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Examining the representativeness of a virtual reality environment for simulation of tennis performance

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Abstract

There has been a growing interest in using virtual reality (VR) for training perceptual-cognitive skill in sport. For VR training to effectively simulate real world tennis performance, it must recreate the contextual information and movement behaviours present in the real-world environment. It is therefore critical to assess the representativeness of VR prior to implementing skill training interventions. We constructed a VR tennis environment designed for training perceptual-cognitive skill, with the aim of assessing its representativeness and validating its use. Participants movement behaviours were compared when playing tennis in VR and real-world environments. When performing groundstrokes, participants frequently used the same stance in VR as they did in the real-world condition. Participants experienced a high sense of presence in VR, evident through the factors of spatial presence, engagement and ecological validity being high, with minimal negative effects found. We conclude that Tennis VR is sufficiently representative of real-world tennis. Our discussion focuses on the opportunity for training perceptual-cognitive skill and the potential for skill transfer.

Introduction

The use of virtual reality (VR) training has received significant attention in recent years and is a growing area of interest in high performance sport. Researchers and practitioners have anticipated that immersive VR systems, such as head mounted displays, can effectively simulate sporting environments and, therefore, be used as a training tool to fast-track learning and athlete development (Craig. 2013; Gray, 2017; Tirp, Steingröver, Wattie, Baker, & Schorer, 2015). Critically, however, there has been a lack of research examining how closely VR represents the key dynamics of real-world sporting environments. Consequently it is unclear whether VR training augments sports performance compared to more commonly used training tools (e.g. the use of 2D video presentations; for recent reviews of VR training, see Neumann et al. (2018), Düking et al. (2018), and Faure et al. (2020)).

Harris et al. (2020) recently developed a framework for testing and validating simulated environments for training purposes. The authors outlined a taxonomy of the types of fidelity and validity considered essential to achieve skill transfer from simulated environments to the real-world performance setting. The framework includes psychological fidelity (perceptual and cognitive features of the display), affective fidelity (emotional responses), ergonomic fidelity (action responses), face validity (structural and functional behaviour of objects) and construct validity (how accurately the simulation matches the real-world). Essentially the taxonomy highlights that there are at least three important factors that need to be considered when determining the potential of VR in sport. These include: (1) the perceptual information needs to closely replicate the real-world environment; (2) athletes decision making should be based on comparable information found in the real-world; and (3) athletes need to able to interact with the environment using actions that closely represent competition (Gray, 2019; Pinder et al., 2011). Achieving these are not an easy feat, and some researchers have posited that VR can impair users processing of sensory information, therein hindering the ability to naturally intercept the virtual objects (Harris et al., 2019; Squires et al., 2016). It is therefore important to assess the representativeness of the VR environment prior to implementing skill training interventions.

Representative learning design is a framework used for designing and testing field-based practice tasks in sport (Pinder et al., 2011). It was adapted from an earlier framework (i.e., representative design; Brunswik, 1956), which emphasised the importance of recreating the performance environment when designing empirical research. The motive underpinning the framework was to better understand how individuals adapt to challenges in their natural performance setting (Araújo et al., 2007; Brunswik, 1956). Consequently, representative learning design highlights the need to couple perception and action in sports training, and to consider how interacting constraints influence movement behaviours (Renshaw & Gorman, 2015; Vilar, Araujo, Davids, & Renshaw, 2012). It is proposed that training tasks that are more representative of the performance setting are more likely to produce learnings that can be applied to the real-world, therein enhancing performance. To guide practitioners and researchers in the development and assessment of training tasks, representative learning design endorses the importance of two factors – functionality and action fidelity (Pinder et al., 2011). Functionality refers to athletes achieving success in training by basing their decision making and actions on comparable information to that of the real competition environment (Loffing et al., 2016; Pinder et al., 2011). Comparatively, action fidelity refers to whether a performer’s action or behaviour remains the same in the training and performance environment (Araujo, Davids, & Passos, 2007; Stoffregen, Bardy, Smart, & Pagulayan, 2003). Therefore, to facilitate skill transfer, perceptual information found in real competition should also be present in the VR training environment, and the perceptual information in VR should be coupled with the ability to perform actions that also occur in real competition (Pinder et al. 2009; Jacobs & Michaels, 2002).

