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Which technology to investigate visual perception in sport: Video vs. virtual reality

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Visual information uptake is a fundamental element of sports involving interceptive tasks. Several methodologies, like video and methods based on virtual environments, are currently employed to analyze visual perception during sport situations. Both techniques have advantages and drawbacks. The goal of this study is to determine which of these technologies may be preferentially used to analyze visual information uptake during a sport situation. To this aim, we compared a handball goalkeeper's performance using two standardized methodologies: video clip and virtual environment. We examined this performance for two response tasks: an uncoupled task (goalkeepers show where the ball ends) and a coupled task (goalkeepers try to intercept the virtual ball). Variables investigated in this study were percentage of correct zones, percentage of correct responses, radial error and response time. The results showed that handball goalkeepers were more effective, more accurate and started to intercept earlier when facing a virtual handball thrower than when facing the video clip. These findings suggested that the analysis of visual information uptake for handball goalkeepers was better performed by using a 'virtual reality'-based methodology. Technical and methodological aspects of these findings are discussed further.

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1. Introduction

In sports involving interceptive tasks, like baseball, soccer, tennis or handball, one of the fundamental elements of performance is the ability to decode a human's or an object's trajectory as effectively as possible, in order to be at the right place, at the right time (Williams, Davids, & Williams, 1999; Williams, Vickers, & Rodrigues, 2002). This anticipation is based on picking up and selecting salient visual information of the situation (Abernethy, 1988). For example, in tennis, the visual information available before the impact between the racket and the ball is critical in order to identify the falling point of the ball (Goulet, Bard, & Pleury, 1992). Similarly in karate, fighters need to uptake visual information from the head and chest of their opponent in order to anticipate their actions (Williams & Elliott, 1999). Finally in handball, goalkeepers seem to focus on the shooter's arm holding the ball to prepare their movement (Debanne, 2003).

To investigate realistic situations, several methods have been used in the literature to analyze visual perception directly by interviewing players (Debanne, 2003), by using liquid crystal glasses that can block vision at a specific time (Müller & Abernethy, 2006; Starkes, Edwards, Dissanayake, & Dunn, 1995), or by recording gaze behavior throughout the action (Dicks, Button, & Davids, 2010; Panchuk & Vickers, 2006; Rodrigues, Vickers, & Williams, 2002; Williams & Davids, 1998). Concerning experimental design, it has been demonstrated that requiring subjects to perform sport actions in *in situ* conditions permits to assess decision-making expertise in sport (Mann, Abernethy, & Farrow, 2010; Travassos et al., 2013). However, using a simulated experimental design may help to examine the influence of one piece of visual information taken by the athlete when several elements evolve at the same time. Using a standardized and reproducible environment may thus be an asset when analyzing visual perception in sports (Loomis, Blascovich, & Beall, 1999). Two methods can be used for that purpose: video-based or virtual reality (VR) method. The goal of this work is to compare the use of these two methods for the analysis of visual perception. It is applied to the duel between a thrower and a goalkeeper in handball.

Video-based methods were used first to analyze visual perception in standardized environments and are still widely employed due to its ease of implementation. It consists in observing a participant's response in front of a sport action recorded during a game-like situation. From a methodological point of view, several approaches have been used to analyze this participant's response. Some were interested in the temporal aspect of the answer by computing the time delay used for responding to the video clip (Williams & Davids, 1998; Williams, Davids, Burwitz, & Williams, 1994). Others tried to identify significant visual information used by the subject by employing a temporal occlusion paradigm (Abernethy, 1987; Farrow & Abernethy, 2003). In this approach, the amount of visual information presented to participants is temporally controlled by cutting off the video clip at different key moments of the action. Such critical instants can correspond to the end of a throwing motion in cricket (Müller, Abernethy, & Farrow, 2006), the beginning of a ball trajectory in soccer (Savelsbergh, Van der Kamp, Williams, & Ward, 2005), the racket/ball contact in tennis (Fukuhara, Ida, Kusubori, & Ishii, 2009), or the ball release from the hand in handball (Cañal-Bruland & Schmidt, 2009; Cañal-Bruland, van der Kamp, & van Kesteren, 2010). However, video-based presentation has several limitations (Abernethy, Thomas, & Thomas, 1993; Bideau et al., 2010; Williams et al., 1994). The first drawback concerns the two-dimensional display of the video projection. With this method, the subject cannot extract stereoscopic information, as in real life. Moreover, many studies have demonstrated the influence of stereoscopic information on motor responses (Mazyn, Lenoir, Montagne, & Savelsbergh, 2004; Yeh & Silverstein, 1992). The second limitation is linked to the viewpoint of the subject during the experiment. As their decisions are based off the view of the camera, it cannot be updated in real-time if the subject moves during the experiment. In a real sport situation, different visual information may be extracted from the environment depending on the subject's viewpoint. Although strong experimental control is often provided, video-based methods have several drawbacks that lead researchers to explore other technologies.

