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# **Virtual thrower vs. real goalkeeper: influence of different visual conditions on performance**

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## **Abstract**

In order to use virtual reality as a sport analysis tool, we need to be sure that an immersed athlete reacts realistically in a virtual environment. This has been validated for a real handball goalkeeper facing a virtual thrower. However we currently ignore which visual variables induce a realistic motor behaviour of the immersed handball goalkeeper. In this study we used virtual reality to dissociate the visual information related to the movements of the player from the visual information related to the trajectory of the ball. Thus, the aim is to evaluate the relative influence of these different visual information sources on the goalkeeper's motor behaviour. We tested 10 handball goalkeepers who had to predict the final position of the virtual ball in the goal when facing: only the throwing action of the attacking player (TA condition), only the resulting ball trajectory (BA condition), and both the throwing action of the attacking player and the resulting ball trajectory (TB condition). Here we show that performance was better in the BA and TB conditions, but contrary to expectations, performance was substantially worse in the TA condition. A significant effect of ball landing zone does, however, suggest that the relative importance between visual information from the player and the ball depends on the targeted zone in the goal. In some cases, body-based cues embedded in the throwing actions may have a minor influence than ball trajectory and vice versa. Kinematics analysis was then combined to these results to determine why such differences occur depending on the ball landing zone and consequently how it can clarify the role different sources of visual information play on the motor behaviour of an athlete immersed in a virtual environment.

## 1. Introduction

Virtual reality is now being used as a tool to analyze and understand motor behavior in sport ([Katz et al., 2006](#); [Bideau et al., 2010](#)). This promising technology has a number of advantages over video presentation or real-game situations. Firstly, all factors can be controlled and manipulated in a systematic manner, ensuring reproducibility between trials ([Tarr & Warren, 2002](#)). Secondly, the effects of these modifications on resulting behaviour can be monitored in real-time. Thirdly, the immersion of the subject in the virtual scene in an egocentric position allows the optical information gleaned from the virtual world to correspond directly to what the participant would see in a real sporting situation ([Cutting, 1997](#)). Finally, the participant's view point is stereoscopic which has previously been highlighted as an important factor when performing interceptive tasks ([Mazyn, Lenoir, Montagne & Savelsbergh, 2004](#)). Given these advantages, this technology has been exploited to analyze and understand players' performance in different sports such as soccer ([Craig, Berton, Rao, Fernandez & Bootsma, 2006](#)), tennis ([Molet et al., 1999](#)), handball ([Bideau et al., 2004](#); [Vignais et al., 2009](#)) and rugby ([Brault, Bideau, Kulpa & Craig, 2009](#)). Moreover this technology can be employed to test team sport strategies ([Metoyer & Hodgins, 2000](#)) or to train athletes in a simulator ([Kelly & Hubbard, 2000](#)). With respect to this latter option, [Kelly and Hubbard \(2000\)](#) have successfully designed a complete bobsled simulator which displays a graphical representation from the driver's viewpoint on a cockpit-mounted monitor.

In spite of these advantages, using virtual reality as a sports analysis tool does raise new questions. One of the most important is the motor response of the athlete immersed in a virtual environment. In fact, the motor behaviour of a subject can be considered as one of the physical measures of presence ([Slater et al., 1996](#); [Slater et al., 2009](#)). In sport, this concept has been used to validate a virtual sport situation. Indeed, [Bideau et al. \(2003\)](#) compared the