Underpinned by action fidelity and functionality, the modified perceptual training framework offers a method to assess the effectiveness of perceptual training tools (Hadlow et al., 2018). This framework targets three factors – the perceptual skill trained, the training stimuli (functionality), and the action response (action fidelity). The perceptual skill trained refers to whether training targets a lower order visual skills (e.g. visual acuity, depth perception, vergence; Erickson, 2007) or higher order perceptual skills (e.g. sport specific decision making or anticipation; Williams & Ford, 2008; Muller & Abernethy, 2012). The type of training stimuli used addresses the similarity between the stimuli presented in training compared to competition. Training stimuli can range from generic (e.g. shapes; Smeeton et al., 2013) to sport specific (e.g. real opponents; Mitroff, Friesen, Bennett et al., 2013; Oudejans, Heubers, Ruitenbeek et al., 2012). The final factor, action response, pertains to whether the response method (i.e., the action in response to the stimuli) in training is analogous to competition. The modified perceptual training framework predicts that skill transfer to competition is heightened when these three factors are more sport specific (Hadlow et al., 2018).

Despite previous work illustrating best practice for designing VR training tools in sport, there has been little research testing the representativeness of training environments prior to their use. As a rare exception, however, Harris et al. (2019a) tested the fidelity of a VR golf putting simulator by (a) assessing expert and novice golfers in VR and real-world environments (action fidelity measure), (b) assessing the perceptual and cognitive demands of the golf simulation using a self-report measure of task load (functionality measure), and (c) comparing the perceived distance to the hole in VR and real-world environments (functionality measure). Results showed that the simulation successfully distinguished expert from novice golfers, and provided task demands comparable to real putting (Harris et al, 2019). Additionally, sense of presence was assessed, which is defined as the sense of being in a VR environment and is thought of as a cognitive state that results from various senses processing information (Slater & Wilbur, 1997). Results showed participants reported a good level of presence, although high variance was reported across participants (Harris et al., 2019). Nonetheless, this work provides a useful example of how to assess and validate the representativeness of VR environments in sport.

The main aim of the present study was to examine the representativeness of a VR tennis simulation. In line with previous suggestions for assessing the validity of VR, we measured action fidelity and the sense of presence when skilled tennis players played VR tennis. Action fidelity was assessed by comparing movement responses (type of stance used and number of steps taken to perform groundstrokes) between VR tennis and the real-world, while sense of presence was measured using the Independent Television Commission- Sense of Inventory (ITC-SOPI) questionnaire. This questionnaire addressed four factors of presence – sense of physical space, level of engagement, ecological validity and negative effects. We hypothesized that Tennis VR would show high levels of representativeness relative to real-world tennis, evidenced by movement responses that closely reflected real-world tennis and a high sense of presence in each factor.

Methods

Participants

Skilled male (n = 14) and female (n = 14) tennis players aged between 12 to 17 years (M = 14.4, SD = 1.6) were recruited from a high-performance tennis academy to participate in this study. This academy brings together talented junior tennis players to train and play under the guidance of three coaches that hold the highest level of qualification. Notably, participants had no experience using VR technology. Informed consent from the participant's and their parents/guardians was provided prior to the participant commencing the study, and the study was approved by the ethics committee at the lead researcher's university.

Virtual reality system design

Development of virtual opponent

A 12-camera Vantage opto-reflective motion capture system (Vicon Motion Systems Ltd, Oxford, UK; 250 Hz) was used to dynamically record the positions and movements of a human actor (skilled tennis player) performing various tennis strokes, and a range of common movements seen during tennis matches (e.g., running forward or out to the side) (see Figure 1). Static and dynamic calibrations were conducted within the 10 x 10-meter capture space to set up the global reference system and calibration volume. The aim of this was to capture all movements performed during tennis matches and import this information into the virtual opponents' characteristics to make their movements as realistic as possible. The actor wore a motion capture suit, fitted with fifty-two retroreflective markers (12.7 mm diameter) on key anatomical locations. A further five markers were affixed to the racquet used to perform strokes to ensure representative swing techniques were captured for each shot type (forehand, backhand, serve, volley). The recorded marker trajectories were then modelled and visualized as a humanoid character that became the virtual opponent that users played against in the VR tennis environment. Positive X was set to the right (displacement along this axis is referred to as lateral or left/right), positive Y was forward (displacement along this axis is referred to as forward/backward), and positive Z upward (displacement along this axis is referred to as vertical).

Development of hitting trajectories

HawkEye was used to capture hitting trajectories of tennis shots. HawkEye is a computer-vision solution that uses six cameras positioned around the tennis court to generate 3D representations of ball trajectories (tennis shots). This capture involved a coach feeding balls to specific parts of the court, and the actor hitting different groundstrokes towards various positions on the court. Additionally, the actor performed serves from the deuce and advantage sides of the court in various hitting directions (wide, tee and body serves). The overall intent being to capture a range of shots that could otherwise be considered to represent the vocabulary of shots (Kovalchik & Reid, 2017) in tennis. These trajectories were then imported into the Tennis VR system. This meant that all shots hit by the virtual opponent were representative of the hitting trajectories of an opponent in a real tennis scenario. Furthermore, the tennis ball in the VR environment was animated to show the type of spin (topspin, backspin or sidespin) accompanying each trajectory. This therefore allowed players to use this information to perceive the trajectory of the ball (as is the case in the real-world). The VR environment was also designed to align with the physics of the real-world environment (e.g., the effect of gravity on the trajectory of an oncoming ball) which allowed the tennis ball to move naturally within the VR environment. Furthermore, the hitting trajectories were also imported into a customised software tool within the VR system to further develop the artificial intelligence (AI) of the virtual opponent.