VR technology can address these limitations. VR consists of creating numerical simulations in immersive environments and is now being used as a tool to analyze and understand performance in sport (Bideau et al., 2010; Craig, 2014; Katz et al., 2006). VR has a number of advantages over video projection. First, in a virtual environment, a subject may react to a simulated opponent while the experimenter carefully controls and modifies visual information being viewed (Bideau et al., 2004). All display parameters can also be controlled and tuned in a systematic manner, ensuring reproducibility between trials. Thus, VR allows for an accurate and standardized experimental protocol (Tarr & Warren, 2002). Second, tracking head movements so that the subject's viewpoint is updated in real-time helps to enhance the sense of presence (Hendrix & Barfield, 1996). This concept can be defined as the feeling of being present in the virtual environment (Sanchez-Vives & Slater, 2005; Slater, Khanna, Mortensen, & Yu, 2009). In addition, images displayed in a virtual environment are stereoscopic, giving the subject salient motion-in-depth information (Slater, Linakis, Usoh, & Kooper, 1996). Moreover, perspective in a virtual environment can be adapted in real-time to correspond to the subject's viewpoint. For these reasons, VR has been extensively used in the literature to understand visual perception during interceptive tasks, especially to understand human action when catching fly balls (Chardenon, Montagne, Buekers, & Laurent, 2002; Fink, Foo, & Warren, 2009; Zaal & Bootsma, 2011). In sports, some VR simulators have been developed to investigate motor and perceptual skills necessary to perform complex motor tasks (Multon, Kulpa, & Bideau, 2011). In tennis, some virtual environments have been designed to create an interaction between an immersed subject and a virtual humanoid (Molet et al., 1999; Noser, Pandzic, Capin, Thalmann, & Thalmann, 1996). In soccer, a VR system has permitted researchers to analyze whether adding spin to a ball in the free-kick situation affects professional players' perception of the ball's future arrival position (Craig, Berton, Rao, Fernandez, & Bootsma, 2006). Nevertheless, none of the previous studies has conducted an experimental study to validate the use of their VR system for visual perception analysis. This can be done by comparing subjects' performance in real and virtual worlds (Zahorik & Jenison, 1998). For example, in handball, Bideau and colleagues have shown that expert handball goalkeepers' response in front of an immersive virtual stadium with a synthetic player throwing the ball towards them was similar to their real-world response (Bideau et al., 2003). This validated VR system has then been used to study different parameters on handball goalkeepers' perception in virtual environment (Bideau et al., 2004; Vignais et al., 2009, 2010) and will be employed in the current study.

Although VR seems to be a strong alternative to real situation for exploring the perception–action loop in sport, it has some limitations, especially in research on manual interceptive actions (Dessing, Peper, & Beek, 2004). The first limitation is the cost and complexity of setting up such a system. Technologies are developing to make it easier to use and cost less, such as the Oculus Rift (Oculus VR Inc., Irvine, CA, USA). Nevertheless, the virtual environment has to be created, the virtual character animated, etc. Moreover, for a fully immersive solution with head tracking technology, it is necessary to take into account the potential (even minor) delay for the viewpoint adaptation. Also, note that compared to video display, the visual information (details, aspects, shapes) are created from a measured movement and need to be processed through several steps (capture, reconstruction, mesh...) before display. Consequently, it can reduce the potential display fidelity compared to the real initial situation (a real image will look more realistic than a virtual one). Concerning fidelity display, the "uncanny valley" concept also needs to be considered when dealing with human appearance in virtual environments: it has been stated that the graphical representation of a synthetic character induces an unpleasant feeling for the subject if this representation is close to the human appearance (Seyama & Nagayama, 2007). Moreover, during VR experiments, participants need to wear 3D glasses to see with a stereoscopic viewpoint or a head mounted display with two small screens in front of each eye. The latter device has drawbacks related to the limitation of field of view, the image resolution produced and the weight of these devices (Rebelo, Noriega, Duarte, & Soares, 2012). Nevertheless, active stereoscopic glasses are now as light and small as regular glasses. In addition to these limitations, given the example of a duel situation between a virtual thrower and a real goalkeeper, the feeling of physically intercepting the ball would be necessary to reproduce the sport situation. Haptic systems, which are still relatively expensive and sizeable, might be used to simulate the contact (Avizzano et al., 2012) with vibration systems for example. Nevertheless, wires would be present when simulating the force feedback necessary to believe in the collision with the virtual ball. Thus using this technology during large and fast motions may appear limited. Moreover, although people easily interact in a real-life situation, this aspect of reality may be hard to implement in a virtual environment, especially for sport situations where time pressure requires real-time interactions.

Potentially, all these parameters can create artifacts and so perturb the perception–action loop process.

Only a few studies have aimed to compare different projection technologies, such as VE and video, to determine which technology is more suited to visual perception analysis into simulated experimental designs. A study by Fukuhara et al. (2009) compared two different techniques of perceptual skills assessment in tennis: a method based on video images and a method based on computer graphics animations. In their first experiment, the authors examined the visual search behaviors and the accuracy of anticipating serve direction of skilled tennis players when facing the two projection types. Results showed that, when facing the video images, subjects observed the racket area for more time during the 150 ms period immediately before the moment of racket-ball contact and performed more accurate predictions. In a second experiment, the authors used the temporal occlusion paradigm to analyze the information pick-up patterns while participants viewed both kinds of displays. It appeared that, when viewing video clips, skilled players made more accurate predictions during the 150 ms period immediately before the racket-ball contact. Although these two experiments supported the potential advantage of using video-based techniques rather than computer-based animations to examine perceptual skills of athletes, the virtual reality system authors employed may appear limited. For example, there was no head tracking nor stereovision provided when facing the animated virtual character. Moreover the model used for the virtual tennis player was somewhat limited by the graphical level of details employed (body limb segmentation and skin representation), even though this factor may not have an influence on the participant's perception (Vignais et al., 2009). Thus, these limits need to be overpassed before we may establish which of the VE and video technologies is more suited to visual perception analysis during simulated experimental designs.