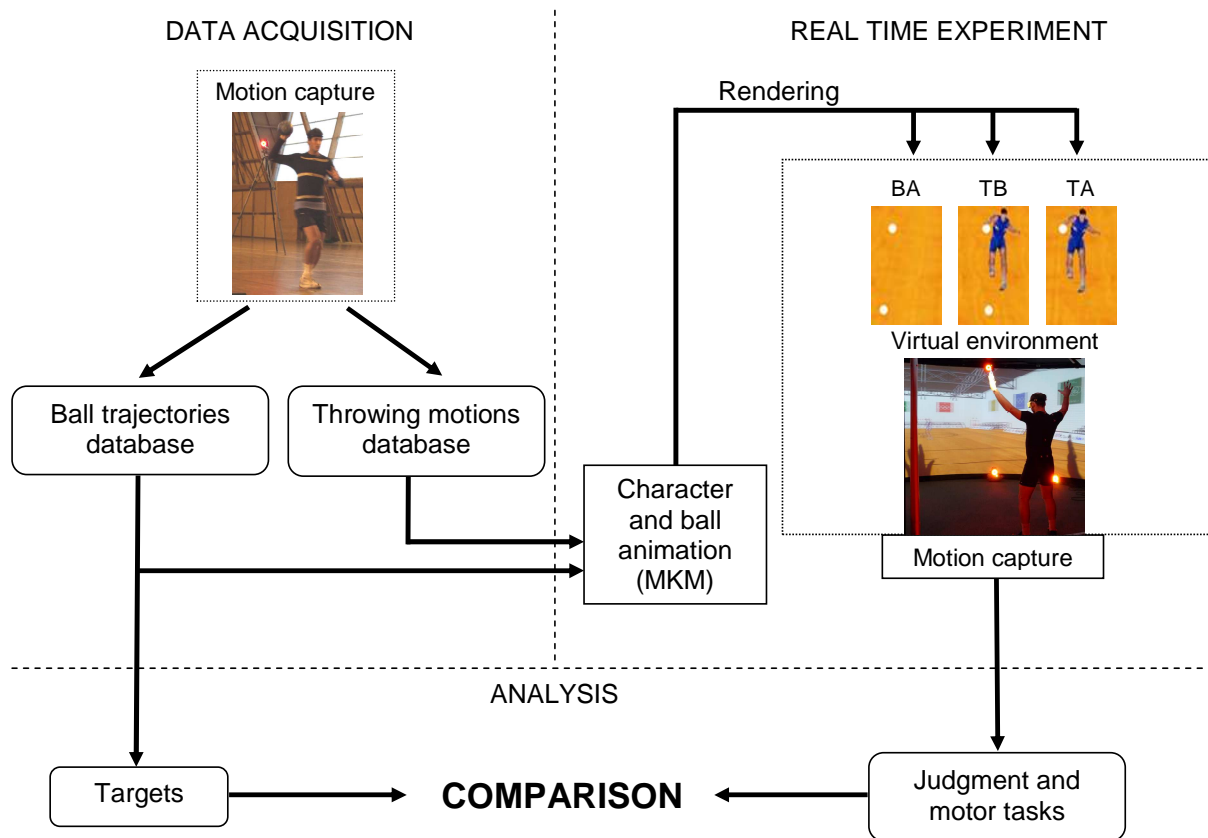
movement of handball goalkeepers during the interception of the same throws made by real and virtual opponents. The results showed that the goalkeepers' gestures in both environments were similar. Nevertheless, of the virtual sport situation used in this case study induced handball goalkeepers to respond realistically, the reason of this motor behaviour remains unanswered. Are some visual elements displayed in the virtual scene more important than others to enable handball goalkeepers to react in a realistic way?

In most ball sports, successful anticipation of what an opponent is going to do next can give a substantial competitive edge. The temporal constraints within a player must act are often very tight, and so early recognition of an opponent's actions or anticipation of where the ball is going can increase the player's chances of making a successful counteracting move. Much of the research to date has focused on identifying the sources of visual information that players use to anticipate an opponent's next move ([Abernethy, Wood & Parks, 1999](#)). While some studies have suggested that successful anticipation is determined by the perception of spatial-temporal information in the trajectory of the ball ([Bastin, Craig & Montagne, 2006](#); [Craig et al., 2006](#); [Lenoir, Musch, Thiery & Savelsbergh, 2002](#); [McLeod, Reed & Dienes, 2006](#)), others have shown that successful anticipatory behaviour depends on the accurate perception of body-based cues ([Jackson, Warren & Abernethy, 2006](#); [Panchuk & Vickers, 2006](#); [Savelsbergh, Williams, Van der Kamp & Ward, 2002](#); [Williams, Davids, Burwitz & Williams, 1994](#)). The general consensus suggests that when the temporal constraints are too tight (e.g. a penalty kick in soccer), players do not have enough time to act on ball trajectory information and consequently use body-based cues ([Savelsbergh, Van der Kamp, Williams & Ward, 2005](#)). In spite of this conclusion, the relative contribution of body-based versus ball flight information in performance has not been properly tested.

Here, we suggest to present body-based cues and ball trajectory information in isolation in order to better assess the relative importance of both types of visual information for performance. Using immersive interactive virtual reality, this study allows dissociation between body-based cues and ball flight information. The relative importance of these two visual elements in performance will be assessed in order to understand why an athlete tends to respond realistically to a virtual sport situation. To this end, we investigate the effects of different visual conditions of a virtual throwing action on the performance of immersed handball goalkeepers.

## **2. Overview**

In order to evaluate the influence of the different visual conditions of a throwing action on the handball goalkeepers' performance, we developed a three-step process (see **Erreur ! Source du renvoi introuvable.**):



**Figure 1: The three-step process includes data acquisition, real time experiment and performance comparison**

- First of all, to realistically animate the synthetic thrower and the ball in the virtual environment, we captured real throwing actions. This led to the creation of a large motion database with throws to various places in the goal.
- Secondly, these captured throws were used by the MKM animation engine (Kulpa, Multon & Arnaldi, 2005; Multon, Kulpa & Bideau, 2008) in order to realistically animate the virtual character. The rendering of these animations was done with three different visual conditions.
- Finally, the movements of the goalkeepers were captured in real time. These data were then analyzed to determine which responses were successful.