Artificial intelligence software development

An artificial intelligence (AI) software program, which was created though VR development platform Unity, was developed and imported into the VR system. This program gave researchers complete control over the virtual opponent's actions, including the type of shot they had available to hit (forehand, backhand, slice etc.), and the direction and velocity of each shot (including the speed, spin and net clearance height). This meant that the researchers could control how the virtual opponent played on a shot-by-shot and point-by-point basis, allowing for patterns of play to be embedded into the VR opponent's playing style. The length and outcome of points could also be pre-determined by manipulating the virtual opponent's abilities (making the opponent hit the ball into the net or hit an unreturnable shot). This allowed the duration of each match to be tightly controlled.

The AI software program was also applied to the human player's experience. The hitting trajectories that the human player had available to choose from were the sum of all the hitting trajectories captured by Hawkeye. This equalled 1600 shots and included several different ball trajectories for all types of shots (forehands, backhands, volleys and serves). For example, if the player swung their racquet with the aim of hitting a forehand cross court, the AI would select one of the ball trajectories from the system that was the closest match to the shot the player intended to hit. During this process, the AI considers the way the player swung their racquet, the swing speed, the angle of the racquet as it contacts the virtual ball (based on sensors attached to the racquet), and the amount of spin the player intended to put on the ball, and then decides which ball trajectory is the closest match to these variables. How closely this matched was determined by the number of trajectories in the system which were similar to the shot intended to be hit by the player. Indeed, one of our aims when capturing trajectories using Hawkeye was to capture as many as possible (1600 trajectories) in order to increase the chance that the players intended shot matched the trajectory outcome in VR. This is a time consuming process, however in the future more trajectories will be added to the system, thereby enhancing how closely the trajectory matches the players intended shot.

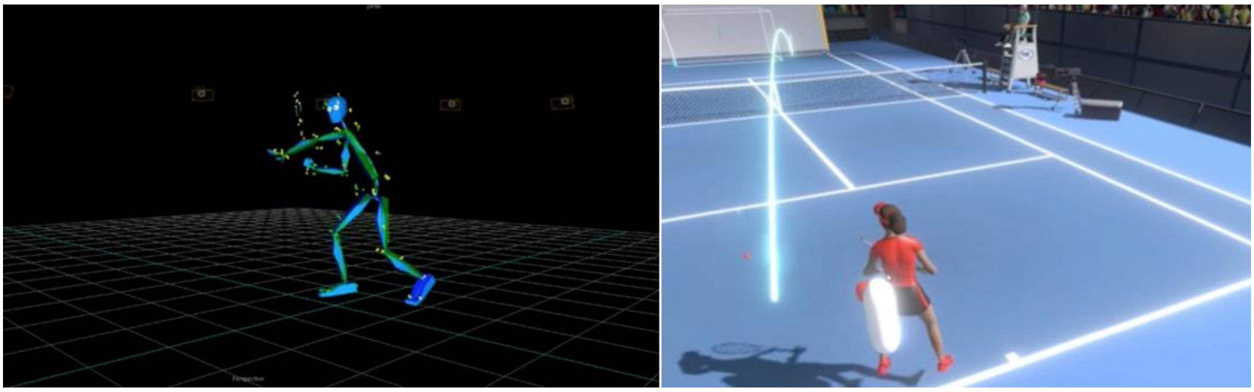

Figure 1. The left image shows the marker trajectories modelled and visualised into a humanoid character. The humanoid in this case is performing a forehand groundstroke. The

image on the right is an example of a ball trajectory (light blue coloured arch) that has been captured using Hawkeye and imported into the VR environment. Notably, the light blue coloured arch showing the flight path of the ball is removed when playing a match.

Experimental Design

A repeated measures design was used whereby all participants performed a tennis task in three conditions. These conditions included playing tennis in VR using a tennis racquet (VR racquet), using a tennis racquet handle (VR handle), and playing tennis in the real-world (real- world). The order in which the VR conditions were performed were counterbalanced across participants. That is, half of the participants completed the VR racquet condition first, followed by the VR handle condition, with the other half of participants completing the VR handle condition first, followed by the VR racquet condition. All participants completed the real-world condition last. We included two VR conditions to assess the influence of using a tennis racquet versus a smaller racquet handle on participant's sense of presence scores, specifically related to presence factors ecological validity and spatial presence. We then assessed the representativeness of VR tennis by using a range of subjective and objective measures related to the action fidelity and functionality of the task. The subjective measures assessed sense of presence in the VR environment whilst the objective measures compared movement behaviour in VR tennis compared to real-world tennis.