Finally, as we have seen in the different studies presented above, two main types of tasks, reflecting differing degrees of perception–action coupling with time, may be used for assessing judgment predictions (Craig, 2014; Farrow & Abernethy, 2003; Mann et al., 2010): (1) the uncoupled task, that emanates from the information processing approach (Abernethy & Russell, 1987; Davids, 2002; Williams et al., 1999; Wright, Pleasants, & Gomez-Meza, 1990); and (2) the coupled task, that is related to the ecological approach of visual perception in which perception informs movement and movement informs perception (Gibson, 1979; Neisser, 1976). This approach has already been employed for the analysis of interceptive actions (Bootsma & van Wieringen, 1990; Brault, Bideau, Craig, & Kulpa, 2010; von Hofsten, 1987). Even if the second task appears more realistic and closer to the real situation, it is critical to explore both. Goodale and colleagues have argued that two different neural pathways are involved in visuomotor tasks processing: the ventral stream is involved in the identification and classification of a visual stimuli during perceptual tasks, as in an uncoupled task, in contrast the dorsal stream is more involved with the control of motor responses in response to a visual stimuli, as in a coupled task (Goodale & Haffenden, 1998; Milner & Goodale, 1995). Although other frameworks for visual anticipation exist (i.e., van der Kamp, Rivas, van Doorn, & Savelsbergh, 2008), it is important for future research involving differing degrees of perception–action coupling to know which technology is most appropriate for the analysis of visual perception into simulated experimental designs. Is the potential difference observed between VR and video display the same during an uncoupled task or during a coupled task? Which one should be used, regarding the approach we want to follow?

The aim of this study is thus to compare two methodologies used to analyze visual perception in sport: video-based and VR-based methods. To make this comparison, exactly the same situation is presented in both environments: a handball thrower that throws the ball toward the goal in which a real goalkeeper tries to stop the ball. To ensure that the situation is exactly the same, the movements of the thrower have been captured at the same time for both environments. As the vision is occluded during the experiment, the performance of the handball goalkeepers in front of the opponent's throwing action displayed in video clip (VC condition) and in virtual environment (VE condition) are then compared for two judgment prediction tasks: an uncoupled task in which the goalkeeper predicts offline where the ball reached the goal, and a coupled task in which the goalkeeper tries to intercept the virtual ball. This study would provide guidance and differentiation elements in the selection of a method for visual perception analysis in simulated sport situations.

2. Materials and methods

2.1. Video acquisition, motion capture and animation process

Video clips and virtual animations used for the two experimental environments have been obtained from the same throwing motions in a single capture session (see Fig. 1).

The film clips used in the VC condition were recorded by using a high definition video camera (Canon HV30, Canon, Tokyo, Japan) sampled at 25 Hz and positioned in the middle of the goal at a height of 1.75 m (see Fig. 2).

Simultaneously, for the VE condition, kinematic data of the throwing movement were captured at 100 Hz by the VICON MX40 motion capture system (Oxford Metrics, Oxford, UK) composed of 12 infrared cameras. The player was equipped with 40 reflective markers placed on standardized anatomical landmarks: sternoclavicular joint, xiphoid process, 7th cervical vertebra, 10th thoracic vertebra, and for both hemi-bodies, occipital and frontal bones, glenohumeral joint, medial humeral epicondyle, lateral radial head, ulnar styloid process, radial styloid process, 3rd metacarpus process, 3rd phalanx of the 3rd finger, anterior iliospinale, posterior iliospinale, medial tibial head, lateral femoral condyle, lateral malleolus, medial malleolus, heel, Lisfranc joint, head of the 2nd metatarsus. This marker placement enabled us to precisely reconstruct joint centers of the subject, and, the position and orientation of each segment in three dimensions. Moreover, six markers were positioned on the ball in order to track its trajectory.

In a real handball stadium, a professional right-handed handball player (age = 24 years, height = 1.84 m, weight = 95 kg) threw to the six lateral zones represented in the goal (see Fig. 2). This 9-zone division was employed to examine the influence of the zone targeted on the goalkeeper's performance. The targeted zone may indeed affect the goalkeeper's response due the kinematical organization of the throwing movement at ball release (Vignais et al., 2010). The player was asked to throw the ball in the middle of each zone as if a goalkeeper was present. Each throw was performed at 9 m from the goal. The athlete had to randomly perform five repetitions per zone, corresponding to a total of 30 throws. The six trajectories, and their associated throwing actions, that arrived closest to the center of each zone, were used in the video projection and virtual animation part of the study. Ball velocities were similar for all six trajectories (20 ± 0.2 m s^{-1}), making ball flight times nearly the same for all six zones. The study was approved by the local ethics committee.

Kinematic data from the throwing motion were labeled and transferred to the MKM (Manageable Kinematic Motions) animation engine (Multon, Kulpa, & Bideau, 2008). In the VE experiment, a synthetic humanoid was animated in a handball stadium scaled with real dimensions (see Video 1). The projection of the virtual world was performed in a VR center made up of three synchronized video

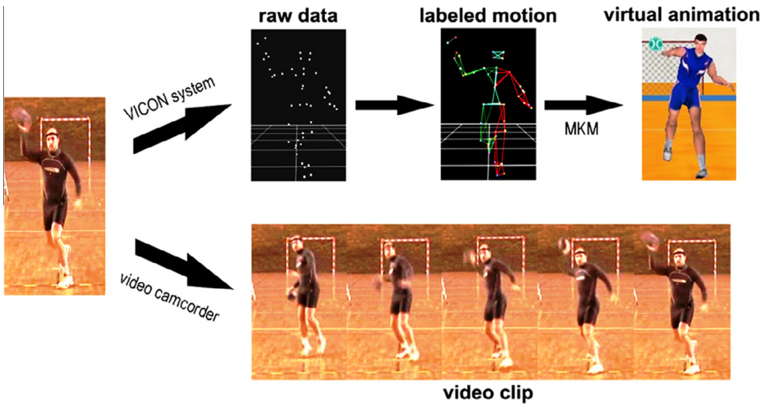

Fig. 1. Video sequence and virtual animation production processes. Throwing motions are captured with the VICON system, labeled and animated in a virtual environment. Throwing action is also recorded with a video camcorder at the same time.