### 3. Motion capture and animation process

In order to animate the virtual character and ball, real handball throwing actions were recorded. A VICON motion capture system (Oxford Metrics, Oxford, UK) was used to record movement kinematics from three top-level handball players. All the throwers were right-handed and had at least ten years experience playing handball in the top French league at the time of the study. Each player was equipped with 36 reflective markers placed on anatomical landmarks to precisely reconstruct the 3D position and orientation of each limb segment, with six markers being reserved for the ball. Each player was asked to throw the ball 12 m from the goal, aiming for different pre-specified target zones within the goal (no goalkeeper was present). For each throw, the participant and ball movement were captured at 200 Hz using 12 infrared cameras. Nine trajectories that arrived close to the centre of each zone were selected and used in the subsequent virtual animation part of the study (see Figure 2).



**Figure 2: handball goal mouth divided into nine zones. Although all of the nine zones were aimed at by the thrower, only zones 1, 3, 4 and 6 were used in the forthcoming analysis.**

Kinematic throwing data, captured using the VICON system, were then incorporated into the MKM (Manageable Kinematic Motion) animation engine ([Kulpa et al., 2005](#); Multon et al.,



2008) to animate the virtual handball player in real time. Based on these captured motions, MKM can automatically synchronize, blend, and adapt actions to different morphologies and to external constraints such as foot contacts. Virtual ball trajectories for the nine zones were calculated using another software module that incorporates data obtained from the motion capture part of the study. Ball velocities were similar for all nine trajectories ( $20 \pm 0.2 \text{ m}\cdot\text{s}^{-1}$ ), making ball flight time very nearly the same for all nine zones.

A realistic handball stadium was created using 3dsmax (Autodesk Inc., San Rafael, CA, USA). The size of the virtual stadium was scaled so that one unit in the virtual environment corresponded to 1 m in reality. The virtual court was 20 m wide and 40 m long with a clearly marked semi-circular area (6 m radius) corresponding to the goal zone.

#### **4. Evaluation of goalkeepers' performance**

After animating the handball throwing actions, 10 elite male handball goalkeepers (playing in the top league and at national level) were placed in the virtual environment (see Figure 3).



**Figure 3: A goalkeeper immersed in the virtual environment.**

Mean age of the participants was 22.6 years (stdev=4.9 years), mean height was 1.81m (stdev=0.09m) and mean weight was 78.2kg (stdev=13.1kg). All participants had normal or corrected-to-normal vision. All participants gave their informed consent before the study began.

In order to enhance the behaviour of subjects, a real goal (3 m × 2 m) was placed where it was virtually represented in the computer generated environment. Goalkeepers were encouraged to touch the real goal posts to enhance the correspondence between virtual and real distances.

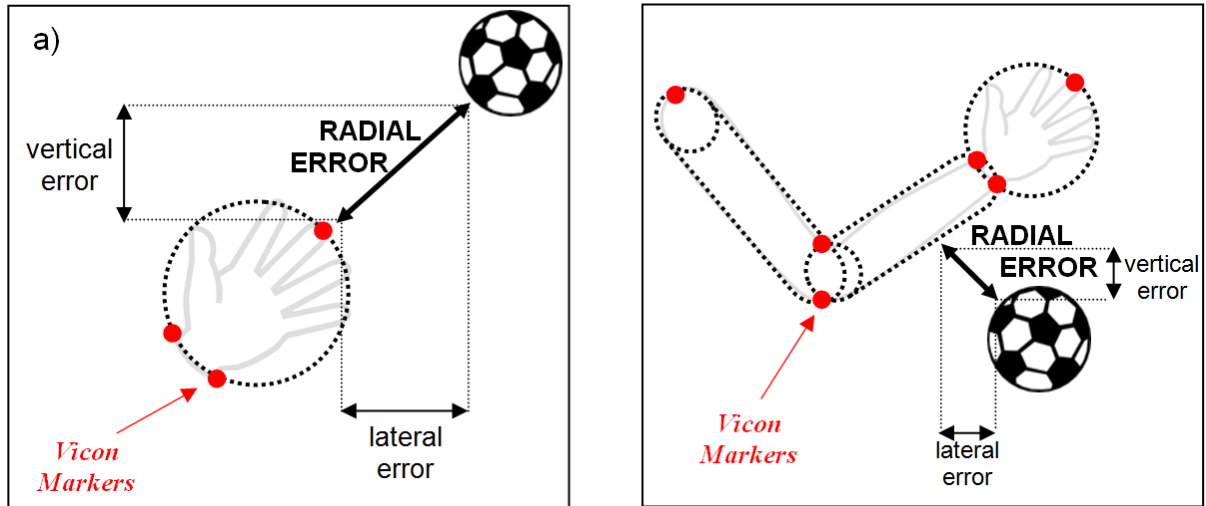
Three synchronised video projectors Barco 1208S (Barco, Courtrai, Belgium) driven by a SGI 83 Onyx2 Infinite Reality (Silicon Graphics, Sunnyvale, CA, USA) were used to project the 3D sports hall environment onto a large cylindrical screen (3.80 m radius, 2.38 m height, and 135° field of vision). A set of glasses synchronised with the system enabled stereovision (60 Hz). The Vicon motion capture system (12 cameras) was used to record goalkeeper's movements and was coupled to the virtual reality display. As the two systems were linked and the goalkeeper's head was tracked, it was possible to change the goalkeeper's perspective in the virtual world in real time (delay < 20 ms).