Procedure

The VR racquet and VR handle conditions followed the same procedure. Initially participants were provided with an opportunity to become familiar with the VR environment. This involved wearing the HTC VIVE PRO headset (470 grams) for 2 minutes, therein providing time to scan and walk around in the VR environment, and rally with the virtual opponent. Once participants felt ready, they commenced the first 10-minute testing block. Immediately after completing the first 10-minute block in each VR condition, participants filled out a presence questionnaire. Participants then completed the second 10-minute block which involved hitting 10 forehand and backhand ground strokes. The real-world tennis condition followed a similar procedure, with the only differences being: 1) participants played on a real tennis court, 2) participants did not complete a sense of presence questionnaire after the first 10-minute block (the presence questionnaire does not apply to experiencing the real-world if no forms of media are present), and 3) a ball machine was used in the second 10-minute block to feed balls to the forehand and backhand sides of participants.

Virtual reality task: Conditions 1 and 2

The Tennis VR task took place in an indoor gymnasium (16m x 10m). The HTC VIVE Pro VR headset was worn by participants to experience the tennis VR environment. The Tennis VR environment was carefully designed to closely represent that of a real-world professional tennis environment (see Figure 2). This included a hardcourt tennis court surrounded by stands with a crowd of virtual people and a live scoreboard. The appearance of the virtual ball was typical of real-world tennis. A tennis handle device (a tennis racquet handle, excluding the frame) was used by participants to hit the virtual ball in the *VR handle* condition. Comparatively, in the *VR racquet* condition, participants used a tennis racquet. In this condition, a small sensor **(**7cm x 4cm x 3cm, 90 grams) was placed on the participant's handle section of their tennis racquet which allowed it to be used for hitting the virtual tennis ball. The first 10-minute block was used to assess the sense of presence of participants during a VR tennis match. Participants played a virtual tennis match using the scoring system typical of real-world tennis, the only difference being the virtual opponent served for the entirety of the match (typically, a total of 18 games were played). Immediately after this match, participants completed a sense of presence questionnaire (5 minutes in duration). The second 10-minute block was dedicated to assessing movement (type of stance used and number of steps taken). This involved the participants positioning themselves in the centre of the court behind the ‘T’ on the baseline. The opponent then fed a ball out to the forehand side of the participant. Participants moved to hit the shot and were asked to direct this shot back down the middle of the court as fast as possible whilst maintaining control of the ball. This was repeated a total of 10 times on the forehand and backhand side. Participants had 6 seconds to recover in between shots. Importantly, the ball trajectories of the forehand and backhand feeds were pre-recorded using a ball machine and inserted into the VR system. This allowed for these ball trajectories to be used in both VR and real-world conditions, therefore participants reacted to ball trajectories that were as close as possible to each other in all conditions (i.e., the ball machine cannot reproduce the exact same trajectory every time, even if the settings are the same). Additionally, a camera (Sony HDR-CX405 HD Camcorder) was positioned in front of participants to film their footwork and stance selections when hitting groundstrokes.

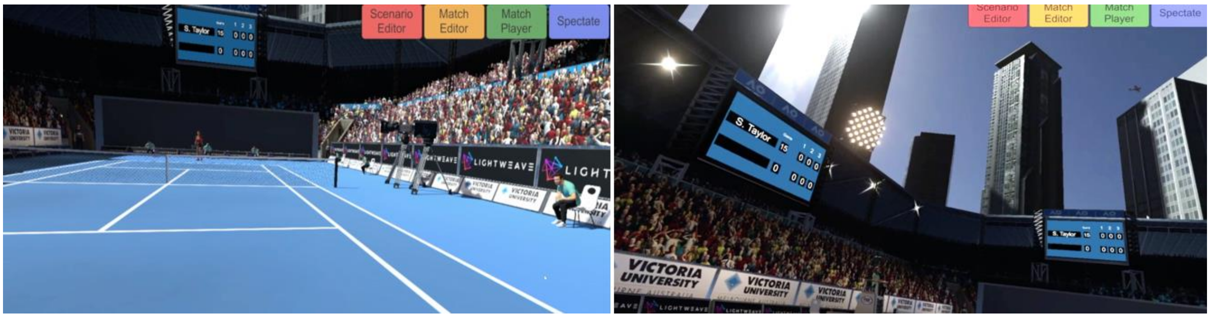

Figure 2. Images of the Tennis VR environment, including (a) the court surface, line judges, camera’s, scoreboard and crowd in the stands, and (b) the sky and buildings that surround the court. These details were included in the VR environment to enhance sense of presence and immerse participants in the environment.