Fig. 2. The handball goal was divided into nine zones. Only black-numbered zones were aimed at. The video camcorder was placed at the center of the goal and at a height of 1.75 m.

projectors driven by a SGI 83 Onyx2 Infinite Reality and a semicylindrical screen (3.80 m radius, 2.38 m height, and 135° field of vision) placed at 4.50 m from the participant. A set of active glasses (see Fig. 3) synchronized at 120 Hz alternately occluded each eye to enable stereovision. Thus the VE was displayed at a frequency of 60 Hz (per eye). Head tracking was also used by using the motion capture system (delay <20 ms). To this end, the middle of the four reflective markers placed on the participant's head was defined as the goalkeeper's viewpoint.

In the VC experiment, the video clip was displayed with the same projection system (see Video 2) at the acquisition frame rate of 25 Hz. The throwing motion was adjusted in such a way that an object in reality 1 m high placed 9 m away (see right and left vertical bars on Video 2) corresponded to 1 m on the video clip and inside the virtual environment. This provided a visual angle of about 6.3°, which was similar to that of the throwing action seen on the real handball stadium.

2.2. Evaluation of goalkeepers' performance

10 elite male handball goalkeepers (playing in the top national handball league in France) gave their informed consent before participating in the experiment. Mean age of the participants was 24 years (±5.2 years), mean height was 1.84 m (±0.04 m) and mean weight was 85.9 kg (±14.4 kg). All subjects had normal or corrected-to-normal vision.

Prior to the experiment, each goalkeeper had a training period to get accustomed to the virtual environment (a real handball goal was placed with the virtual world to enhance his immersion) and the response tasks. They randomly viewed five throws of each of the VC and VE conditions. These training trials were not included in the subsequent analysis.

After warming up, handball goalkeepers were asked to react to the two experimental VC and VE conditions. The order of presentation of the experimental conditions was different for each subject.

Fig. 3. The VR center composed of a control station, three video projectors (not visible on the figure above), a semicylindrical screen and stereoscopic glasses.

In both conditions, the trajectory of the ball was visualized for 4 m: from the point of release (9 m) to the cut-off point (5 m). Both conditions were randomly presented to the participants. Based on the specific terms used by Farrow and Abernethy (2003), two response tasks were performed for each experimental condition:

– An uncoupled task: goalkeepers had to move their hand to the position in the goal where they thought the ball would have ended up. This action had to be made as quickly as possible after viewing the throwing action. To evaluate the position shown by the goalkeeper, the central position of each hand was computed from the markers. When the hand was located in the zone corresponding to the ball trajectory, it was considered as a 'correct zone' judgment. Thus the percentage of correct zones was calculated for each subject. The radial error between hand and ball was then computed (see Fig. 4). This error corresponds to the distance between the final position of the hand and the ball's virtual position in the hand plane. The response was considered successful when hand and ball circles intersected, allowing the computation of the percentage of correct responses.
– A coupled task: the goalkeeper had to stop the virtual ball as in a real match situation. To determine if one of his limbs has intercepted the ball, all his limbs were recorded in real-time and represented as cylinders (trunk, arms, forearms, thighs, shanks and feet) and spheres (head and hands) into the virtual environment. Then, as the motion capture system and the VR center were synchronized, we computed the distance between all the body segments and the ball at each frame. By recording the minimal distance of the nearest segment, we were able to detect collision between the real goalkeeper's limbs and the virtual ball in real time. The percentage of correct responses and radial error (and its components) were then computed as depicted in Fig. 5. In addition to these data, a specific parameter is also computed for the coupled task: the goalkeeper's response time which corresponds to the interval of time between the release of the virtual ball and the peak acceleration of the goalkeeper's forearm (Vignais et al., 2009).

The six throwing actions previously selected were randomly presented in VC and VE conditions. Only the ball trajectories corresponding to zones 1, 3, 4 and 6 are used for the study because goalkeepers randomly used their upper limbs or lower limbs to stop the virtual ball in zones 7 and 9. Nevertheless, throwing actions towards these two zones were randomly included in the protocol to vary end positions of the ball (each of these trajectories was repeated two times per condition and per response task). In addition, each ball trajectory of zones 1, 3, 4 and 6, and its associated throwing motion, was repeated three times for each condition. Thus 16 throws were displayed per condition and per response task. Finally, each participant had to react to a total of 64 trials. A short break was given half way through the experiment.

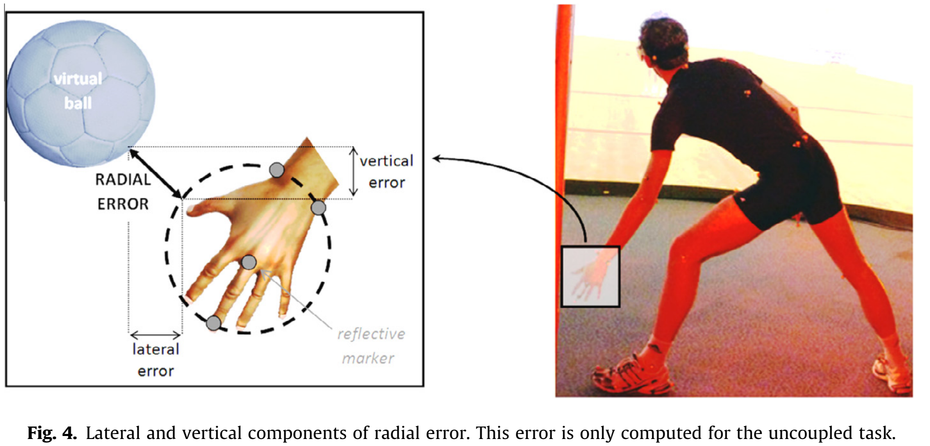

Fig. 4. Lateral and vertical components of radial error. This error is only computed for the uncoupled task.