Three experimental conditions representing the different types of visual information were randomly presented to the participants. The 'ball only' condition (BA) involved the goalkeeper judging the arrival position of the ball while seeing only the trajectory of the ball from the point of release (12m) to the cut-off point (6m) (see Video1.avi), the 'thrower only' (TA) condition involved the goalkeeper making an action when presented with only the complete throwing action of the thrower (pre-release to release point) (see Video2.avi), and the 'thrower and ball' condition (TB) involved the goalkeeper making a judgment when presented with both the throwing action and the resulting ball trajectory (see Video3.avi). These three

experimental conditions allowed us to systematically isolate the two visual information sources a goalkeeper might use to guide his actions.

Two response modes were then performed: a motor task condition and a judgment task condition.

- Judgment task condition: in this experiment, the goalkeeper was equipped with only 11 reflective markers: 4 on their head for head tracking, 3 on their right hand, and 4 on their left hand to record final hand positions. The markers were placed on the hands in such a way that the central position of the hand could be easily calculated, with the additional marker allowing the left hand and right hand to be distinguished during analysis (see Figure 4a). After the end of the throwing action, goalkeepers were asked to then move their hand as quickly as possible to the position in the goal where they thought the ball would have ended up.
- Motor task condition: this experiment required the goalkeeper to get their limb to the right place at the right time to stop the virtual ball. The goalkeeper reacted to the same randomised throws displayed in the judgment condition. The goalkeeper was asked to react as if he was in a real match situation. Each goalkeeper was equipped with 36 optoelectronic markers placed on the same anatomical landmarks as in the motion capture part of the real handball throwing actions (see Figure 4b).



**Figure 4: Position of the optoelectronic markers, simplification of segment reconstruction and computation of the radial error in the judgment task condition (a) and in the motor task condition (b).**

Before the experiment began, each participant was given a training period to familiarise them with the environment and the task. During this time the participants randomly viewed a sample of three throws from each of the three visual information conditions (three BA throws, three TA throws, and three TB throws). Trials from the training period were not included in the subsequent analysis.

A total of four different trajectories were randomly presented for the different visual conditions. They corresponded to zones 1, 3, 4 and 6 (see Figure 2). The four different ball trajectories were randomly repeated five times for each condition giving a total of 20 throws per condition. 10 other throws to different target locations in the goal were randomly included so as to create more variability in end arrival position for the goalkeeper. In fact a total of 140 trials  $[(5 \text{ repetitions per zone} \times 4 \text{ zones aimed} \times 3 \text{ visual conditions}) + 10 \text{ other throws}] \times 2$  response modes) were presented to each goalkeeper. A short break was given after each block of 30 trials.

In order to estimate and compare goalkeeper's perceptual and motor responses, two kinds of data analysis were performed:

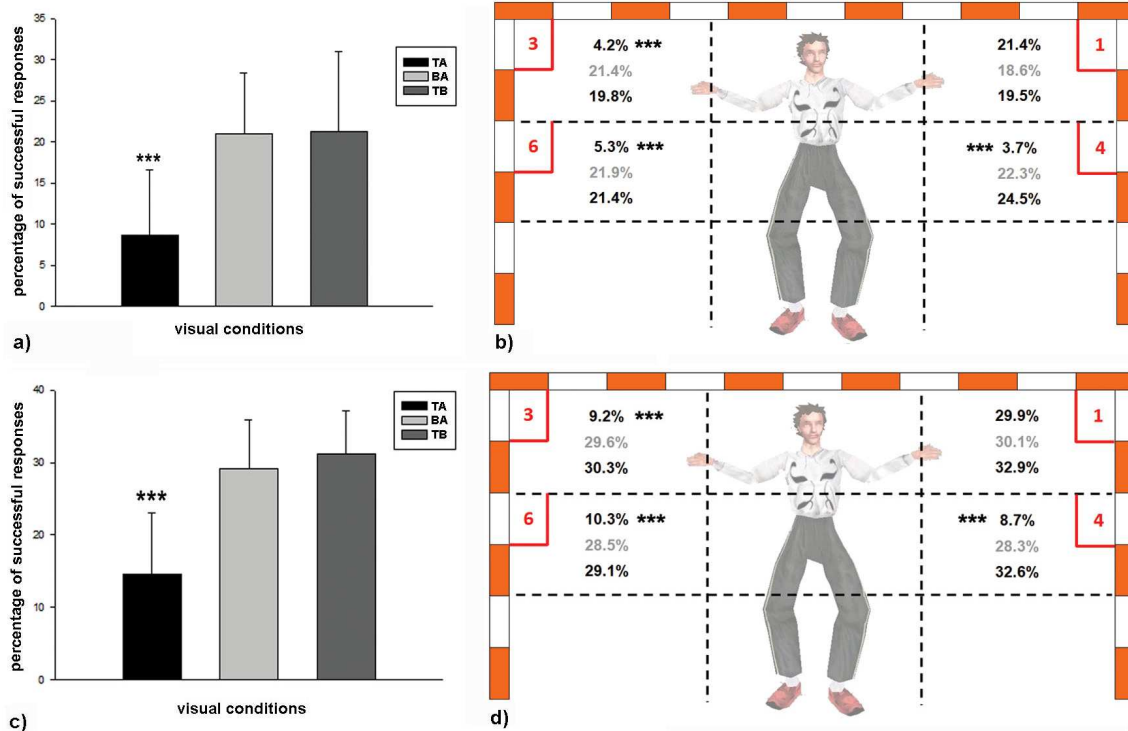
- Judgment task condition: the hand and the ball were both represented by spheres (see Figure 4a) during the process analysis. We calculated the radial error which was the difference between the final position of the hand and the virtual ball's arrival position in the goal mouth. As zero radial error equated a correct response we used this measure to calculate the percentage of successful judgments.
- Motor task condition: a detection of the collision process was used in the virtual environment by representing the goalkeeper's limbs as cylinders (trunk, arms, forearms, thighs, shanks and feet) and spheres (head and hands) from joint centre positions (see Figure 4b). This full body representation enabled us to determine if there was a collision between the virtual ball and the goalkeeper in real time (a visual feedback was displayed after each throw). The collision detection process provided us the percentage of successful interceptions.

## 5. Results

The first part of the analysis looked at how the different visual conditions influenced the participants' effectiveness. The percentage of successful responses was also analysed.

During the judgment task, a prediction was considered successful if the end-position of the hand sphere was in contact with the end-position of the ball sphere (see Figure 4a).

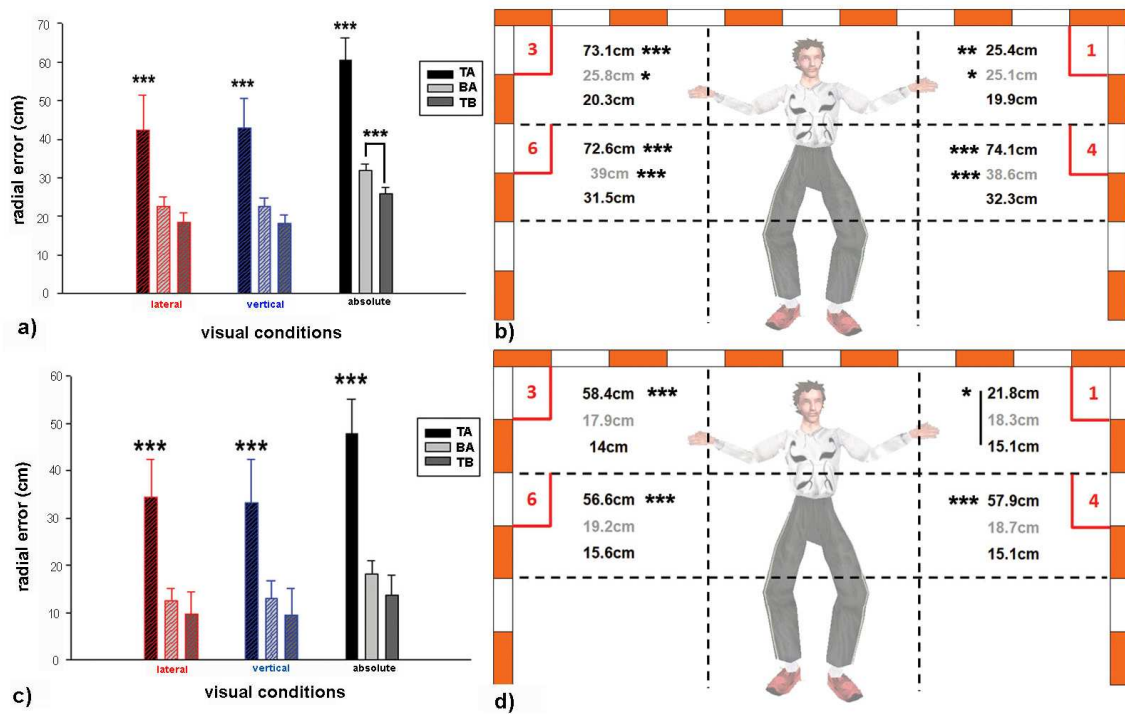
During the motor task, a parry was considered successful if the representation of the interceptive limb was in contact with the ball sphere (see Figure 4b).