Real world tennis: Condition 3

In the real-world condition, the first 10-minute block involved participants playing a tennis match against an opponent on a real tennis court. Differing from the VR environment, this tennis court did not include a surrounding stadium. The opponent in this condition was the same player used during the hitting trajectory capture on the Hawkeye tennis court, whereby their hitting trajectories were transferred into the VR environment and used by the virtual opponent to hit shots. Therefore, participants played against the same opponent in the real-world and VR conditions (participants were not aware of this). The second 10-minute block followed the same process as both VR conditions with two exceptions. First, a ball machine was used to feed balls to participants forehand and backhand sides (instead of the virtual opponent in the VR conditions). Every ball trajectory sent by the ball machine was identical to the trajectories used in both VR conditions. Second, participants did not complete the post task sense of presence questionnaire.

Subjective Measures

Sense of presence questionnaire

The Independent Television Commission- Sense of Inventory (ITC-SOPI) questionnaire (Lessister, Freeman, Keogh, Davidoff, 2001) was used to assess sense of presence. This questionnaire is measured on a 5-point Likert scale, with 1 corresponding to “strongly disagree”, and 5 corresponding to “strongly agree”, and has been shown to be a reliable and valid tool for assessing presence using interactive displays and other types of media (e.g. VR, television, computer, IMAX). It consists of 44 items divided into four factors, including: 1) spatial presence (r = 0.94), 2) engagement (r = 0.89), 3) ecological validity (r = 0.76), and 4) negative effects (r = 0.77). Spatial presence indicates a sense of physically being in the VR environment, including interacting with and having control over the different parts of the environment. This factor is strongly related to the sense of ‘being there’. Engagement describes the level of psychological involvement in the VR environment and the level of enjoyment the user experiences. Ecological Validity indicates how strongly the user believes the VR environment is lifelike and real. This includes how lifelike the user rates their movements. For these three factors, a score of 5 is considered the highest level of presence possible and a score of 1 is the lowest. Negative Effects relates to any negative physical or psychological reactions the user experiences, including dizziness, feeling tired, nauseas, developing a headache and eyestrain. In this factor, a score of 1 is considered the least amount of negative effects experienced with a score 5 being the maximum amount.

Objective Measures

Stance

The stances that participants used to hit forehand and backhand groundstrokes were recorded using a video camera (Sony HDR-CX405 HD Camcorder). This involved a tennis coach (level 3 coaching accreditation) watching vision of participants hitting groundstrokes and assessing the type of stance used. Types of stances included open, closed and semi-open stance. A closed stance was defined as when the feet and body were turned sideways to the net (see Figure 3). The open stance was defined as when the feet were aligned parallel to the net. The toes may have pointed forward or to the side, however if participants were aligned parallel to the net, this was an open stance. The semi-open stance is a stance in between closed and open, and was defined as when the feet were diagonal relative to the net. Like the open stance, the toes may have pointed forward, to the side or obliquely. This measure was taken at the point in which the participants racquet was in position to contact the ball. When there was question over which stance was used, a second opinion was obtained from a level 3 accredited coach and a decision was made after critiquing and discussing the case.

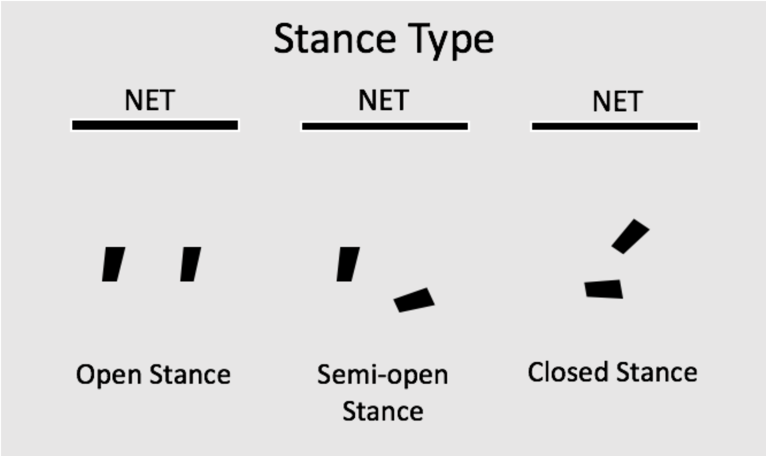

Figure 3. Illustrating the three different types of stance players used when performing groundstrokes during the second 10-minute block of the VR Task.

Number of steps

A video camera (Sony HDR-CX405 HD Camcorder) was used to assess the footwork of participants when performing forehand and backhand groundstrokes in VR and real-world conditions. Footwork referred to the number of steps participants took between the moment when the ball was fed to the moment when participants finished their forehand or backhand follow through with their racquet.

