although pressure was perceptually experienced and influenced participants' motor strategies, skilled athletes were able to suppress these effects at the performance level.

This dissociation indicates that skilled athletes may possess adaptive control strategies that allow them to maintain task performance even under pressure. While the perception of pressure affected motor preparation—manifested as a reduction in ball-holding duration—it did not lead to performance deterioration. This could be attributed to motor skill automatization and the stability of sensorimotor routines in experienced players.

Such findings support the utility of mixed reality (MR) as a tool for simulating performance pressure. Specifically, for skilled athletes, MR-based training can elicit changes in subjective and behavioral responses without excessively impairing actual performance, enabling effective and targeted pressure training.

Similar patterns have been reported in VR-based sports training research. For example, Gray demonstrated that VR batting training, when adaptively designed to match the performer's skill level, not only improved virtual task performance but also successfully transferred to real-world batting outcomes and long-term competition levels (Gray, 2017). These findings further reinforce the potential of MR systems to elicit meaningful cognitive and motor adaptations that generalize beyond the training context.

Furthermore, the absence of significant differences in shooting accuracy across the Free, Human, and Virtual conditions suggests that participants were able to execute similar avoidance strategies and motor decisions under virtual defensive pressure as they would under real human defense. This indicates that the use of virtual defenders in MR can provide a sufficiently realistic context for training pressure resilience, offering a viable alternative to human-based defensive drills—especially for situations requiring repetition, customization, or safety.

This advantage is further enhanced by the unique capabilities of MR systems, which allow for fine-grained modulation of perceived pressure (e.g., avatar height, proximity, or timing) in ways that are difficult to achieve with human defenders. This precision enables the design of targeted training interventions that go beyond conventional practice, especially for exploring edge cases or rare in-game situations.

# 8 LIMITATIONS

**Participant Characteristics.** All participants in this study were nine skilled male basketball players with over eight years of competitive experience and a height range of 170–180 cm. While this design ensured consistency in skill and physical attributes, it also introduced selection bias that may limit the generalizability of our findings. In particular, the small sample size poses statistical limitations. This homogeneous and limited sample precludes examination of how athletes of different genders, skill levels, or physical statures might perceive and respond to virtual defensive pressure.

**Limited Scope of Pressure Factors.** The type of pressure manipulated in this study was primarily spatial and physical—based on the defender's appearance and proximity. However, real-game pressure also includes temporal constraints, audience effects, and situational stress, none of which were represented in the experimental design. Accordingly, the pressure experienced in this MR system reflects only a subset of the multifaceted stressors encountered during actual competitive scenarios.

**Constraints on Measurement Indices.** The evaluation of pressure effects in this study was limited to three indices: subjective workload (NASA-TLX), preparatory movement (ball-holding duration), and final outcome (shooting accuracy). While these are meaningful and practical measures, they do not capture the full range of cognitive and motor changes under pressure.

**Simplified Task Design.** The target action in this study was restricted to three-point shooting in a "closeout" situation. The task did not involve more complex offensive behaviors such as dribbling, passing, or decision-making under multiple response options. As a result, the system may not fully replicate the dynamic and strategic demands of in-game scenarios involving high cognitive load and action selection.

**Variability Due to Human Execution.** In the Human defender condition, the closeout movement was manually executed by the defender, resulting in slight trial-to-trial variability in timing and running trajectory. Additionally, in all conditions, the passes delivered to participants were manually thrown by an experimenter. These sources of human error may have introduced noise into the measurements of ball-holding duration and perceived mental workload.

## 9 FUTURE WORKS

**Expansion to Decision-Making Tasks.** While this study focused on a single shooting action, actual gameplay requires players to make rapid decisions among multiple options such as shooting, driving, or passing. As a next step, we plan to implement multi-option tasks where the player selects the appropriate offensive action based on the virtual defender's movement, distance, and spatial context.

**Development of Multi-User Training Environments.** The current system is designed for a single user. In the future, we aim to construct a synchronized multi-user MR training environment in which multiple players, each wearing an HMD, can interact with virtual players in the same shared space. This would allow for team-based tactical training and the development of coordinated actions such as positioning and spacing, thereby extending the system's utility from individual skill acquisition to group-level strategy training.

**Application to Remote Training.** By capturing the player's motion in real time using motion capture or IMU sensors and reflecting it in a virtual avatar, it becomes possible to construct a training system in which athletes can practice together in a shared virtual space despite being geographically apart. For example, remote coaches could observe and provide feedback on live movement data, or distributed athletes could engage in synchronized tactical practice, paving the way for a distributed sports education platform.

**Integration of Interactive Virtual Player Control.** Currently, the virtual defender operates using pre-recorded motion data. Future implementations may incorporate interactive control, allowing users (e.g., coaches or training partners) to operate the virtual defender in real time via controllers or user interfaces. This functionality would enable the virtual defender to respond dynamically to each scenario, enhancing the variability and adaptability of training exercises.

## 10 CONCLUSION

This study demonstrated that virtual defenders in mixed reality (MR) can exert psychological and behavioral pressure on skilled basketball players comparable to that of real human defenders. Notably, avatars replicating human appearance, height, and motion induced similar subjective workload levels (NASA-TLX), suggesting that realistic pressure can be effectively reproduced in MR environments. Adjusting the virtual defender's height alone significantly influenced ball-holding behavior and perceived pressure, indicating that visual cues can be used to systematically scale difficulty without physical contact. While differences in cognitive load and preparation time were observed, shooting performance remained stable, implying that skilled athletes employed adaptive motor strategies even under MR-induced pressure. These findings suggest that MR can serve not only as a simulation tool but also as an effective environment for training psychological resilience and pressure tolerance without degrading performance.

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