**Figure 5: Mean percentage of correct responses for all goalkeepers during the judgment task (a) for each zone aimed (b), and during the motor task (c) for each zone aimed (d) (\*\*\*) ( $p < 0.001$ ).**

As expected, the participants were most successful when they were presented with TB information during the judgment task ( $21.3 \pm 9.7\%$ ) and during the motor task ( $31.2 \pm 5.9\%$ ) (see Figure 5a and 5c). The participants were only marginally less successful for the BA condition (judgment:  $21.1 \pm 7.3\%$ ; motor:  $29.1 \pm 6.7\%$ ), but performance was statistically worse with the TA information (judgment:  $8.6 \pm 7.9\%$ ; motor:  $14.5 \pm 8.6\%$ ) after a two-way repeated measures analysis of variance (judgment:  $F(2,54)=46.082$ ;  $p < 0.001$ ; motor:  $F(2,54)=100.226$ ;  $p < 0.001$ ). This marked reduction in performance for the TA condition was seen in all zones except zone 1 (see Figure 5b and 5d).

The second part of the analysis focuses on the influence of the different visual conditions on goalkeepers' accuracy. With this aim, the radial error was calculated and examined (see Figure 4).



**Figure 6: Mean radial error (and its lateral and vertical components) for all goalkeepers during the judgment task (a) for each zone aimed (b), and during the motor task (c) for each zone aimed (d) (\* $p<0.05$ ; \*\* $p<0.01$ ; \*\*\* $p<0.001$ ). Lateral and vertical components have not been represented in the goal (b and d).**

A repeated measures analysis of variance revealed a significant difference for the radial error between the different visual conditions during the judgment task ( $F(2,54)=803.501$ ;  $p<0.001$ ) and during the motor task ( $F(2,54)=257.762$ ;  $p<0.001$ ). A Tukey HSD post-hoc analysis shows that the radial error obtained for the TA condition (judgment:  $61.3\pm5.3$ cm; motor:  $47.8\pm7.3$ cm) was significantly greater than the BA

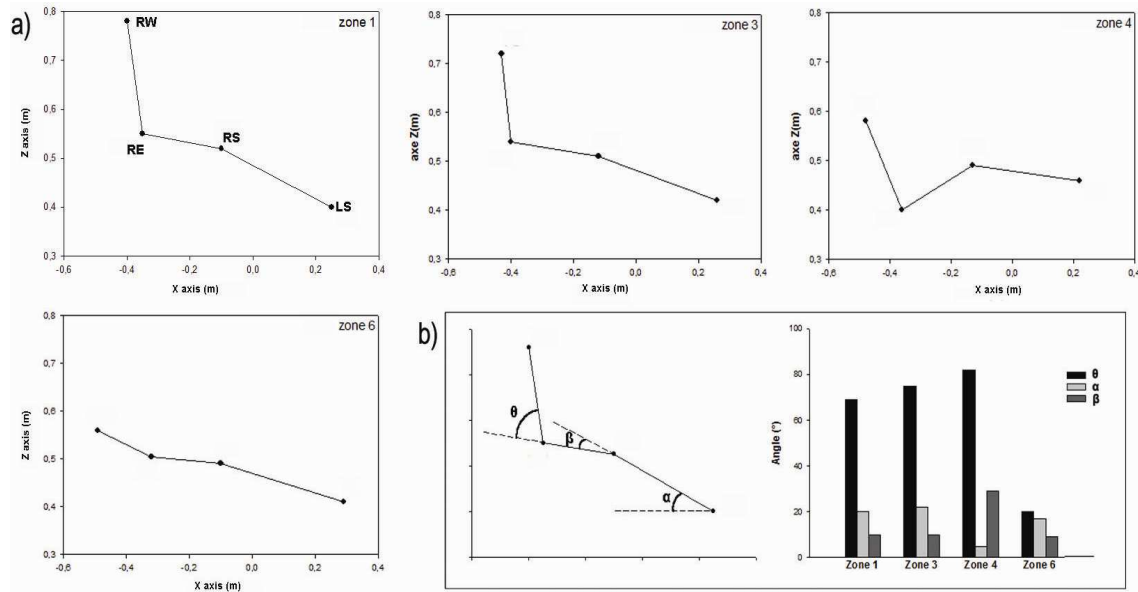
condition (judgment:  $31.8 \pm 1.4$ cm; motor:  $18.2 \pm 2.9$ cm) and the TB condition (judgment:  $26.2 \pm 1.8$ cm; motor:  $13.6 \pm 4.4$ cm).

## **6. Discussion**

The aim of this study was to see how different sources of visual information influence the goalkeepers' motor behaviour in a virtual environment. By separating the presentation of body-based movement cues and ball trajectory information, we were able to look at the relative contribution of each of them individually and together. The results show that body-based cues alone do not provide sufficient information for expert goalkeepers to accurately predict where the ball is going in the goal. Indeed, regarding the final limb position results, we obtained extremely larger errors for the TA condition compared to the BA and TB conditions. Although the BA condition was significantly more successful than the TA condition, it does not seem that seeing the throwing action with the ball trajectory (TB condition) improve performance compared to the BA condition, except for the goalkeepers' accuracy during the judgment task.