Statistical Analysis

Mixed effects regression models were used to estimate differences between each condition. For numeric variables including the presence factor scores, a mixed effects model was used with random effects for each participant and a fixed effect for the condition (VR racquet, VR handle). Likelihood ratio tests were run to assess the effect of shot type and condition by comparing the full model against the model without the effect in question. Assessments about the magnitude of effects between groups were based on linear contrasts of the model fixed effects and their 95% confidence intervals using the Holm method to adjust for multiple comparisons. The variable stance was assessed by transforming each type of stance into numeric format. Mixed effects regression models were then used with random effects for each participant and a fixed effect for condition type to observe whether stance type differed between conditions**.** Proportions were then calculated by summing the times each participant used the same stance when hitting forehands and backhands in the real-world as they did in the VR conditions. This number was then divided by the total number of participants to reveal the proportions for each shot type and condition. A total of 8 participants (4 male and 4 female) did not complete the real-world condition (4 missed due to being absent and 4 were injured). This was treated by removing the comparison of real-world and VR conditions for these participants. All analyses were performed in the R language (R Core Team, 2014) and the *lme4* package (Bates et al., 2015) was used for the mixed modelling.

Results

Sense of presence questionnaire

Spatial presence

Participants spatial presence scores were considered to be in the high range in the VR racquet (M = 3.60, SD = 0.58, 95% CI [3.39, 3.80]), and VR handle (M = 3.69, SD = 0.47, 95% CI [3.49, 3.9]) conditions (p = 0.18) (see Figure 4).

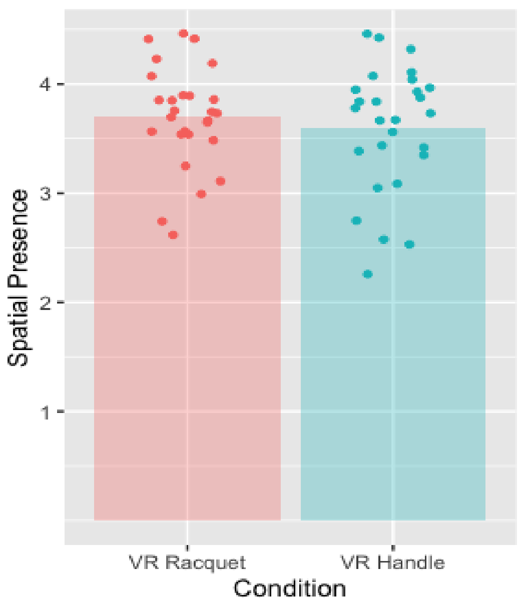

Figure 4. Comparison of the mean and individual spatial presence scores across VR Conditions.

Engagement

Engagement scores were considered to be in the high range in the VR racquet (M = 3.89, SD = 0.59, 95% CI [3.66, 4.11] and VR handle (M = 3.84, SD =0.58, 95% CI [3.62, 4.07] conditions. There was no significant difference in the level of engagement found between VR conditions (p = 0.7) (see Figure 5).

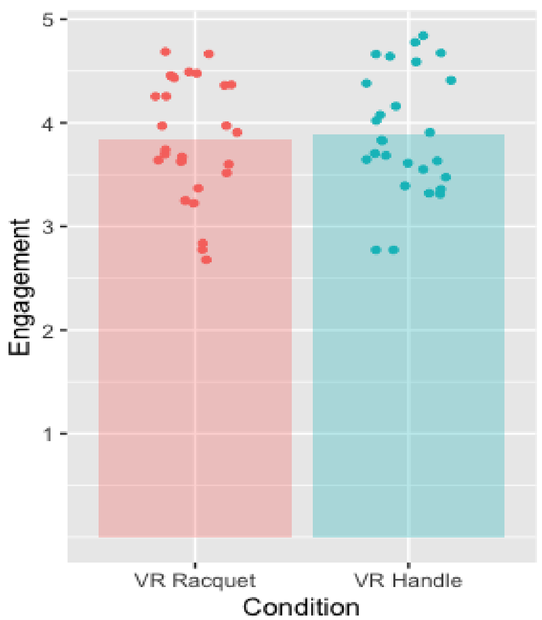

Figure 5. Comparison of the mean and individual engagement presence scores across VR conditions.

Ecological validity

Participants scores in ecological validity were considered to be in the high range in the VR handle (M = 3.79, SD = 0.47, 95% CI [3.6, 3.97] and the VR racquet condition (M = 3.69, SD = 0.5, 95% CI [3.5, 3.88], p = 0.29). No significant difference in ecological validity scores was found between VR conditions (see Figure 6).