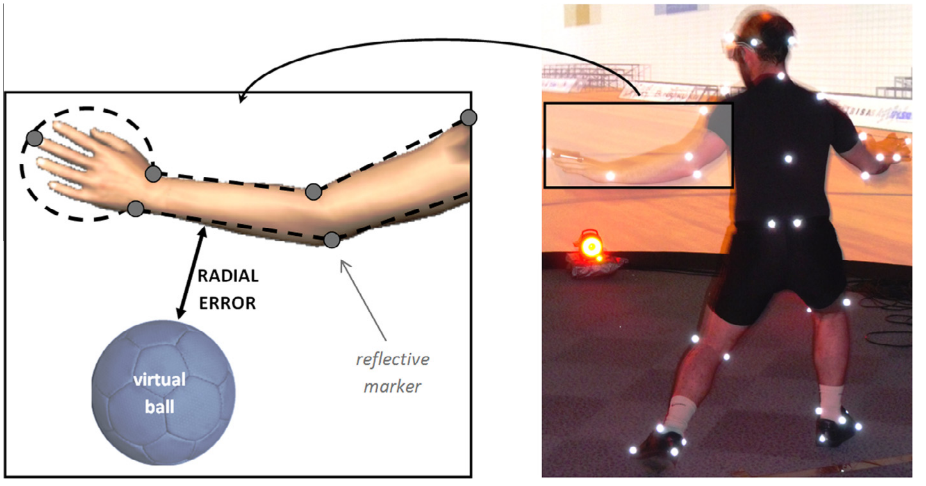

Fig. 5. Radial error representation (lateral and vertical components have not been schematized) for the coupled task.

2.3. Data analysis

The dependent variables in this study were: the percentage of correct zones (for the uncoupled task only), the percentage of correct responses, the radial error and the goalkeeper's response time (for the coupled task only). The independent variables corresponded to the condition (VC vs. VE), the response task (uncoupled vs. coupled task) and the targeted zone in the goal (zones 1, 3, 4 and 6). Thus a series of 2 (conditions) × 2 (response tasks) × 4 (targeted zones) repeated measures analysis of variance (ANOVA) was used to assess the percentage of correct responses and the radial error ($\propto = 0.05$). Moreover, for the radial error statistical analysis, we also examined the dimensions separately, namely the lateral and the vertical components, as it has been previously reported that using video clip may induce a lack of accuracy in height perception (Abernethy, 1987, 1990; Salmela & Fiorito, 1979; Williams & Burwitz, 1993; Williams et al., 1999). As the percentage of correct zones and the goalkeeper's response time were associated with a specific response task, a series of 2 (conditions) × 4 (targeted zones) repeated measures ANOVA was used to examine these dependent variables ($\propto = 0.05$). Significant effects were further investigated using Tukey's HSD post hoc analysis (RDCT, 2011).

3. Results

3.1. Percentage of correct zones

The percentage of correct zones corresponded to the ratio of the number of predictions in the correct zone divided by the total number of trials in that zone. This variable was calculated for the uncoupled task only.

Fig. 6 shows that handball goalkeepers judged more correct zones in the VE condition comparing to the VC condition (mean ± *SD* were 78.1 ± 26.9% for VC and 91.6 ± 18.3% for VE). This difference appears significant after performing an ANOVA ($F_{1,9} = 27.3$, $p < .001$). No significant difference was found between zones targeted ($F_{3,27} = 0.5$, $p = .69$) and no interaction effect appeared between zones and projection ($F_{3,27} = 0.57$, $p = .64$).

3.2. Percentage of correct responses

A response was considered correct if the final position of the hand intersected the final position of the virtual ball for the uncoupled task (see Fig. 4). For the coupled task, a contact between one of the goalkeeper's limbs and the virtual ball corresponded to a correct response (see Fig. 5).

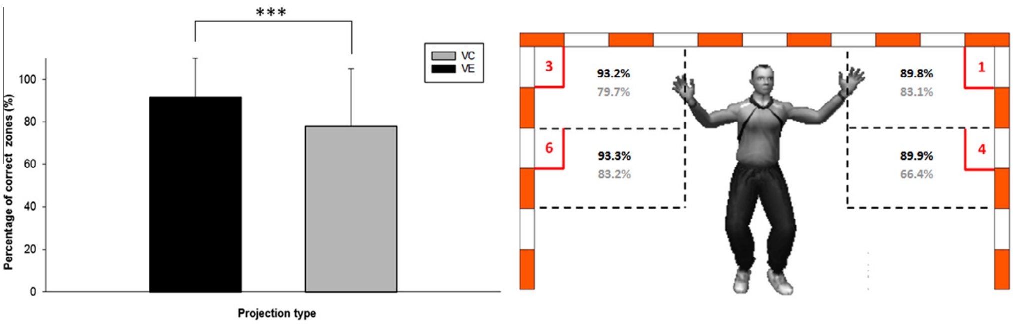

Fig. 6. Percentage of zones correctly judged for all trials (left) and for each zone (right) during the uncoupled task (***$p < .001$).

From Fig. 7, one can observe that handball goalkeepers were significantly more efficient for the VE condition than for the VC condition during the uncoupled task (mean ± *SD* were 24.2 ± 6.8% for VC and 32.9 ± 7.2% for VE) and the coupled task (26.3 ± 8.9% for VC and 37.1 ± 7.6% for VE) ($F_{1,9} = 15.28$, $p < .01$). However, no significant differences were found between response tasks ($F_{1,9} = 1.63$, $p = .23$) or between zones ($F_{3,27} = 0.44$, $p = .73$). Moreover, no interaction effect was found between conditions and response tasks ($F_{1,9} = 0.23$, $p = .64$), between conditions and zones ($F_{3,27} = 0.18$, $p = .91$), and between response tasks and zones ($F_{3,27} = 1.75$, $p = .18$).