However, we observed a decrease in successful responses in all zones, except zone 1, for the TA condition. This finding could be explained by the biomechanical analysis of the throwing actions (see Figure 7).





**Figure 7: Segment configuration of the throwing action at ball release in frontal plane for each zone aimed (a) and histogram of related joint angles (b). The different joints represented are: left shoulder (LS), right shoulder (RS), right elbow (RE) and right wrist (RW).**

As it can be seen from Figure 7, the patterns of final limb positions are very similar for throwing actions in zones 1 and 3. Segmental positions and joint angle values of both throwing actions seem very close. It can be suggested that participants have confused the throwing actions for zone 3 for that of zone 1 (see Figure 7a). Moreover it is possible that goalkeepers were able to identify kinematic cues of the throwing action for zone 1. Given these similarities in final limb position, the last part of the analysis aims to see how the throwing actions differed. In other words, what biomechanical parameters changed most significantly from one throw to another? The analysis of body segment angles showed greatest differences in the elbow angle (see Figure 7b). Differences, though small, were also found for dipping of the shoulder and elevation of the elbow respectively to the shoulder. Although biomechanically these differences in limb segment orientation partly determine where the ball will land in the goal, they are

probably too subtle for the goalkeeper to use them as reliable visual information, except for throws in zone 1.

These findings are very interesting when considered in light of other research in this area. Previous studies have attempted to show that expertise in goalkeeping resides in the ability to pick up pertinent information from the movement kinematics of the attacking player ([Savelsbergh et al., 2002](#); Savelsbergh et al., 2005; Franks & Hanvey, 1997; Williams et al., 1994). In a virtual environment it seems that handball goalkeepers are able to use body-based cues only for specific throwing actions. Overall it would appear that body-based information on its own is not sufficient to make accurate judgements about (and consequently movements toward) where the ball will end up in the handball goal. Information picked up from the ball trajectory is necessary to refine judgement and motor tasks. This kind of visual information helps the handball goalkeeper to react in a realistic way in the virtual environment. A recent study by [Jackson and Mogan \(2007\)](#) also revealed the importance of ball flight information in making anticipatory judgements in tennis. Using a spatial occlusion technique to selectively omit key components of the tennis serve, they found the most detrimental effects in performance occurred when no ball information was present. Expert tennis players' performance in judging where the ball would land on the court was severely compromised, with the percentage of correct judgements falling to chance level. Interestingly when these same players were asked to judge the utility of different sources of information (body-based vs. ball), they claimed positional information pertaining to the arm and racquet was most informative.

## **7. Conclusion**

To conclude the results presented in this study help to clarify the role different sources of visual information play on the motor behaviour of an athlete immersed in a virtual environment. They reinforce the importance of being able to track at least part of the ball trajectory to correctly predict where the ball is going to end up. However, body-based cues can be significant depending on the throwing action. Future studies will attempt to see which kind of visual cues of the throwing movement can be detected. Moreover, these findings have to be compared with other virtual sport situations.

## **8. Acknowledgments**

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## References

- Abernethy, B., Wood, J. M., & Parks, S. (1999). Can the anticipatory skills of experts be learned by novices? *Research Quarterly for Exercise and Sport*, 70, 313–318.
- Bastin, J., Craig, C., & Montagne, G. (2006). Prospective strategies underlie the control of interceptive actions. *Human Movement Science*, 25, 718–732.
- Bideau B., Kulpa, R., Menardais, S., Fradet, L., Multon, F., Delamarche, P., & Arnaldi, B. (2003). Real handball goalkeeper vs. virtual handball thrower. *Presence: Teleoperators and Virtual Environments*, 12(4), 411-421.
- Bideau, B., Multon, F., Kulpa, R., Fradet, L., Arnaldi, B., & Delamarche, P. (2004). Using virtual reality to analyse links between handball thrower kinematics and goalkeeper's reactions. *Neuroscience Letters*, 372(1-2), 119-122.
- Bideau, B., Kulpa, R., Vignais, N., Brault, S., Multon, F., & Craig, C.M, (2010). Virtual reality, a serious game for understanding performance and training players in sport. *IEEE Computer Graphic Applications*, in press.
- Brault, S., Bideau, B., Kulpa, R., & Craig (2009). Detecting deceptive movements in 1 vs. 1 based on global body displacement of a rugby player. *International Journal of Virtual Reality*, 8(4), 31-36.
- Craig, C. M., Berton, E., Rao, G., Fernandez, L., & Bootsma, R. J. (2006). Judging where a ball will go: The case of curved free kicks in football. *Naturwissenschaften*, 93, 97–101.
- Cutting, J. E. (1997). How the eye measures reality and virtual reality. *Behavior Research Methods Instruments and Computers*, 29, 27-36.
- Franks, I. M., & Hanvey, T. (1997). Cues for goalkeepers. high-tech methods used to measure penalty shot response. *Soccer Journal*, 42, 30–38.