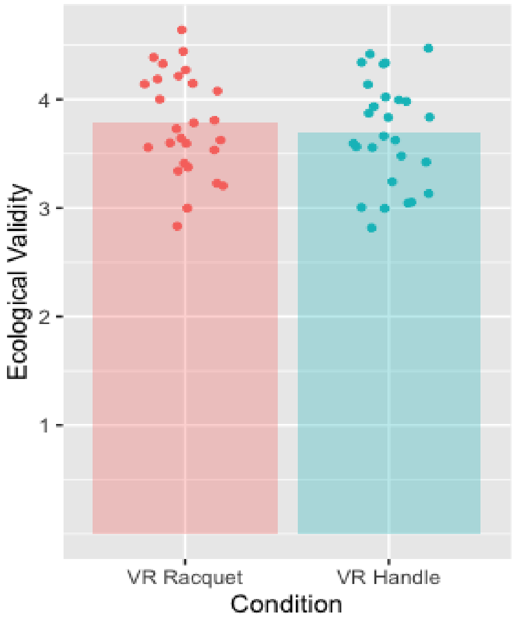

Figure 6. Comparison of the mean and individual ecological validity presence scores across VR conditions.

Negative effects

Based on the 1 – 5 scaling system with 1 being the lowest possible score, negative effects scores were similarly low in the VR racquet condition (M = 1.37, SD = 0.74, 95% CI [1.13, 1.61] as well as the VR handle condition (M = 1.26, SD = 0.45, 95% CI [1.02, 1.50] (p = 0.5).

Objective measures

Stance

Analyses revealed that participants used the same stance when hitting forehand groundstrokes in the VR conditions as the real-world condition for 85% (17/20) of forehands and 70% (14/20) of backhands. A likelihood ratio test revealed no significant effect of condition in our model (p = 0.12). Notably, all participants used the same type of stance for all ten shots hit (i.e. if they used an open stance on shot 1, they continued using this stance for the remaining nine shots). A significant effect for shot type (p = 0.0001) was found, with participants using an open stance to hit forehand groundstrokes 96% (95% CI [89, 100]) of the time, compared 14% using an open stance (95% CI [7, 22]) when hitting backhand groundstrokes. The interaction in our model (condition x shot type) was not significant ($p = 0.55$).

Steps

The effect of condition on our model was found to be significant ($p = 0.0001$). This equated to participants taking 0.6 less steps in both the VR racquet condition (M = 5.0, 95% CI [4.8, 5.3]) and the VR handle condition (M = 5.0, 95% CI [4.8, 5.2]) compared to the real-world condition (M = 5.6, 95% CI [5.4, 5.9], $p = 0.001$). A likelihood ratio test revealed that the interaction in our model (condition × shot type) had no significant effect on the number of steps taken prior to performing a forehand or backhand groundstroke ($p = 0.08$) (see Figure 7).

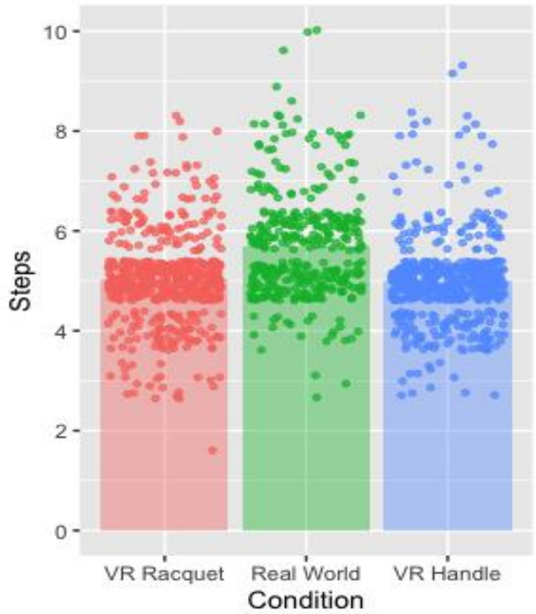

Figure 7. Comparison of the mean and individual number of steps taken across VR and real-world conditions.

Discussion

This study examined the representativeness of a VR tennis environment relative to a real- world tennis setting. There were two key findings from this study. First, participants scored in the high range for presence factors (engagement, ecological validity and spatial presence) during both VR conditions. Notably, this result occurred without any accompanying reports of negative effects. Second, the action responses of participants – namely the type of stance used to perform groundstrokes – were representative of real-world tennis.