3.3. Radial error

During the uncoupled task, the radial error corresponded to the minimal distance between the final position of the hand and the virtual ball (see Fig. 4). During the coupled task, the radial error was equal

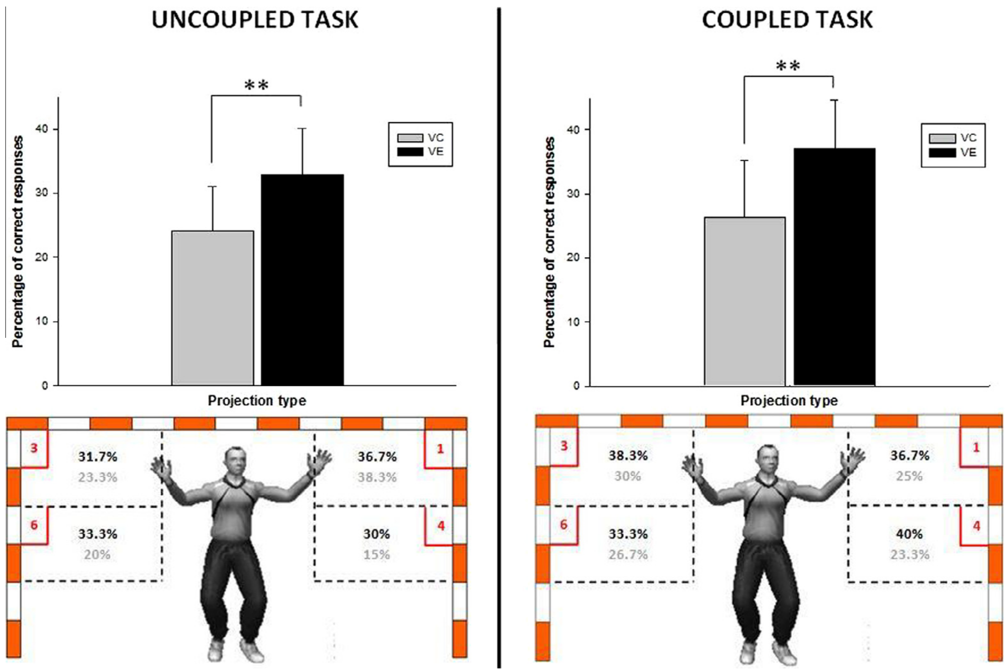

Fig. 7. Percentage of correct responses for uncoupled and coupled tasks for all trials (top) and for each zone (bottom) (**$p < .01$).

to the minimum distance between the virtual ball and the closest goalkeeper's limb at any time of the interceptive action (see Fig. 5).

In Fig. 8, one can observe that the radial error is higher for the VC condition in lateral (during the uncoupled task, mean ± *SD* were 9.5 ± 1.8 cm for VC and 7.5 ± 1 cm for VE; during the coupled task, 10.9 ± 4.8 cm for VC and 6.9 ± 2.3 cm for VE), in vertical (during the uncoupled task, 11.6 ± 2.4 cm for VC and 7 ± 0.8 cm for VE; during the coupled task, 13.1 ± 6.5 cm for VC and 6.8 ± 2.4 cm for VE) and in absolute (during the uncoupled task, 15 ± 2.5 cm for VC and 10.3 ± 0.8 cm for VE; during the coupled task, 17.1 ± 6.5 cm for VC and 9.7 ± 2.2 cm for VE). The less important accuracy observed for the VC condition was significant for zones 4 ($p < .05$) and 6 ($p < .05$) during the coupled task.

There was a statistically significant condition × response task interaction effect on radial error in lateral ($F_{1,9} = 13.04$, $p < .01$), in vertical ($F_{1,9} = 6.56$, $p < .05$) and in absolute ($F_{1,9} = 13.38$, $p < .01$). Post-hoc analyses revealed that this interaction effect was due to a higher radial error in VC condition than in VE condition when considering only results obtained during the uncoupled task (lateral: $p = .2$; vertical: $p < .01$; absolute: $p < .001$). The same report has been made during the coupled task (lateral: $p < .001$; vertical: $p < .001$; absolute: $p < .001$). Goalkeepers were also significantly less accurate in VC condition during the uncoupled task than in VE condition during the coupled task (lateral: $p < .05$; vertical: $p < .01$; absolute: $p < .001$). In the same lines, radial error was significantly greater in VC condition during the coupled task than in VE condition during the uncoupled task (lateral: $p < .01$; vertical: $p < .001$; absolute: $p < .001$).

Moreover, there was a significant difference between lateral and vertical components of the radial error during the VC condition after running a paired *t*-test ($t_{79} = 2.04$, $p < .05$). Conversely, no statistical difference was observed between lateral and vertical components for the VE condition ($t_{79} = -0.71$, $p = .24$).

Finally, there was no interaction effect between conditions and zones targeted ($F_{3,27} = 1.13$, $p = .36$), and between response tasks and zones ($F_{3,27} = 0.69$, $p = .57$).