Jackson, R. C., Warren, S., & Abernethy, B. (2006). Anticipation skill and susceptibility to deceptive movement. *Acta Psychologica*, 123, 355–371.

Jackson, R. C., & Mogan, P. (2007). Advance visual information, awareness and anticipation skill. *Journal of Motor Behavior*, 39, 341–351.

Katz, L., Parker, J., Tyreman, H., Kopp, G., Levy, R., & Chang, E. (2006). Virtual reality in sport and wellness: promise and reality. *International Journal of Computer Science in Sport*, 4(1), 4-16.

Kelly, A., & Hubbard, M. (2000). Design and construction of a bobsled driver training simulator. *Sports Engineering*, 3(1), 13-24.

Kulpa, R., Multon, F., & Arnaldi, B. (2005). Morphology-independent representation of motions for interactive human-like animation. *Computer Graphics Forum*, 24(3), 343-352.

Lenoir, M., Musch, E., Thiery, E., & Savelsbergh, G. J. P. (2002). Rate of change of angular bearing as the relevant property in a horizontal interception task during locomotion. *Journal of Motor Behavior*, 34, 385–401.

Margery, D., Arnaldi, B., Chauffaut, A., Donikian, S., & Duval, T. (2002).

OpenMASK: Multi-threaded or modular animation and simulation kernel or kit: A general introduction. Proceedings from: *Virtual Reality International Conference 2002*,

Laval: S. Richir, P. Richard, B. Tavel eds.

Mazyn, L.I.N., Lenoir, M., Montagne, G., & Savelsbergh, G.J.P. (2004). The contribution of stereo vision to one-handed catching. *Experimental Brain Research*, 157(3), 383-390.

- McLeod, P., Reed, N., & Dienes, Z. (2006). The generalized optic acceleration cancellation theory of catching. *Journal of Experimental Psychology: Human Perception and Performance*, 32, 139–148.
- Metoyer, R., & Hodgins, J. (2000). Animating athletic motion by example. Proceedings from: *Graphics Interface 2000*, Montreal: M. McCool eds.
- Molet, T., Aubel, A., Capin, T., Carion, S., Lee, E., Magnenat-Thalmann, N., Noser, H., Pandzic, I., Sannier, G., & Thalmann, D. (1999). Anyone for tennis? *Presence: Teleoperators and Virtual Environments*, 8(2), 140-156.
- Multon, F., Kulpa, R., & Bideau, B. (2008). MKM: a global framework for animating humans in virtual reality applications. *Presence: Teleoperators and Virtual Environments*, 17(1), 17-28.
- Panchuk, D., & Vickers, J.N. (2006). Gaze behaviors of goaltenders under spatial-temporal constraints. *Human Movement Science*, 25, 733–752.
- Savelsbergh, G. J. P., Williams, A.M., Van der Kamp, J., & Ward, P. (2002). Visual search, anticipation and expertise in soccer goalkeepers. *Journal of Sports Sciences*, 20, 279–287.
- Savelsbergh, G. J. P., Van der Kamp, J., Williams, A. M., & Ward, P. (2005). Anticipation and visual search behaviour in expert soccer goalkeepers. *Ergonomics*, 48, 1686–1697.
- Slater, M., Linakis, V., Usoh, M., & Kooper, R. (1996). Immersion, presence and performance in virtual environments: An experiment with tri-dimensional chess. Proceedings from ACM VRST '96: *The ACM Virtual Reality Software and Technology*. Hong-Kong, China: ACM.

Slater, M., Khanna, P., Mortensen, J. & Yu, I. (2009). Visual realism enhances realistic response in an immersive virtual environment. *IEEE Computer Graphic Applications*, 29(3), 76-84.

Tarr, M. J., & Warren, W. H. (2002). Virtual reality in behavioral neuroscience and beyond. *Nature Neuroscience*, 5, 1089–1092.

Vignais, N., Bideau, B., Kulpa, R., Craig, C., Brault, S., & Multon, F. (2009). Virtual environments for sport analysis: perception-action coupling in handball goalkeeping. *International Journal of Virtual Reality*, 8(4), 2009.

Williams, A. M., Davids, K., Burwitz, L., & Williams, J. G. (1994). Visual-search strategies in experienced and inexperienced soccer players. *Research Quarterly for Exercise and Sport*, 65, 127–135.

## Figures Captions

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## **Supplementary Material Captions**

Video1.avi: view of the virtual throwing action in the 'ball only' condition (BA).

Video2.avi: view of the virtual throwing action in the 'thrower only' condition (TA).

Video3.avi: view of the virtual throwing action in the 'thrower and ball' condition (TA).