Results from the sense of presence questionnaire revealed that participants experienced a high sense of presence during both VR conditions. The high range of scores for engagement (VR racquet condition, M = 3.89 out of a possible max score of 5) suggest that participants were highly engaged in the VR experience. Likewise, the high scores found for spatial presence and ecological validity indicate that participants felt they could effectively interact with the VR environment with a strong sense of control. One could argue that a limitation of common training tools used by coaches (e.g., watching 2D vision) is their lack of engagement, with many tools inhibiting the ability to interact and therefore influence the course of events shown in the display. The results from this study suggest that players using Tennis VR will have a subjective learning experience that feels enjoyable, engaging and interactive, whilst having a strong sense of 'being there' in the performance environment. Notably, there is little research assessing sense of presence in sport simulations (e.g., 2D video presentations or VR environments). Harris et al., (2018) is a rare exception, but we cannot compare our results with their study as different questionnaires were administered. Future research should explore whether sense of presence is associated with the novelty of the VR experience or whether it is preserved over time.

With regards to the action responses, the type of stance used to perform groundstrokes in VR tennis paralleled the stance used in real-world tennis (85% match between VR and real-world for forehands, 70% for backhands). This is indicative of *action fidelity* – a core tenant of representative learning design. We acknowledge, however, that a significant difference was observed between VR and real-world tennis in the number of steps taken when performing groundstrokes. This difference equated to 0.6 fewer steps (mean difference) in VR tennis. We suspect this might have been caused by player's movements being constrained by the VR headset (e.g., the wire attached to the headset, and the headset's mass). Additionally, although field of regard (total area that can be captured by a person) was not restricted in the VR environment, field of view (the extent of the environment that can be seen at a given moment) was limited, which may have influenced perception and action when playing VR tennis. It is also possible that players actions (such as number of steps) were influenced by the presence of the crowd in the VR environment, therein causing differences to the real-world condition where no crowd was present. Certainly research has shown that surroundings within VR environments can induce a sense of anxiety (Stinson and Bowman, 2014). Further research is warranted to understand the factors that potentially influence movement behaviour.

Representative learning design contends that for skills to transfer from training to competition, players must base decision making and action responses on comparable information to that of the real competition environment (Loffing et al., 2016; Pinder et al., 2011). It has been shown that skilled tennis players use ball flight information to anticipate the falling point of the ball and decide the type of stance they will use to perform the upcoming shot (Williams, Vickers, & Rodrigues, 2002). Therefore, our results suggest that the ball flight information presented in the VR simulation prompted participants to move to the ball and position their bodies (type of stance used) in a representative way, thus prompting real-world action responses. However, because participants responded to the same ball trajectory ten times in a row for both types of groundstrokes, participants may have used prior knowledge of the ball's landing position to anticipate some shots, rather than using ball flight information. Nevertheless, these findings show that real-world action responses can be reproduced in this VR Tennis simulation, which is promising for transferring skills from VR to the real performance environment.

The similarity in results between the two VR conditions in this study is worth noting. Specifically, our results revealed that using a smaller racquet handle device did not significantly change action behaviours (stance and number of steps taken) and sense of presence compared to using a tennis racquet. However, future research should compare the arm biomechanics and swing velocities of groundstrokes when using the handle device as compared to the tennis racquet. This may provide insights about whether using the handle device creates any negative effects on swing technique in the real-world (e.g., different swing patterns, racquet head speed changes). Likewise, follow-up investigations should explore the ability of players to control the direction of their shots (e.g., ability to hit cross court and down the line towards a target) in VR during different match-play situation (e.g. high-pressure situations) and whether this is influenced by the type of racquet used.

Given that our tennis VR environment effectively simulated real-world tennis performance, we hypothesise that VR tennis can be used as a training tool to enhance perceptual-cognitive skill in tennis (presuming the training program is appropriate for the player engaging with the tool). With this in mind, a unique feature of VR technology is the capability of manipulating any aspect of the environment in real time. This includes utilising AI to control the strengths, weaknesses and tactics of opponents on a point by point basis, changing the speed abilities of the opponent, and altering other environmental variables such as crowd noise to induce a sense of pressure on players. This provides an opportunity to expose athletes to specific situations they will face during real competition (e.g., experiencing booing or loud cheers from a crowd during a close tie break in tennis). This level of environmental manipulation is not possible in the real-world training environment and is therefore a significant advantage of VR.

Conclusion

This study applied key principles of representative learning design and the modified perceptual training framework to examine the representativeness of a VR tennis environment for simulation of tennis performance. The assessment of spatial presence, engagement and ecological validity suggest that Tennis VR provides a high level of presence with minimal negative effects. The movement behaviour in the VR environment indicates that Tennis VR represents real-world tennis movements. The next step in this line of research is to examine whether Tennis VR can facilitate the development of pattern-recognition skill; that is, the ability of players to identify patterns of play or an opponent's tactics during a match. An exciting question is whether it is possible to use Tennis VR's AI capabilities to prepare players for patterns of play that are likely to be used by upcoming opponents.

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