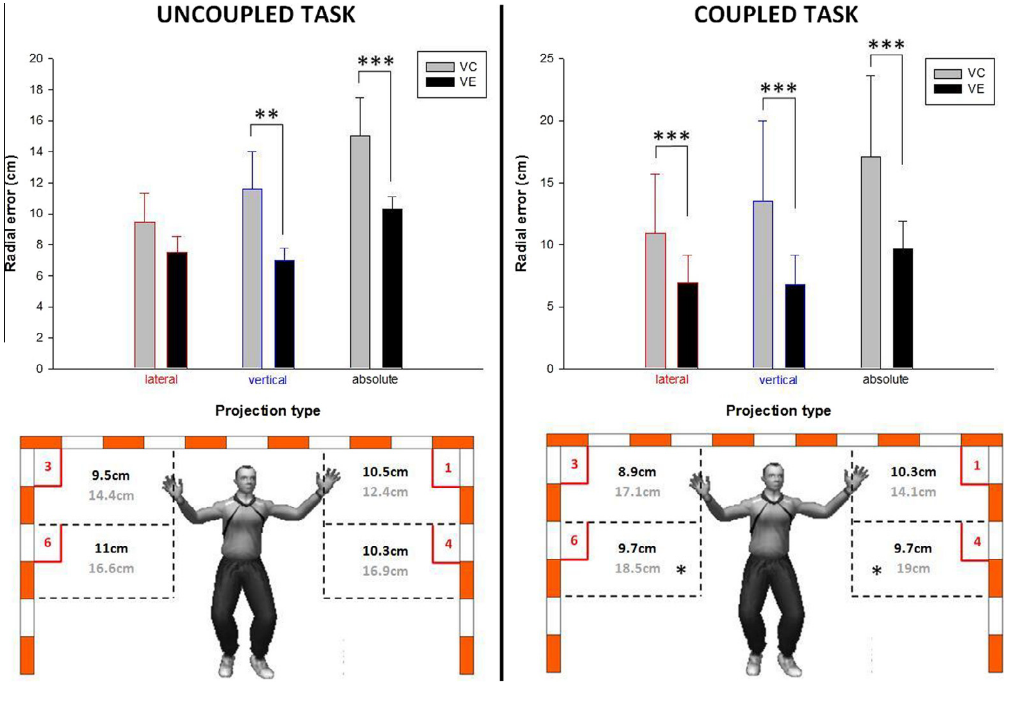

Fig. 8. Lateral, vertical and absolute components of the radial error for uncoupled and coupled tasks for all trials (top). For each zone (bottom), only significance between absolute components of the radial error were given (*$p < .05$; **$p < .01$; ***$p < .001$).

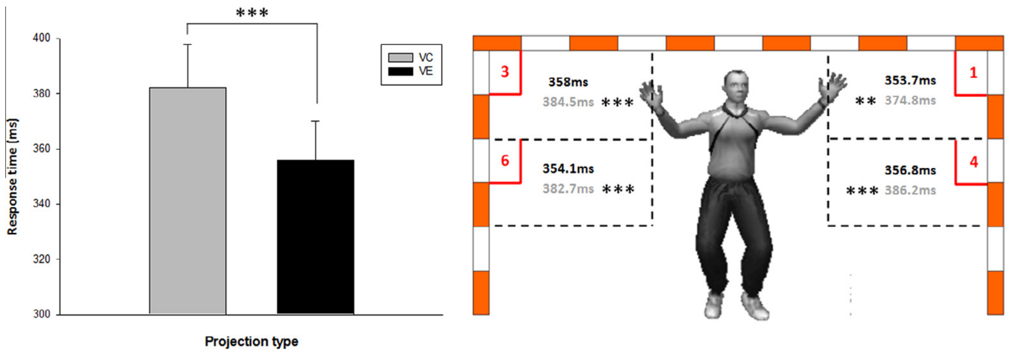

Fig. 9. Response time according to the VC or VE condition. Mean values are given in total (left) and for each zone (right) (**$p < .01$; ***$p < .001$).

3.4. Response time

During the coupled task, we also established the response time differences across both visual conditions and for each goal zone (see Fig. 9).

According to Fig. 9, one can see that handball goalkeepers began their interceptive motion earlier when facing the virtual animation (mean ± *SD* were 382.1 ± 15.7 ms for VC and 355.9 ± 14.3 ms for VE). Thus a main effect of the projection type was found related to the goalkeepers' response time ($F_{1,9} = 76.4$, $p < .001$). Moreover, there was no effect of the zones targeted ($F_{3,27} = 1.13$, $p = .36$), and no interaction effect between conditions and zones ($F_{3,27} = 0.34$, $p = .8$).

Moreover, to show the relationships between the goalkeeper's response timing and the quality of his response, we computed the Pearson correlation coefficients between the 'response time' and the 'percentage of correct responses' ($r_{78} = -.24$, $p < .05$), and between the 'response time' and the 'radial error' ($r_{78} = .41$, $p < .05$). Although these coefficients appear weak, they are both significant according to the number of degrees of freedom, that is, the threshold value for significance is 0.22 for 78 degrees of freedom (Pearson & Haetlet, 1976) for a 95% confidence interval.

4. Discussion

This study aimed to determine which technology is more appropriate for visual perceptual analysis in simulated sport situations: video clips (VC condition) or virtual environments (VE condition). This comparison has been made on the performance of handball goalkeepers for two kinds of perceptive judgment tasks usually performed in the literature: uncoupled and coupled tasks. In the uncoupled task, the goalkeeper just shows with his hand where he thinks the ball will be. To evaluate performance with the two technologies, the percentage of correct responses and the radial errors are analyzed. The percentage of correct zones has also been computed during the uncoupled task. In the coupled task, the goalkeeper tries to intercept the ball as in a real situation. An additional parameter is then analyzed: the response time.

For the two tasks (uncoupled and coupled), the results showed that the percentages of correct zones and correct responses were significantly greater for VE condition than for VC condition. In the same way, the radial error was significantly lower for VE condition than for VC condition. The goalkeeper's performance is thus better with the VE condition. Concerning the response time computed only for the coupled task, the results showed significantly smaller values for the VE condition; the participants were thus faster to start their interceptive task with this technology.

The first difference between VC and VE conditions that may explain the better performance within the virtual environment is the stereoscopic information (stereoscopic vision and 3D adapted viewpoint). For example Lenoir and colleagues compared one-handed interceptive task performance of catchers with high and low binocular depth vision (Lenoir, Musch, & La Grange, 1999). Subjects with a low stereopsis made significantly more temporal errors than subjects with a high stereopsis. In the same way, Mazyn and colleagues asked participants with normal and weak stereopsis to catch tennis balls with monocular and binocular viewing at three different speed conditions (Mazyn et al., 2004). They found that the negative effects of a lack of stereovision increases as temporal constraints become more severe. These findings relate to the response times obtained in the current study. During the coupled task, goalkeepers were significantly faster in front of virtual environments than video clips. The significant correlations between response time and percentage of correct responses on one side, and radial error on the other side, showed that this faster reaction of the goalkeeper is linked to a better performance. This result suggested that, when facing the video-recorded throwing action under time pressure, goalkeepers need more time to get sufficient visual information to initiate a successful reaction.

Another important difference between VC and VE conditions is the presence of head tracking in the latter. Hale and Stanney have shown that, when head tracking is used, subjects with a deficient stereovision can perform similarly to normal sighted subjects and experience a comparable sense of presence when viewing through stereoscopic displays (Hale & Stanney, 2006). Thus, motion parallax cues can be considered as a decisive factor of performance. The fact that goalkeepers can freely move their head in both uncoupled and coupled tasks may thus partly explain the better performance observed in virtual environment. Moreover, when using the VC-based technique in association with the occlusion paradigm, like in the current study, the lack of visual information due to this occlusion may lead to movement variations (Pinder, Davids, Renshaw, & Araújo, 2011). This argument may also help clarifying why lower performance has been obtained for the VC condition in this study.

Our results demonstrate that there is a significant lack of accuracy in height perception when using video clips (see Fig. 8). This is in accordance with previous studies from the literature (Abernethy, 1987, 1990). Salmela and Fiorito examined the visual cues used in ice hockey goalkeeping by using the temporal occlusion paradigm (Salmela & Fiorito, 1979). They proved that subjects were more successful in predicting the side rather than the height of the shot. In the same way, Williams and Burwitz asked subjects to watch video clips of five different soccer players kicking penalties (Williams & Burwitz, 1993). Participants had to indicate to which of the four corners of the goal the ball was directed to. Results showed that 62% of errors were associated with incorrect height predictions and 25% with incorrect side predictions. As this lack of accuracy was not significant for the VE condition, it may be related to the loss of dimensionality associated with the two-dimensional video projection (Williams et al., 1999). Although the perception of distance in VE may also be questionable according to the projection modality employed and the measurement protocol used (Grechkin, Nguyen, Plumert, Cremer, & Kearney, 2010), our results indicated that the influence of distance perception on goalkeeper's performance was more affected in the VC condition.

In our results, there was an interaction effect of the response task and the condition on the goalkeepers' accuracy (see Fig. 8). The goalkeeper was more precise during the coupled task in VE condition than during the uncoupled task in VC condition. This result may be of interest when researchers have to select a type of task to investigate visual perception during simulated experimental designs. Only a few studies from the literature have aimed to compare the influence of the response condition on the participant's performance. For instance, Farrow and Abernethy have studied the influence of an uncoupled and a coupled tasks on tennis players' judgment predictions (Farrow & Abernethy, 2003). They showed that expert players' predictions were more accurate in the coupled task than in the uncoupled task, like in our study. In a more recent study by Ranganathan and Carlton (2007), the influence of the task on baseball batting was investigated in a virtual environment. The authors examined the batters' ability to distinguish between two kinds of pitches under two response conditions. In the uncoupled task, batters had to verbally predict the type of pitch, and in the coupled task, batters were asked to swing a baseball bat to try and hit a virtual ball. Contrary to our findings, they showed that batters were more precise in the uncoupled task than in the coupled task. The authors explained their conflicting results by the difficulty of the task: there was a large difference between swinging a bat with temporal constraints and predicting the type of pitch verbally. In the current study, the degree of difficulty may also explain why there is low impact of the response task. In the uncoupled task, we asked participants to move their hand, which may appear more difficult than verbally predicting the final zone in the goal. However, even if selecting the final position of the ball with the hand is more physically difficult than a verbal description, geometric differences exist between measures used to evaluate performance for each task: for the uncoupled task, only the hand was used to compute the error while in the coupled task, when the goalkeeper tries to intercept the virtual ball, anybody segment was used to compute the error. The comparison of the two tasks thus has to be taken with caution.

Movement kinematics of the handball thrower may also be questioned as it has been obtained while facing a video camcorder, and not a real handball goalkeeper. Although the same type of protocol has been used to analyze movement kinematics in handball (Schorer, Baker, Fath, & Jaitner, 2007), visual perception in rugby (Jackson, Warren, & Abernethy, 2006), cricket (Müller et al., 2006), and tennis (Fukuhara et al., 2009), a video clip does not necessarily represent an action performed in a real situation (Shim, Carlton, & Kwon, 2006). However, as the kinematics of the throwing motion were the same for both projection technologies, it did not affect our results.

Concerning the timing of the motor response during the coupled task, we showed that goalkeepers were significantly faster in front of virtual environments than video clips, and that this timing was correlated to a better performance. However, we did not provide information about being "at the right place at the right time" (Peper, Bootsma, Mestre, & Bakker, 1994). More precisely, time was taken into account in the detection of collision since the radial error was computed at each frame. This meant that, if the hand was on the ball trajectory but not at the right instant, there was no collision detected between them. Nevertheless, data processing did not allow to know if the goalkeeper was late or in advance when he missed the ball. Future works will have to take this timing into account.

In future work, it could also be interesting to evaluate the influence of each parameter separately, i.e. head tracking and stereovision, in order to assess their relative impact on performance. As this contribution may be different according to the experimental situation and temporal constraints, it would be interesting to evaluate the influence of these parameters in different simulated sport situations. VE-based and VC-based projection techniques could also be used throughout a training program to evaluate their impact on perceptual skills acquisition.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.humov.2014.10.006.

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